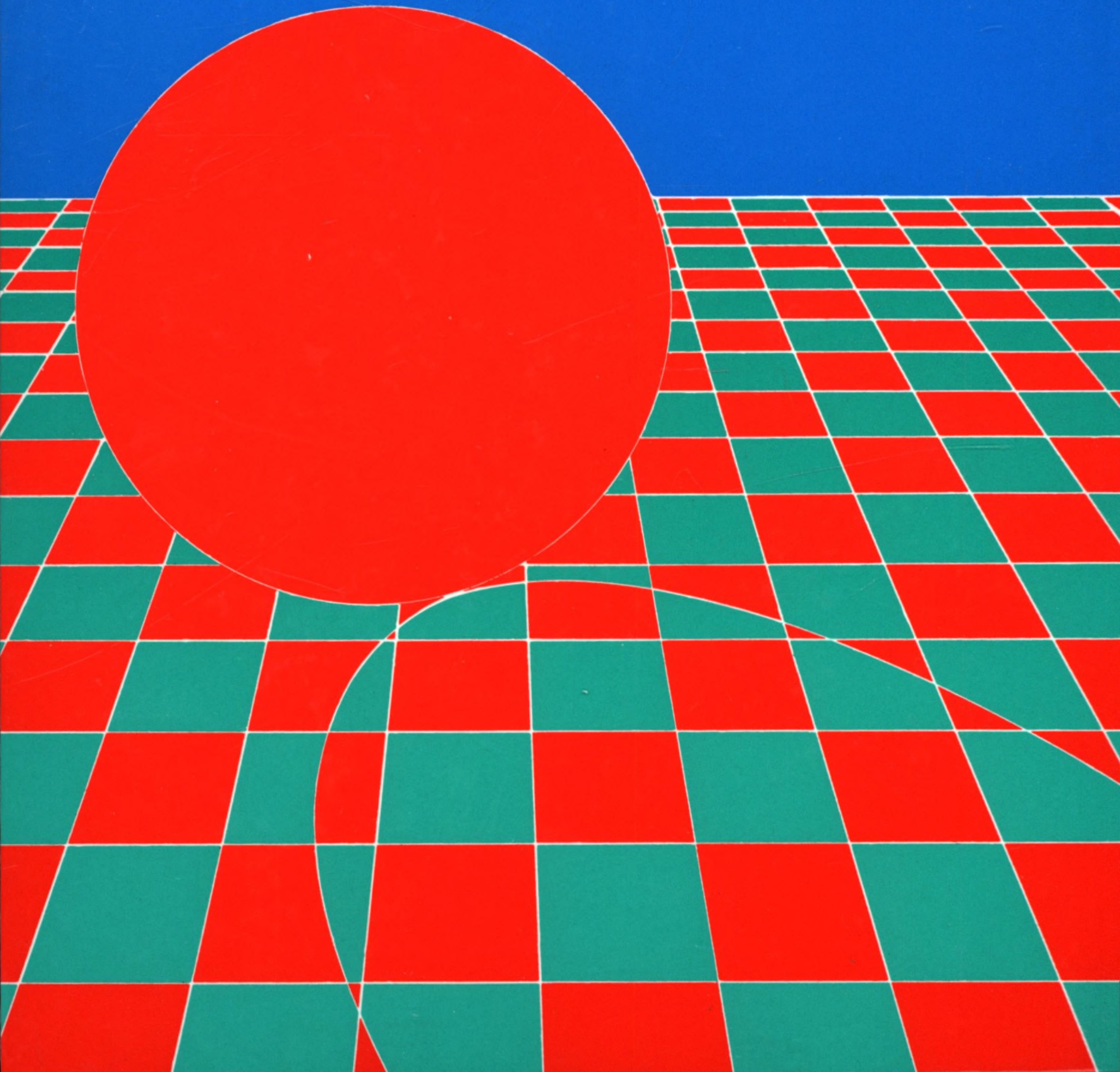
COLOUR DYNAMICS

environmental colour design

Antal Nemcsics



COLOUR DYNAMICS
Environmental Colour Design

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This book defines colour dynamics and their effect on the environment – the first book as far as the publishers are aware to look at man, his environment, and colour as an integral system.

The theory of environmental colour dynamics, including the fundamentals of chromatics, is comprehensively covered. Uniform colour space (which is directly related to colour stimuli), colour composition relationships resulting from colour vision processes, and the applicability of colour preference and colour-association test results in environmental design are discussed in detail.

There is thorough coverage of the psychosomatic effects of colour, colour harmony, and the relations between colour and space, colour and function, colour and illumination, colour and environmental damage, and colour and the community.

The book will fill a gap in the market as recognition of the importance of colour to the quality of life becomes increasingly more widespread.

Readership: Colour designers, environmental designers, architects, industrial designers, landscape gardeners, colour psychologists, interior designers, industrial psychologists, ergonomists.

Antal Nemcsics graduated from the Academy of Fine Arts in Budapest in 1950 and in 1966 was awarded his M.Sc. In 1985, he obtained his D.Sc. from the Hungarian Academy of Sciences. The author of 96 publications in various languages, Professor Nemcsics has also been awarded a number of prizes, including the International Prize for Fine Arts, and, most recently, the Niveau prize for the textbook *Chromatics – Colour Dynamics*, in 1989.

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Contents

Preface

The text for *Colour Dynamics—Environmental Colour Design* is aimed at everyone engaged in environmental design including researchers, architects, artists, and all kinds of designers—especially those involved in interior and industrial design. The book is also particularly useful for students because, at a time when the teaching of colour in design institutions has waned, never before has colour been seen as such an important aspect of all branches of design.

The content of this book represents an authoritative and comprehensive analysis of all the issues influencing the colour experience and its application in design. The term "colour dynamics" reflects the author's recognition of the allusive nature of colour which, until recently, has somehow become impossibly detached from the environmental design process. This detachment results from a series of historical phenomena which can be traced back to the foundation of the principles of modern science in the Age of Enlightenment and beyond to the birth of specialism during the Quattrocento. Indeed, only sixty or so years ago W. R. Lethaby pronounced "Science is what you know" and "Art is what you do". Unwittingly, perhaps, he compounds the two as quite discrete cultures. By contrast, the study of colour necessitates an erosion of disciplines and integration of art and science. In drawing together the body of knowledge from a variety of sources and specialisms, the author—himself a scientist, researcher, urban colourist, and accomplished painter—explains the colour sensation as an integrated system involving relationships between man, his ability to see colour, and his environmental setting.

The structure of the book is as follows. Chapter 1 introduces the concept of colour dynamics as a new branch of science. Chapter 2 focuses on the mechanics of colour perception (a complex process involving quality of illumination, the nature of the surface receiving light, and the function of colour vision), colour mixing, and colorimetry. Beyond a review of the evolution of colour ordering systems, Chapter 3 devotes special emphasis to a detailed description of the Coloroid System. This is a comparatively new system of ordering conceptually the three dimensional world of chromatic space based upon intervals of colour harmony. This system was researched and developed by the author at the Technical University, Budapest, expressly for application as a design tool by architects, designers, and artists. After an explanation of colour phenomena, such as adaptation, colour constancy, and colour contrast, Chapter 4 turns to aesthetics and examines the impact of the eye and brain on the meanings of colour. This section continues with an exhaustive historical survey of colour preference leading to examples of colour association and symbolism.

The three concluding chapters begin a sequence of important sections concerned with the practical application of colour. For instance, Chapter 5 presents the psychological functions of colour and the influence of illumination on our preception of built space, and Chapter 6 deals with the theories, structures, and scales of colour harmony. Finally, Chapter 7 is devoted to the application of colour dynamics to a wide variety of interior and exterior architectural settings.

In setting out to provide a full coverage in depth of all the factors relating to our experience of colour this book makes its contribution to the growing debate concerning the quality of the built environment. It also aims to foster an enthusiasm for, and understanding of, this complex subject and, above all, stimulate readers to use colour. After all—and in the words of Sir Hugh Casson—"...the best way to study colour is to use it".

Tom Porter

Introduction

Man has created an artificial environment around himself, and spends most of his life there. This new environment has not only protected him from the adversities of nature but has promoted his creative inclinations resulting, among others, in the birth and development of technical culture. This, in turn has brought about an industrial environment, with new sources of risk for mankind.

In our age any activity—directed towards the construction of our environment, involving not only architecture, but all creative and productive activities affecting either the whole or some elements of this environment,—has to assume a new responsibility aimed at reducing these sources of danger to help our orientation for the safety of life.

Technical development, however, has also raised our demands on our environment. Actually, environment is expected to satisfy—as far as possible—not only physical but also our intellectual needs. We yearn for an environment where our abilities can be developed, activities experienced, and which can also be said to be beautiful.

Environment is characterized by the interrelations of its elements, their forms, surface qualities and colours. In science, the systematic study of space elements and form relationships has long traditions. It has, however, only recently been realized that colour is an important factor not only in the appearance of the environment, but also its "proper use"; much depends on the colour of environmental elements. It could be shown experimentally that within certain limits, colour is more determinant for space sensation than geometrical dimensions or proportions of space; space wall colouring of space boundaries may be more stimulative than a dose of a drug, or more reassuring than a tranquilizer. At the same time, due to the advent of artificial light sources, relativity of colour impressions is manifest to anybody. As a consequence colour designers are faced by an ever-increasing number of seemingly unmanageable problems.

Study of the environmental impact of colours is the subject of colour dynamics, a new branch of science. Colour dynamics considers the environment, man living in this environment, and the outer appearance of environmental elements, i.e. colour sensation as an integral system. Correlations are sought between these three elements—colour, man and environment—and conclusions are drawn on the impact of colours selected for environmental elements on man living and working in the environment. Colour dynamics integrates the results of several disciplines such as physics, physiology, psychology, aesthetics and sociology.

Man shaping his coloured environment is himself subject to the colour effects of this environment. His colour sensations do not arise as independent entities but in interaction. The observed relations between colour sensations are often perceived as colour composition rules, and are utilized in creative activities. Thereby, for instance, contrast phenomena—investigated in physiology, to better understand the mechanism of vision, or in experimental psychology to determine perceptional equidistance—become components of planar or spatial composition.

Man's judgement concerning his colour sensations is dependent on his environment. These judgements are the indispensable foundations of his creative activities. Knowledge about colour preference and colour association are conscious or intuitive elements of creative activity. Colour harmony as an ordering principle between colour sensations is closely related to the message to be expressed. The psychosomatic effects of colours also belong to the armoury of environment design. The practice of colour design of our environment affects the built environment, but this process invariably assumes a natural environment to which visual contact should be established. However, the blue sky, and green leaves interact with the colours of an interior not only when one is looking out of the window. Psychological mechanisms elicited by colours in nature persist in perfectly closed spaces.

Mankind, by its building activity, creates for itself a second Nature, an artificial world, which—beyond being part of a tangible reality—is also a bearer of social features, an expression, a reflection of demands, conscious–mental existence, habits, and conditions of man as a social being. This is whereby architecture, i.e. the activity of organizing, and directing the complex, material, mental and social process of space formation, becomes an art. This art always exploited colour as a means of expression. Colour helps built space to become not only a complex product of a wide range of high grade practical and theoretical experience, technical–scientific knowledge, or what is more, a recognition of social conditions,—but an expression of the integrity and humanity of man living in built environment.

To let designers really handle colour as a tool in realization of his objectives, "colour had to be liberated"—as LÉGER put it, or—as formulated by MOHOLY-NAGY "the artist dealing with colours has to integrate the scientific knowledge of a physicist and the technological skills of an engineer with his own imagination, creativity and emotional force". Painter professors of Bauhaus such as ALBERS, ITTEN, KANDINSKY, KLEE, MOHOLY-NAGY, and KEPES, or architects such as GROPIUS and BREUER, did much for the liberation of colours to become a tool of space formation. Unfortunately, almost up to our days material obstacles prevented colour from becoming a "free" means of expression in the hands of designers. Common efforts of several disciplines seemingly rather unrelated to arts had to precede the advent of conscious environmental colour design.

By now, it has been recognized that colour is able to devastate, build up, or modulate space, to modify the spatial position of planes or the importance of masses. In fact we are now able to provide designers with numerical relationships, reflecting the function of space or the relationship between colours. It is its visual appearance which makes the built environment an experience to us. Visual appearance is influenced by the intensity, nature and direction of illumination. In this respect, illumination techniques have opened up unprecedented possibilities to architecture, and it is the task of colour dynamics to translate all this to the language of design.

In his environment, man is exposed to a wide range of influences. Colour may dampen or enhance these and may protect him from harmful effects. Environment designers have to be acquainted with these possibilities. Colour dynamics, relying on several other disciplines, may give increasingly satisfactory answers to an ever widening range of questions.

This book will first present the basic concepts of chromatics, then interactions between colour, man and environment, and finally the principles of colour design relying on these interactions. Much emphasis is laid upon correlations between colour perceptions, since acquaintance with our environment has to begin with formulating relation systems between our perceptions. Nothing but space, form, and colour sensations can be considered as the compositional elements of environment design. Elaboration of relations between colour perceptions cannot disregard the eliciting stimuli which are objectively measurable physical magnitudes. The designer has to be acquainted with these correlations, on which the recognition of the relationships of colour, man and environment, and any conscious creative activity are based.

Although this book will present the various current colour systems, we will give preference to the Coloroid colour system. This system was intentionally devised for the design of coloured environment, and presents a balanced systematization of colour sensations not only from the point of view of perception but also of aesthetics. It is completely suitable for describing colour harmonies, involving unambiguous colour symbols directly convertible into the physical magnitudes eliciting colour perceptions and hence is suitable to visualize colours. Nevertheless, the system is simple and easy to understand and therefore well suited to demonstrate relationships between colours. Relations of colour, man and environment will be expressed with colour symbols of this system. Experiments underlying psychometric scales of the Coloroid colour system, as well as those on which their colour harmony relationships were based will be described. Methods for using colour symbols in design practice and the construction of various different colour scales will be presented.

Design of coloured environment means a duality—it is both a technical and an artistic activity. Knowledge indispensable for the technical side of this activity, as well as general guidelines for the artistic aspects will be offered.

Lastly, let me finish this introduction on a somewhat personal note and recommend this book—with all of its formulae, diagrams and nomograms unusual for designers—into your cognisance. I have been active as a painter for over 30 years. Some of my paintings are in public collections, and perhaps half a thousand are privately owned. I have designed acres of murals, stained glass windows, and mosaics, prepared colour designs, and checked its execution for a wide range of buildings, schools, hospitals, industrial plants, churches, airports, and urban centres. During my work, in the process of creation I was often faced with theoretically uncleared chromatic problems. Their solution, the development and execution of suitable experiments, the confrontation of the results with observations of others and the description of the conclusions transformed me from an artist into a research worker. By now I have been active as a researcher in colour dynamics for 25 years, I organized and still lead research at the Technical University of Budapest. I always endeavoured to solve problems in cooperation with physicists, mathematicians, psychologists, physiologists, sociologists, art critics, engineers and other specialists. Results have been reported in several publications. I have been learning to report intelligibly on conclusions of creative and research work by way of lecturing on them to students in architecture for about 30 years.

This book is intended not only for researchers but also for designers, architects, painters, interior designers, industrial designers—for all those who would like to avail themselves of the power of colours to make our built world nicer, more convenient and more human. Colour will be treated as a means of creation, a phenomenon close to sentiments but seeming rather distant from mathematics and the exactness of engineering. Nevertheless, I do not wish to appeal to the Reader's sentiments, neither to ponder aesthetics, nor disclose secrets of the creation process. In fact, rather than secrets, relations on this aspect of creation will be communicated, which when missing, paralyze creativity. I intend to tell anything I know on colours by means of numbers, and graphs. My desire is to describe my experiences in the realm of colours as clearly, as practically and with the accuracy of an engineer as was done by LEONARDO DA VINCI, both a creator and researcher, in his "Trattato della pittura". This is a technical book for creative people with my own experience and skills, who are not afraid of mental effort in getting better acquainted with the tools of their creative work.

1. Colour Dynamics—a Science

After World War II, architectural creation ever more consciously applied as a means of expression that particular property of the outer appearance of materials which we call colour. It has become clear that colours at the surface of the built space, and harmonizing assemblies of these colours are not negligible determinants of space sensation. At the same time, practitioners of a wide range of sciences such as physiology, psychology, anthropology, and sociology became interested in the effect of colour environment on man. Other sciences such as physics and aesthetics, joined them and sought correlations between colour sensations which could provide composition relationships, insight to colour harmony, for those creatively concerned with colour. Characteristic of publications reporting these achievements is their variety, heterogeneity, a mainly one-sided approach to problems, and a superficial treatment of the results, problems and methods of other disciplines. Thus up to the present day no common theoretical and conceptual basis has developed, which could permit an unambiguous evaluation of the subject, and serve as foundation for complex research. Colour dynamics as a science, and the theory of architecture, are expected to elaborate these foundations since the role of colour in built space, and the way how colour complexes may affect space sensation, have to be determined from the point of view of those creatively concerned with colour, i.e. among others by architects themselves.

At present, however, the literature on the theory of architecture is as yet unable to hand down to the creative architect in a ready-to-use form even the most essential relations between colour, built space and man living in this space which may transform built space into something more attractive and more practical. It is the task assumed by the new science called colour dynamics to explain these relations; colour dynamics is primarily concerned with relationships between environment, surface aspects of environmental elements, and man living in this environment. It studies the correlations of colour, man and environment. It investigates the effect of colours selected for environment elements on man living in this environment. Thus, colour dynamics is a complex of theoretical and practical activities with the purpose of finding objective relationships between man and environment colours, as well as of consciously shaping our colour environment.

1.1. The Colour

Both in everyday practice and between specialists, much confusion arises from the use of the word "colour" for several concepts. In common usage, no distinction is made between the visible radiation penetrating the eyes, and the resulting imprint on our mind. Definitions in dictionaries usually refer only to the first concept, i.e.: "colour is the property of material phenomena perceptible by seeing, based on the reflection of light beams of different wavelengths". On the other hand, in accordance with the International Vocabulary of Illumination, the Hungarian Standard MSz 9620 makes a distinction

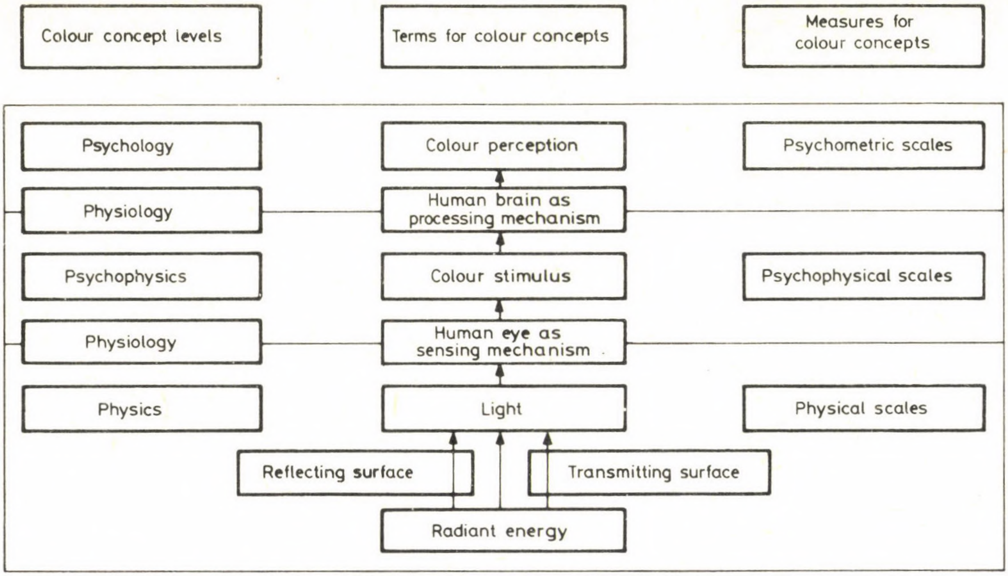


Fig. 1.1. The colour

between two concepts both named colour: "psychophysical colour" is called the characteristic of radiation penetrating the eye due to the differences of its spectral distribution, while "perceived colour" is the imprint elicited by this radiation in our consciousness. In the technical literature, radiation proper is called "colour stimulus", while the conscious concept elicited by it, is "colour perception"—but often, mainly if there is no risk to confound the two, simply the word *colour* (couleur, Farbe) is used.

Relations between concepts denoted by "colour" are illustrated in Fig. 1.1. The middle column of the figure indicates names for different colour concepts in publications, the left one the field of science concerned with colour in the given context, while the right one shows the nature of scales suitable to quantify the concept meant by the given term. Let us consider this figure beginning from the bottom.

First of all, colour defines a physical concept: radiant energy in the wavelength range of 400 to 700 nm. This energy may be described either directly, or as a narrow wave band reflected from, or transmitted by a surface. This light is, strictly speaking, coloured light. Use of the word "light" is only meaningful if our sensing mechanism the eye is involved.

A physically defined radiation penetrating the eye and eliciting colour sensation is the "colour stimulus", a psychophysical concept. It can be valued on psychophysical scales.

Colorimetry is concerned with the establishment of correlations between colour stimuli as well as their systematization and measuring. Colorimetry is a borderland between physics, physiology, and psychology. Colorimetry involves the concept of colour space based on additive colour mixing, developed on the basis of GRASSMANN's findings (1853). It is the basis of the International Colorimetric System (CIE* 1931). The

* CIE = Corporation Internationale d'Eclairage.

concept of a visually homogeneous colour space relies on theoretical and experimental findings for the d*s* element by Judd (1968), as well as by Wyszecki & Stiles (1967). It has been applied for correcting the Munsell colour system relying on the idea of perceptional colour space. The corrected Munsell Renotation is considered as model for different UCS colour spaces.

The achievements of colorimetry have been exploited for the practical measurement of colour stimulus in a variety of industrial applications. The quantitative evaluation of colour stimulus (commonly called colorimetry) means in a strict sense the prediction whether two visual stimuli of different spectral distributions elicit the same colour sensation under given conditions or not. Measurement of colour stimulus offering a reproducible and exact determination of the colour of building material has entered architecture, and this initiated a cooperation between colorimetrists and architects. Along with this cooperation numerical expressions of colour compositions, mainly of colour harmony relationships became a necessity. To meet this demand, at first colour symbols describing relationships between colour stimuli seemed adequate but it has now become apparent that colour symbols suitable for colour space design have to meet requirements other than the measurement of colour stimuli. Colour symbol values have to express the three characteristics of colour space: hue, saturation and lightness, and aesthetically uniform variation of the colour space; one should be able to display colours by numerical symbols, the latter should be convertible to CIE *XYZ* coordinates.

Environment colours correspond to a wide variety of colour ranges in the colour space. Therefore environment colour design is expected to create harmony between colours of rather different hues, saturations and lightnesses. So it is much more important to have an aesthetical uniformity of the entire colour space than a reliable equality of just distinguishable colour differences. Endeavours with colorimetric studies resulted in psychophysical scales closely approximating the ability of the human eye to distinguish colours in different colour domains, but these scales are of limited usefulness when aesthetics are concerned.

Colour stimuli are transformed to colour sensations by our processing mechanism —the brain. The concept of colour sensation belongs to the domain of psychology and it can be evaluated by psychometric scales.

In everyday wording, words for colours such as red, green, ochre, brown, identify colour perceptions. When colour designers speak of cold or warm colours, they refer in fact to laws of colour composition, colour harmony relationships, or perhaps to colour adaptation or contrast phenomena; in other words they deal with correlations between colour sensations.

That element of the consciousness concept elicited by effects via our sensory organs —which cannot be analyzed further—is called sensation. The term colour perception, in turn denotes that kind of consciousness concept by which the observer is able to distinguish two adjacent parts of the visual field, having the same size, shape, and texture, and this difference can be attributed to the different spectral distribution of the observed radiations. Colour perceptions may vary in three respects, namely by hue, saturation and lightness. Geometrical representation of colour perceptions is simplest in a cylindrical coordinate system. Colours of the same hue lie in the semi-plane limited by the achromatic axis, colours of the same saturation compose coaxial cylindrical surfaces, while colours of the same lightness are in horizontal planes normal to the achromatic axis.

Different colour systems contain colours in the spatial arrangement mentioned above. The colour solid constructed in conformity with the system's principle is generally illustrated by means of a collection of colour samples. It is endeavoured to distribute colour samples inside the colour solid as evenly as possible. Namely a colour collection of any colour system is expected to help comparative colour determination making use of colour sample codes, and approximation by interpolation of the codes of colours missing from the collection is feasible only when colour samples are perceptionally equidistant from each other.

Colour systems belong to four groups according to their code system: systems are based on additive or subtractive colour mixing, as well as on printed screen, or colour sensation parameters. Practical experience has shown that it is the idea of using colour sensation parameters which meets demands of those concerned with colours in their creative work, such as architects the best. Therefore in recent years several attempts have been made to develop an ideal perceptional colour system.

For an architect concerned with environmental colour design, colour is a tool serving both technical and artistic goals. The distinction of colour sensations by unambiguous codes is required, in the first case, for defining technical parameters associated with various colour sensations, and in the second, by the need to express in a numerical way compositional relations between colour sensations. Beyond that, the colour designer, in addition to finding his way among colour sensations, has to be able to determine interrelations by estimation and measurement. The measuring system has to comprise directly or indirectly international units. Such a colour sensation measuring system based on the Coloroid system will be proposed later.

In the Coloroid system, the colour code is the representation of a colour sensation qualifying colour perception, but exactness of the code is determined by its relation to the colour stimulus eliciting the colour perception. In using the term "colour" it is often unclear whether colour perception or colour stimulus is meant. In everyday use, the colour "red" means a colour sensation but talking about its effects, red may indicate a stimulus i.e. a psychosomatic effect, but also perception meant as an associative effect. Adapted colour is a perception, but one that—rather than to be elicited purely by a correlate stimulus—is the result of a modification of the primary colour perception by the environment. Colour remembrance is also a content of consciousness but it is not elicited by a visual stimulus, and it is colour remembrance which generates the phenomenon of colour constancy. The term "preferred colour" is, in turn, a value judgement concerning colour sensation. Colour contrast is meant as a relation between colours, but in fact it reflects a relation between colour stimuli. Colour stimulus and colour sensation are inseparable, one being a consequence of the other; our laws of composition, aesthetic expectations for colour appearance, as well as their role in the built space can be interpreted only by their interrelations. This is why the two concepts of colour are not always distinguished in the technical literature, which often speaks simply of colour, although, an ever increasing number of scientific disciplines and professions join the research on colour relations. Artists, architects, psychologists, sociologists, aestheticians try to formulate relationships which in fact concern colour perceptions, but (to support their statements) they often refer to colour stimuli. Psychophysics, psychosomatics, and proxemics admittedly approximate the problem of relations between colour sensations on the basis of colour stimuli.

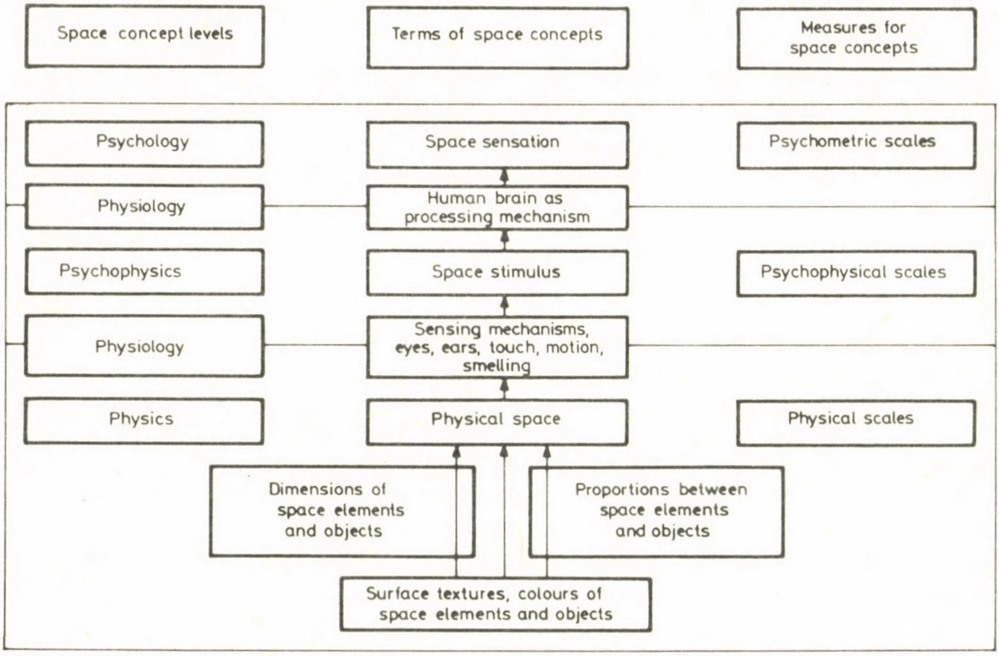


Fig. 1.2. The space

Since this book is primarily intended for those interested in a creative use of colours we usually mean colour perception, but for simplicity most often the term "colour" will be applied. But in every case when unambiguity requires it the exactly qualified terms are used.

1.2. The Built Space

The concept of built space is no less complex than the word "colour", which, as we have seen means both colour stimulus and colour sensation.

Space like colour has more than one meaning. Relations between concepts defined as space* are illustrated in Fig. 1.2. In the middle column are shown the names of different spatial concepts applied in the literature or suggested by the present author, in the left-side one the fields of science concerned with the given aspect of space, while in the right-side column are entered the scales used to quantify the given concept. In the following we discuss this figure from the bottom upwards.

The widely used definition of space—i.e. being the form of existence of matter characterized by three dimensions—refers to physical space. It involves dimensions, proportions and correlations between space elements, objects, but also texture and colour of space elements and objects.

* Omitting, of course, those of "cosmos" and of "time space".

Our sensing organs receive stimuli from the physical space. Their entirety is space stimulus, an essentially abstract concept pertaining to psychophysics. Space stimulus differs from physical space only by being centered on man. It contains up and down, front and back. A built space represented by a blueprint is a space stimulus, a term including dimensions, their correlations, and the topological order of the three dimensional elements of the given space. It expresses the existence in space but also to be a space, with all its spatial attributes. Space stimulus elicits space sensation, a consciousness content obtained by sensing the real space visually, auditively, tactilely, olfactorily, motionally, etc. Space stimulus is transformed to space sensation by our processing mechanism, the brain.

A concept other than space stimulus is meant by applying the word "space" in expressions such as compressed space, narrow space, monumental space, drifting space. Space sensation, the consciousness content elicited by a space stimulus depends on the relationship between its plastic elements as presented to us by the direction, intensity, quality of light, by surface texture and colour conditions. For man, space does not exist as a thing-in-itself (noumenon), but as effects elicited by these plastic elements. The statements good or bad space refer to space sensations. Space sensation belongs to the field of psychology and can be valued by psychometric scales. Judgements about a built space usually involve the concept of space sensation. In the field of theory of architecture, RIEGL (1927) was the first to attribute significance to the concept of built space by stating that Roman buildings manifest a space aspect quite different from that of Greek ones. He, of course, did not yet distinguish space sensation and the space stimulus eliciting it.

Modernists at the turn of the century, performers of the abstract "white revolution" (F. L. WRIGHT and VAN DER ROHE) who were especially and creatively interested in space laid great emphasis on demonstrating space, that is, they wanted to elicit a definite space sensation by a definite space stimulus; even they did not consider the two as separate entities. The slogan "white revolution" refers to an expulsion of colours from buildings, by painting everything white. Even GIEDION (1969), who recapitulated the space problem, did not differentiate between space stimulus and space sensation.

A more refined formulation of concepts related to built space arose only when disciplines earlier ignoring architecture, such as anthropology, psychology, sociology, became interested and started to study its relations from the aspect of space sensation. Of course, their statements often intermingle the two space concepts, such as in the definition by HALL (1963) for the two proxemic varieties of built space, where the terms "sociopetal" and "sociofugal" were applied, defining thereby different space sensations, although the terms were deduced from space stimulus. It can be seen that in the use of the space concept, similar ambiguity to that with colour prevails.

Starting from the function of space, KAHN (1953) investigated the relation between space sensation and function. According to him the function of space is decisive for space sensation. This idea leads to theoretical problems about the relation of space creation and artistic activity. The same emerged in the works of VENTURI (1966) who was concerned with the function of content and form in architectural space sensation, and also by KEPES (1965) who discussed the scope of our visual information on space. Let me take their arguments one step further by stating that the surface appearance and colour of an environmental element contributes to the expression of the form, while its function contributes to the expression of the content of built space.

In our days, built space is being also studied by gestalt psychology, applying the same terminology in investigating the conditions of space sensation as that applied for the conditions of colour perception. Their language differs, however, from that used by architects, this in turn from that of painters, colorimetrists or colour designers. This is why here, when using the concept of both built space and colour, we wish to make a distinction between stimulus and sensation, the consciousness content elicited by it.

1.3. The Function of Colour in Space Experience

Man living in a built environment, the user of a built space, is protected from the tribulations of nature, he utilizes the services of his surroundings and enjoys comfort from these services. In addition to its actual measurable properties required for the physical and biological existence of man, built environment has other qualities, too.

Built space acts upon man in several ways: by the proportions, the relationship and shape of its elements, the order of forms, by surface appearance, and colours of the elements, by the relation between space proportions, by the expression of function, by the relation between the expressivity of function and the function proper, and by the shape and colour associations expressing function. This effect materializes as an emotional experience of the actual space, and space sensation. Space sensation is an experience about a given space, an accomplishment of one's own personality. The function of colour in this experience has not yet been considered by the theory of architecture, let alone a formulation of the relation of built space to colour. This book intends to fill this gap at least in part.

The content of space sensation may be deduced from two components, such as space perception itself, and its relation to the function of the real space. Space perception is a content of consciousness generated by space stimuli representing the connection of being part of a three-dimensional space and observing it from the outside (spatiality). So, primarily the role of colour in space perception will be examined. As the purport of space perception is determined to a certain degree also by the function of the real space, and the expression of this function is assisted by colour, also this feature of the colour will be considered.

1.3.1. The Function of Colour in Space Perception

Space perception is a complex process to which several sensory organs contribute. Among them, visual and auditive stimuli and those arising from motion in space are the most important. All these add up to a space stimulus eliciting our space perception.

Space stimulus is elicited by measurable and tangible real space, composed of space elements as well as of correlations between shapes and surface appearances all describeable by physical magnitudes. We obtain most of our information about the objective correlations, shapes and surface appearances of space elements by reflection, absorption or transmission of light by the surface of the element delivers visual stimuli to us from the space.

Assuming that the surface appearance of space elements is of the same finish, texture, and colour, and that the elements are illuminated from the same direction, with the same intensity and spectral distribution, then due to visual and motional parallaxes, overlapping, line and air perspective, light–shadow effects, a space perception with a linearity directly proportional to that of the change of the real space is elicited.

Colour identity as a condition means that light incident from the surfaces into our eyes has the same wavelength; that is, colour sensation is the same throughout, and also, that for the same angle of incidence, the ratio of the quantity of light incident on, and reflected by surfaces is the same everywhere, and in the reflected light incident on the eyes, the ratio of complementary radiations, hence, saturation, is felt to be the same throughout.

To examine the function of colour, let us assume that stimuli arriving into our eyes come from the elements of such an objective space where dimensions, proportions and relations of the elements do not permit overlapping and the interpretation of line perspective relations; further the onlooker does not move in space, missing the help from laws of motion parallax in space perception. If these conditions are met, and in addition direction, intensity and spectral energy distribution of light within the space are constant and the former restriction of equal hues, saturations and lightnesses of surface colours holds, the objective space can be judged only by evaluating the perceived colour sensation differences.

Intensity differences of the stimuli emitted by space element surfaces and reaching our eyes permit us first of all, to decide on the spatial position of the light source, then from hue, saturation and lightness differences of space element surfaces, on the distance of space elements from the onlooker, hence on the space itself.

It is known by experience that the more remote an object, the more hue component of the colour sensation generated by its surface is shifted to hues of shorter wavelengths, its saturation toward achromatic colours, and that its lightness component varies as a function of the two other components and of the position of light source. This experience helps our space sensation although its significance can really be perceived only if the former condition of colour identity is abandoned. In reality, this is always the case. With space elements painted different colours, it cannot be decided anymore, which element is the closer and which is the farther away. Orange and red, even if in reality more distant, are felt to be nearer than blue or green. Saturated colours are felt to be nearer than are unsaturated ones. Very dark surfaces emit very little or no stimuli to the eye, so that these are not sensed, rendering space perception impossible.

1.3.2. The Role of Colour in Expressing the Function of Space

Colour contributes to space sensation also by expressing the function of space. Function of the built environment is a demand raised to social level. Structural relations in a system composed of man and the elements of his environment are defined by a complex function having three components: utility function, aesthetic function and informative function. Let us see now how colour—colour stimulus and colour perception—contributes to the realization or expression of these functions.

Environment is the scene of human activies, serving human demands. Much of these demands refer to the utility function of environment. Built environment is required to protect from the rigours of weather, to endure dynamic forces generated by our machinery, to protect from such factors as excessive temperature fluctuations, intense noise, and other factors from working processes detrimental to health. A recent requirement is feeling of comfort in one's milieu so as to stimulate the development of our mental and physical abilities.

Colour has a significant function in meeting these demands. Due to its psychophysical and psychosomatic effects, it may raise our blood pressure, or change the composition of blood and gastric juices. Colour can make one feel healthy or ill. A person in an environment of preferred colours feels better, his/her ambition to work increases. Some colours favour concentration, others cause deconcentration.

Just as anything else, built space and all its elements are separable unities of content and form. Environment fulfills its aesthetic function if it expresses its utility function in conformity with the unity of content and form, where the utility function is the content, while form is expressed by shape and colour of environmental elements. Since the content of objects in our environment, let alone, in our built environment, is its function, the built space and objects within, its content can only be grasped, and fully expressed by means of their proper functioning, and operation. Practical and spiritual components of the function are interdependent. Even the remark may be risked that aesthetic design of an object or built space is impossible when ignoring its functions. As a conclusion, there are no aesthetic prescriptions of general validity.

In designing colour relations for a built environment as a human creation, it is also a question of what importance is attributed to practical functions of the environment for human life in general. Every work and activity is linked to emotions, thoughts and ideas, therefore every object, tool or built space demands its share of these mental, emotional, ideological threads, in conformity with its role, significance and function in one's life. Colours of the built space as elements of form in the couple content and form, are made necessary by the sensation of function, giving rise to a harmony sensation of the indissoluble unity between content and form in our consciousness. Of course, the sight of some colour complex may cause aesthetic pleasure, but detached from the content of space i.e. from its function, this pleasure lacks the effect of complete space experience.

Those who wish to express the message of built space have to know about relations between environmental structures, i.e. about the so-called compositional relationships in order to be able to create proper relations between forms—and within that—of colour perceptions. These relations comprise those between colour perceptions, i.e., colour harmonies. Thus, the design of space sensation also exploits colour harmonies in this space.

Informative functions of space are features which interpret the functions of the environment and its elements and explain how to use and operate these elements. A significant part of the informative functions of the environment are borne by chromatic information. According to their message, chromatic information may be interpreted either as logic, or as aesthetic information. Both kinds of information are borne by the same elements but every form of message has its own structure. Their characteristics are determined partly by differences in their visual system, complexity and structure, and partly as psychic differences between their communication content. Information content is transmitted by highlighting, contracting and grouping some visual symbol elements in the informative surface or space, while omitting others. A colour group draws our attention when it is clear-cut and its structure is easily intelligible.

Chromatic information of a logic nature i.e. the various standardized color codes are practical tools which appeal to our logical mind. They transmit messages and serve also to influence observers in their decisions and control their attitudes and behaviour.

Aesthetic chromatic information is primarily emotional expression of inner conditions, and is expected to have mental and emotional effects by commonly accepted semantics. By their operative and recording functions visual codes are not only bearers of the meaning of the content of built space and its social concept, but also expressions of the approach and culture typical of the creative subject. Chromatic in built space information necessarily and conveniently takes the form of colour harmony relations. This is why it is of prime importance to examine colour harmony relations.

1.4. Development of the Concept of Colour Dynamics. Aim and Message of Colour Dynamics as a Science

Colours of space elements dynamically affect man staying within a built environment. Consideration of these effects, and examination of their components is the essence of colour dynamics. The term "colour dynamics" emerged in the '40s. Its generalization may be attributed to three authors: Frieling (1968), Birren (1961) and Déribéré (1968) who started to apply it independently but almost simultaneously. For all three of them, colour dynamics implied primarily the colouring of the workplace environment taking various psychophysical and psychosomatic effects of colour on man into consideration, such as the effects on tiring, mental and bodily concentration, ability and performance. Therefore as is common knowledge, colour dynamics has been associated with ergonomics which developed during the same period. This public attitude still persists. In fact, however, none of the above mentioned authors considered colour dynamics as part of ergonomics. In their essays they stressed the space forming effect of colour, studied the aesthetic relations of colour to built space, involving a wide range of space functions rather than workplace surroundings alone.

Their work—just as the introduction of the term "colour dynamics"—relied on the proliferation of results of psychophysical and psychosomatic studies starting in the '20s and '30s. Here we may mention authors such as Koffka and Harrower (1931) who recognized that shaping properties depended on coldness or warmness of colours, or Cook (1933) who was concerned with colour adaptation, or Esher and Desrivières (1964) having observed the different stimulating effects of radiations of different colours on living organisms. Relations of built space, colour and man have already been pointed out by early studies on colour preference and colour association. Luckiesh (1916) investigated, among others, the variation of colour preference in daylight and in artificial illumination. On the other hand, Karwoski (1929) looked at the relations between colour and sound.

Independently or as a reaction to the "white revolution", architectural creativity at the beginning of this century was also examining the possibility and right of colour to reappear in built space. At the beginning of his career, Le Corbusier (1960) committed himself to the space forming role of colour. An outstanding fact in this respect was his taking stand together with Léger at the 1933 CIAM Congress in Greece. About this Léger wrote in his mémoires (1954): "The pure tones, blues, reds, yellows escaped from my pictures to reappear in posters, in shopwindows, at roadsides and on road signs.

Colour became liberated to become a reality on its own. It has obtained a new impulse, and its effect became independent of the objects including or bearing it before". It was at that time, that a new avantgarde school of architecture grew interested in colour thus set free. Again, LÉGER put it, in connection with LE CORBUSIER's 1925 "New Spirit" pavilion: "Of course, the reception was other than unambiguous, the decisive step has nevertheless been taken, its consequences will soon appear". And: "How to create the sensation of space, how to disrupt barriers? Simply by colour, by walls of different colours! A dwelling which I may call a habitable rectangle, will transform to a flexible rectangle. Light blue walls recede, black walls advance, yellow walls disappear. The new possibilities are enormously wide...".

The importance of colour in the shaping of space has already been recognized by Bauhaus where a number of the most eminent painters of that age, such as KLEE (1925), ALBERS (1963), KANDINSKY (1914), ITTEN (1961) acted as professors.

After World War II, the two schools of thought working on the elaboration of colour to built space relations gradually converged in a process marked by publications by GÖRSDORF (1953c), GLOAG (1957), FASANI (1960), FRIELING (1960), BANHAM (1962), HARDY (1967), DÉRIBÉRÉ (1968), BIRREN (1969), PORTER (1976), SPILLMAN (1977), GERICKE (1981), DARMSTADT (1984), PRÖLSS (1984), BRINO (1985b) and NEMCSICS (1985a). The present author's activity also contributed to the development of a unified approach to colour dynamics. It is no coincidence that the International Conferences on Colour Dynamics organized in 1976, 1982, and 1988 in Budapest were attended by representatives of both trends. By the '80s, international events concerned with environment colour design became frequent. Amongst others international colour design competitions were launched in Stuttgart.

Nowadays we regard colour dynamics as a dual activity. One side is the disclosure of man-to-colour of complex man-to-coloured environment relations, and the elaboration of methodologies for the design of coloured environment. The other side is the utilization of these findings in environment design practice. These activities involve the collection and systematization of knowledge on relations of man, colour and built space offered by different disciplines as well as to devise and realize research to fill the gaps. This activity has taken momentum worldwide whereby the science of colour dynamics came into being.

Colour dynamics as a new science is concerned with the relations between the surface appearance of environment and environmental elements, and man living in this environment. It studies the interrelations of colour, man and environment. Thus, colour dynamics as a science is a complex of theoretical and practical activities directed towards the disclosure of objective relations between man and coloured environment, as well as towards a conscious environment colour design.

Rather than to be a collection of everyday experience, colour dynamics is a science. Although it investigates and processes the spontaneous, intuitive transformation of the environment by individuals, it handles its information by scientific methods, applying scientific methods in environment colour design. It has been proven both theoretically and practically that it is possible to conduct these activities by exact, scientific methods.

Environment design—including any architectural activity—has increasingly access to results of this new science. Its practical application helps our built environment to cope better with its function, to be more beautiful and more sophisticated. It helps us to

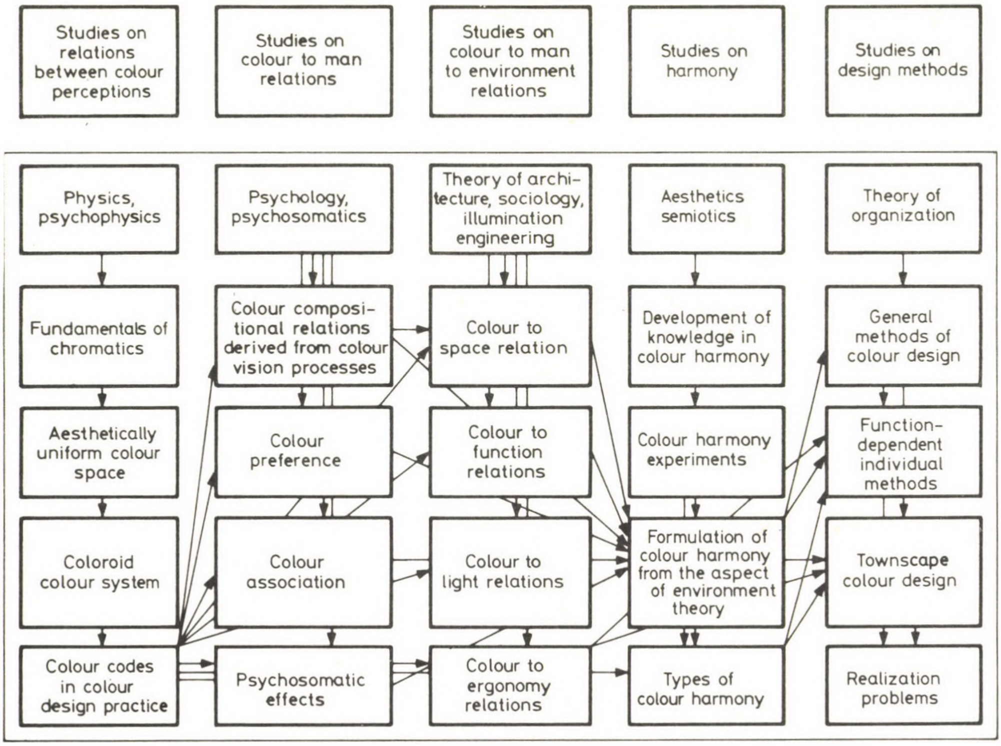


Fig. 1.3. The content of the science of colour dynamics

expand mental and bodily abilities, to compensate for harmful effects of our overwhelming industrialized environment, to develop an adequate space perception and to understand spatial relations and correlations between spatial processes. Conscious application of colours is expected to direct and orient man between multiplying and often depressive environmental hazards.

The science of colour dynamics has five different but inseparable branches (Fig. 1.3), the achievements of each are interdependent. Knowledge and relations amassed by other sciences are collected and purposefully systematized, and its special research problems are based on this foundation.

The fundamental problem of colour dynamics is to find relations between colour sensations, to develop an aesthetically uniform colour space and a colour system fairly approximating to it, further to introduce a new system of colour coding suitable for practical colour design.

The second group of problems is concerned with man to colour relation independent of the environment. This involves colour composition problems in connection with the processes of colour vision. Such problems are e.g. stimulus thresholds and difference thresholds, colour adaptation, colour constancy, colour contrast, colour preference, colour association, and the psychosomatic effects of colour.

The third group of problems includes the complex relation between colour, man and built space, including problems of colour and space, colour and mass, colour and form, colour and texture, colour and function, colour and illumination, of offsetting harmful environmental effects by colour, and finally of the social functions of colour.

The fourth group of problems is related to colour harmony research, the establishment of colour composition relationships for use in practical colour design: the determination of levels and parts of the concept of colour harmony, and of the fundamental and accessory conditions of eliciting colour harmony sensations.

The last, fifth group of problems is the development of the most effective methods of colour design, the best way of incorporating the finding of colour dynamics into practice. Statements are made exploiting practical observations obtained from realized colour designs.

This book is concerned with the achievements in all the mentioned domains of colour dynamics as a science, and their practical applications.

2. Fundamentals of Chromatics

Part of our impressions from our environment are registered as colour perceptions. The colour of objects can be appraised by seeing, that is, by means of the nervous system transmitting light stimuli perceived by the eyes. This appraisal involves—in addition to naming colours in the everyday sense—also the possibility to explore their interrelations.

One of the first attempts to find relations between colours can be read in the "Upanishads" of India dating from about the 7th or 8th century B. C., attempting to derive every colour from red, white and black. In his work "De Coloribus", ARISTOTLE was already concerned with the origin of colours. "Where darkness and light meet, colours arise", a statement decisive for a long period of the trend of later chromatic research.

LEONARDO DA VINCI, a universal master of the Renaissance, was the first to distinguish colour perceptions as subjective qualities from the colour stimuli producing them, which he took as objective qualities.

Researchers in the 17th century were the first who consciously broke with the Aristotelian concept of colour, although KIRCHNER distinguished white from yellow still only by their specific lightness. It was DESCARTES who first stated that basic colours were different by hues. BOYLE's famous work on colours appeared in 1670. He explained that the theory by ARISTOTLE—namely that black and white are primary sources of every colour—does not hold. By decomposing white light by means of a prism NEWTON not only produced the full spectrum, but also recognized that its two ends were visually similar.

NEWTON's colour circle found its first practical application in 1730 by LE BLOND, engraver in Frankfurt, who observed that yellow, red and blue were the primary colours for subtractive colour mixing. At the same time, GAUTIER of Paris recognized that by mixing these three colours nearly all the colours of the spectrum could be obtained.

The idea of combining the various broken shades and pure colours in a unified system originated in 1745 from MAYER, a mathematician in Göttingen. The basic idea of his system was that any shade could be produced by mixing from the three basic colours, as well as from black, and white. "The Natural System of Colours" by HARRIS, published in 1766, already made a distinction between saturated and non-saturated colours. He was the first to attempt to define the concept of complementary colours. To systematize various tonalities of colours mixed in equal proportions, LAMBERT, a physicist and mathematician, transformed the colour triangle of MAYER to a colour pyramid in 1770.

In 1810, GOETHE composed a circle of six colours, underlying colour circles of various colour systems used until recently. GOETHE investigated the conditions governing colour perception, as well as associational and symbolic contents, related to colours. In the colour system constructed in 1810 by RUNGE, a painter, colours were placed on a spherical surface. HAYTER, in his "New Practical Procedure for Three Primitive Colours" published in 1800, systematized colours on the basis of subtractive colour mixing, while in the system of French chemist CHEVREUL, published in 1861, colours were accommodated inside a semi-globe.

In 1850, HELMHOLTZ, physician and mathematician, had developed the theory of additive and subtractive colour mixing.

By the second half of the 19th century, BEZOLD (1876) investigated the relation between colour vision and colour appearance, while ROOD (1879) and HÖFLER (1826) have considered the idea of perceptional colour space. Fundamentals of chromatics are, however, rooted in 20th-century physics, physiology and psychology.

2.1. Visible Radiant Energy

Radiation may be defined as energy emitted in form of electromagnetic waves or particles. Direct visual perception can be elicited only by visible radiation.

2.1.1. Visible Radiation and Light

Perception by the human eye is restricted to electromagnetic radiation of 380 to 780 nm wavelength. In terms of the perception, radiation in this range is called light. In everyday usage, not quite precisely, visible radiation itself is equated with light. For the sake of brevity, in this book, we have also adopted this usage. (See Fig. C1; the coloured figures in annex at the end of the book.)

The frequency range of visible radiation is about 3.8×10^{14} to 7.9×10^{14} s^{-1}.

In physical terms, light can be characterized in three ways:

— as transverse harmonic vibration in a given range of frequencies;

— as electromagnetic perturbation propagating in space, the field intensity vectors of which are normal to the direction of propagation;

— as the flow of elementary energy quanta, in which the energy of each quantum (photon) is inversely proportional to its wavelength.

Light energy emitted from the radiation source and incident on a surface is partly reflected and partly absorbed by the object. The energy of absorbed light may be transformed to heat, initiate photochemical reactions (e.g. in the eye), generate photoelectric effects, fluorescence, or other physical phenomena.

2.1.2. Light Sources

In general, solids emit visible light on heating beyond a certain temperature. The total energy emitted as light and its energy distribution as a function of wavelength depend on temperature. An exact analytical expression for this function can be given only for *black bodies* which totally absorb all radiation energy.

Comparing thermal radiants of the same temperature, we find that the specific power emission of black bodies is the highest at any wavelength. According to Planck's law, spectral distribution of intensity of the emitted light is:

$$I(\lambda, T) = \frac{\mathrm{d}E(\lambda, T)}{\mathrm{d}\lambda} = \frac{c_1}{\lambda^5} \frac{1}{\exp\left(\frac{c_2}{\lambda T}\right) - 1}, \qquad (1)$$

where $dE(\lambda,T)$ is the energy emitted by 1 m^2 of a black body at temperature TK in 1 sec in the wavelength range of λ to $\lambda + d\lambda$; c_1 and c_2 are universal constants of values ($c_1 = 3.73 \times 10^{-16}$ W m^2, $c_2 = 1.438 \times 10^{-2}$ m K); λ is the wavelength in meters.

Figure 2.1 shows the intensity distribution of an absolute black body (or PLANCK radiant) at a set of temperatures.

Emission by non-black radiants in the visible spectral range has been correlated with black-body emission. Such light sources are described in terms of various "apparent" temperature values. This is not the actual temperature of the body, but the temperature of a black body which would emit light of the same or nearly the same colour. This temperature is defined as the *colour temperature* of the given light source.

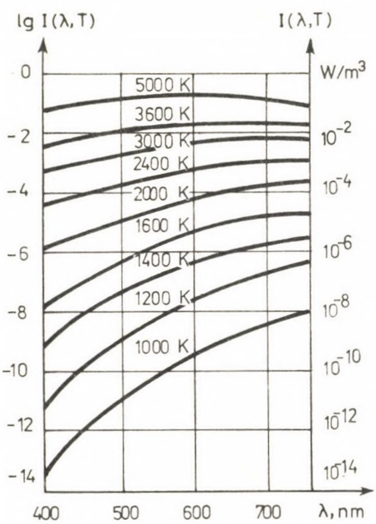


Fig. 2.1. Intensity distributions of the radiation of an absolute black body at various temperatures

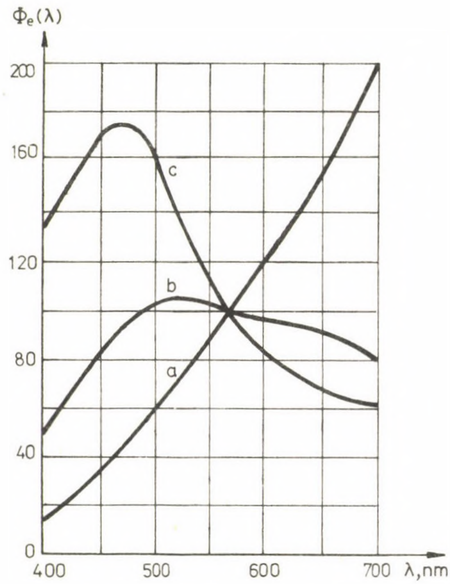


Fig. 2.2. Relative spectral power distributions of (a) a gas-filled tungsten bulb, (b) the Sun, and (c) daylight

Colour temperature defined by the spectral distribution of black-body radiation is unsuited for the characterization of *selective radiants*. Such thermal radiants where the relative spectral distribution of the emitted specific output is the same as that of a black body at a given temperature, are called *gray radiants*.

Figure 2.2 shows relative spectral output distributions of a gas-filled tungsten light bulb, the Sun, and the daytime cloudless northern sky. (As reference the output emitted at $\lambda = 560$ nm by a black body at the colour temperature T_s of a selective radiant is taken. If the selective radiant emits the same output at a wavelength λ, then $\Phi_e(\lambda) = 100$.) The corresponding colour temperatures are: $T_s = 2900$ K, 5000 K, 15 000 K.

2.1.3. Photometric Magnitudes

The magnitudes below may be interpreted both as physical and photometric magnitudes. In the first case radiation is expressed in energetic units, in the second case according to the sensor of the CIE photometer. Here only the most important conceptual definitions —rather than a didactic outlay—of photometry have been compiled.

CIE standard photometer observer is a radiation sensor with a relative spectral sensitivity curve fitting the visibility function $V(\lambda)$, or the visibility function $V'(\lambda)$ for darkness vision.

The *spectral luminous efficiency* is the ratio of radiation outputs at wavelengths λ_m and λ if under defined photometric conditions the two radiations induce the same perception of lightness. λ_m has been chosen so that the maximum value of ratio should be 1. Its values were set by CIE for vision in light ($V(\lambda)$) in 1924, and for vision in darkness ($V'(\lambda)$) in 1951. In the following, visible radiation will be interpreted as a photometric magnitude.

A logical system of photometric units would be based on the evaluation of emitted output according to the spectral luminous efficiency. Historical development brought about, however, that a standard light source was selected as reference unit, and thus the basic magnitude of the present photometric system is the luminous intensity, the basic unit of which is the candela.

Luminous flux (Φ_v, Φ; unit: lumen, lm) is a magnitude derived from the emitted output. It is evaluated by the effect of the radiation on a selective sensor, a spectral sensitivity of which is assigned by convention to spectral luminous efficiency values.

Luminous flux and radiation output are related by:

$$\Phi_v = K_m \int_{380\,\text{nm}}^{780\,\text{nm}} \Phi_e(\lambda)\, V(\lambda)\, d\lambda\,, \tag{2}$$

where $\Phi_e(\lambda)$ is the spectral distribution of the radiation output, $V(\lambda)$ is the reading of the photometer sensor at the given wavelength, and K_m the maximum spectral utilization of light, internationally agreed value of the latter is actually 683 lm W^{-1}.

Lumen (lm) is the SI unit of luminous flux defined as the light flux emitted by a uniform point radiant of 1 candela intensity at unit (1 steradian) solid angle.

Luminous intensity (I_v, I, unit: candela, cd) is the ratio of the luminous flux emitted by the light source at an elementary solid angle including the given direction, and of this elementary solid angle:

$$I_v = \frac{d\Phi_v}{d\Omega}\,. \tag{3}$$

Candela (cd; $1\ \text{cd} = 1\ \text{lm sr}^{-1}$) is the SI unit of luminous intensity: the luminous intensity of a black radiant of $1/600\,000\ \text{m}^2$ surface normal to the surface at the solidification temperature of platinum and at a pressure of 101 325 Pa (N m^{-2}).

Illuminance (at a given point of a surface) (symbol: E_v, E; unit: lux, lx) is the ratio of luminous flux incident on a surface element containing the given point and of the area of this surface element:

$$E_v = \frac{d\Phi_v}{dA}\,. \tag{4}$$

Lux (lx; $1\ \text{lx} = 1\ \text{lm m}^{-2}$) is the SI unit of illuminance; illuminance of a surface of $1\ \text{m}^2$ area by 1 lm of normally incident, uniform luminous flux.

Average spherical luminous intensity is the mean luminous intensity of the light source in all directions of space.

Luminance (L_v, L; unit: watt per steradian, $\mathrm{W\,sr^{-1}}$) is the ratio of the luminous flux passing, or incident on, or crossing the surface element containing the given point, propagating in an elementary solid angle containing the given direction, and of the product of this elementary solid angle and projection of the surface element normal to the given direction:

$$L_v = \frac{\mathrm{d}^2\Phi_v}{\mathrm{d}\Omega\,\mathrm{d}A\cos\vartheta}. \tag{5}$$

Quantity of light (Q_v, Q; unit: lumen sec, lm s) is the product of luminous flux by the time of irradiation.

Luminous efficacy (η_v, η; unit: lumen/watt, $\mathrm{lm\,W^{-1}}$) is the ratio of emitted luminous flux and of the absorbed light output.

Luminous efficiency (V): ratio of the output of radiation weighted by function $V(\lambda)$ by the reference output:

$$V = \frac{\int_0^\infty \Phi_e(\lambda)\,V(\lambda)\,\mathrm{d}\lambda}{\int_0^\infty \Phi_e(\lambda)\,\mathrm{d}\lambda} = \frac{K}{K_m}. \tag{6}$$

Optical efficiency of radiation O is the ratio of the output emitted in the visible domain by the total radiation output:

$$O = \frac{V}{V_s}. \tag{7}$$

(V_s is obtained by integrating within 380 to 780 nm using the formula for the luminous efficiency.)

Light exposure (H_v, H; unit: lumen second, lm s), is the surface concentration of the emitted quantity of light:

$$H_v = \frac{\mathrm{d}Q_v}{\mathrm{d}A}\int E_v\,\mathrm{d}t. \tag{8}$$

Luminous exitance (at a given surface point) (M_v, M; unit: lumen per m^2, $\mathrm{lm\,m^{-2}}$) is the ratio of the luminous flux emitted by a surface element containing the given point and this surface element:

$$M_v = \frac{\mathrm{d}\Phi_v}{\mathrm{d}A} = \int L_v\cos\vartheta\,\mathrm{d}\Omega. \tag{9}$$

Spectral concentration is the ratio of the fraction of the photometric magnitude x_v pertinent to an elementary band of the spectrum containing the given wavelength and the bandwidth.

Spectral distribution is the distribution of concentration values of the photometric magnitude as a function of wavelength.

Relative spectral distribution, $S(\lambda)$, characterizes a radiation (by a radiant or light source) in terms of the relative spectral distribution of some magnitude characteristic of the radiation.

2.2. The Chromophoric Surface

Part of light incident on the surface of an object is reflected according to laws of regular reflection, another part is reflected diffusely, while the rest penetrates the object, where it is partly absorbed, and transformed to other forms of energy. Objects which absorb all the energy of the penetrating light are called opaque while those which transmit part of the penetrating light are called transparent or translucent. Also light scattering takes place inside the latter.

2.2.1. Light Reflection in General

From the aspect of reflection, objects are characterized by the overall reflectance factor:

$$\varrho = \frac{\Phi_r}{\Phi_0}, \quad (10)$$

where Φ_r is reflected luminous flux; Φ_o is incident luminous flux.

In practice, most surfaces simultaneously exhibit regular and diffuse reflection. So, the overall reflectance factor can be decomposed to two parts:

$$\varrho = \varrho_t + \varrho_d, \quad (11)$$

where ϱ_t and ϱ_d are respective quotients of regularly and diffusely reflected incident luminous fluxes. From mirror surfaces, practically the total luminous flux is regularly reflected.

In case of dull surfaces—as compared to diffuse ones—regular reflection is negligible.

2.2.2. Regular Light Reflection

Incident luminance B is reflected from a reflective surface of reflection factor ϱ_1 at a luminance $\varrho_1 B$ as if the light were emitted by the mirror image of the light source behind the surface.

For any solid, the reflection factor depends on the angle of incidence. For light incident on transparent materials, the reflection factor in the plane of incidence, or of its component polarized normally to it, is given by Fresnel's equations.

2.2.3. Diffuse Light Reflection

A surface where distribution of the reflected light follows the cosine law is said to be perfectly diffuse. Such a reflector behaves as if it perfectly absorbed the light incident from any direction, then emitted its definite proportion in conformity with the cosine law. Such a surface seems equally bright from any direction. The magnitude of diffuse reflection depends on the microstructure of the surface. Surface colour is much influenced by the wavelength dependence of the reflectance factor. Wavelength dependence of reflection by coloured surfaces is seen in Fig. 2.3.

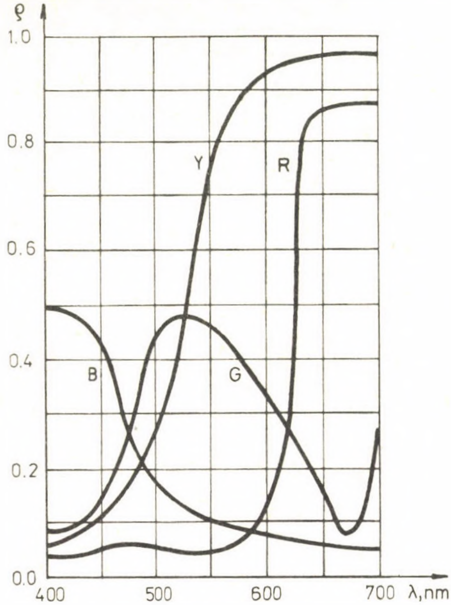


Fig. 2.3. Reflection coefficients of yellow (Y), red (R) and blue (B) surfaces vs. wavelength

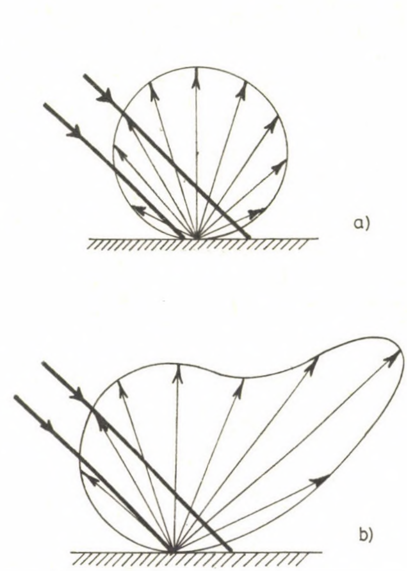


Fig. 2.4. Angular distribution of intensities of light reflected by a surface in case of a) diffuse and b) mixed reflection

In Fig. 2.4. the angular distribution of the intensity of light reflected from a surface for diffuse (a), and for mixed (b) reflection is seen. Wavelength dependences of regular and diffuse reflection generally differ. To eliminate disturbances due to regular reflection, in practical colorimetry, directions of illumination and observation are usually specified. Most specifications require perpendicular illumination and observation at 45°.

2.2.4. Losses of Light in Traversing a Medium

The colour of solids (more precisely, colour of light arriving from a solid to our eyes) is often determined by absorption and diffusion processes inside the solid, rather than by surface reflection. Part of the energy of light traversing a medium may be transformed into other forms of energy (such as thermal, chemical) by interaction between radiation and material. From the aspect of colour, only variations in the energy of light or of its components are of interest; energy loss is irrelevant. (Except for light originating from fluorescence, which is the basis of optical illuminants and fluorescent paints used in textile and paper industries, such being applied to emit colour signals.)

Definition of the absorption factor is similar to that of the reflectance factor:

$$\alpha = \frac{\Phi_a}{\Phi_0}, \tag{12}$$

where Φ_a and Φ_o are the absorbed and incident luminous fluxes, respectively.

The absorption factor thus defined cannot be considered as a material constant, since it depends also on geometrical and other factors. Instead of that, the internal absorption factor of a material of unit optical path length, the so-called absorptivity, is often applied.

In the case of transparent materials, light is not scattered inside the medium, thus path length of the light inside the material can easily be calculated. Light loss is proportional to the path inside the medium; its percentage is independent of the intensity of incident light. Light loss across the material may also be correlated to the concentration of the absorbent (Beer's law). Light absorbing properties of materials may also be described in terms of density (optical blackness). In terms of absorption factor:

$$D = -\log(1-\alpha)\,. \tag{13}$$

2.3. The Mechanism of Colour Perception

2.3.1. The Organ of Colour Vision

Our vision organ is composed of three parts: eyes, optic nerve tracks and optic centres in the central nervous system (Fig. 2.5).

Eye is a complex organ accommodated in a bony orbit. The eyeball is an approximately spherical body surrounded by several membranes. Attached to its front part there is a more curved spherical segment, the transparent cornea. Behind the cornea there is the so-called anterior chamber filled with humour. Behind the chamber there is the circular iris, of lighter or darker colour, an opaque, contractile diaphragm perforated by the pupil contacting the eye lens. The eye lens is flexible and deformable, permitting the sound eye to form a sharp image practically between infinity and 25 cm. The quantity of entering light is controlled by the pupil (Fig. 2.6).

Behind the eye lens is positioned the vitreous body enclosed by several membranes. The outermost one is the sclera, surrounding the choroid, and the innermost one is the retina

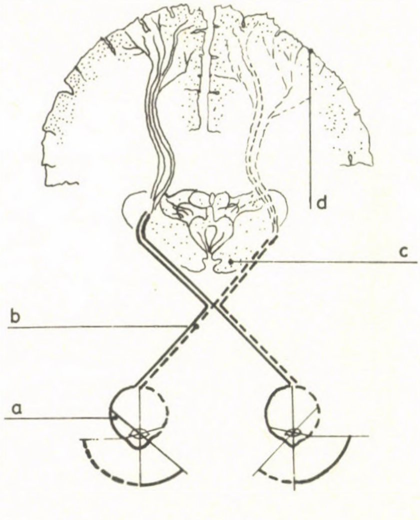


Fig. 2.5. Scheme of vision mechanism: a) eye; b) optic nerves; c) primary visual centre; d) cerebral cortex

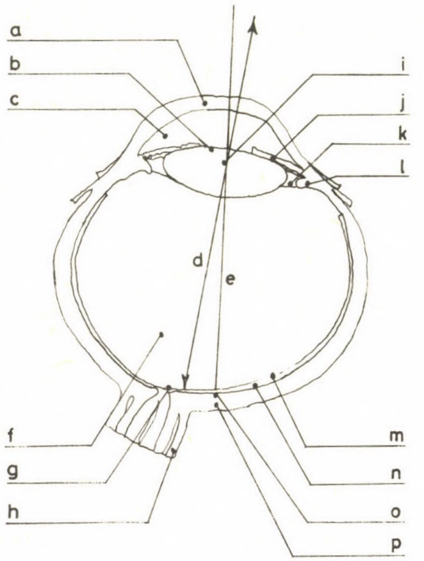


Fig. 2.6. Structure of the eye: a) cornea, b) pupil, c) anterior chamber, d) optic axis, e) visual axis, f) vitreous body, g) blind spot, h) optic nerve, i) lens, j) iris, k) zonule, l) ciliary body, m) retina, n) choroid membrane, o) fovea, p) sclera

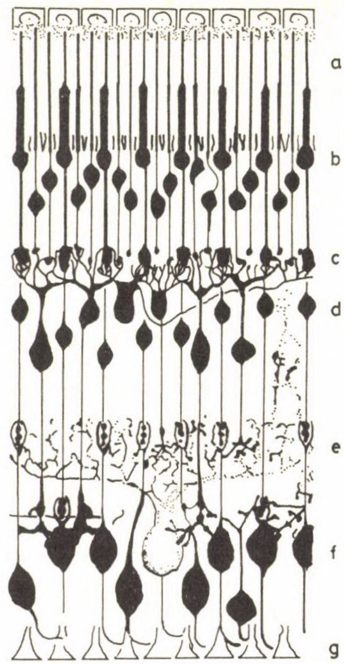


Fig. 2.7. Structure of the retina. Letters conform to Polyák's nerve cell symbols. a) rods, b) cones, c) horizontal cells, d) bipolar cells, e) amacrine cells, f) ganglion cells, g) Müller's radial filaments

accommodating optic cells (Fig. 2.7). Retina is a mesh-like membrane coating the greater, hind part of the eyeball's inner surface. It is composed of ten layers, although it is hardly 0.5 mm thick.

Continuation of the retina is the optic nerve, made up of about 1 000 000 nerve filaments of the retina cells. These filaments leave the eyeball at a definite point of the fundus, the so-called blind spot. Since here there are no nerve endings, no image arises. The central, yellow-pigmented part of the retina is the yellow spot (macula lutea), the middle part of the latter is the fovea centralis. Half of the filaments of the optic nerve passing from the eye to the brain cross in the brain stem, then disjoin again to reach the subcortical primary visual centre, and thence, the cortex.

2.3.2. The Process of Colour Vision

The density of light sensors on the retina averages 1.2×10^5 mm^{-2}. The two kinds of light sensors: rods and cones, have different properties. The photosensitive matter of cones is not yet known perfectly. At a low illumination only the rods—scotopic vision —, while at a higher level of illumination, also the cones—photopic vision—are active. Specific sensitivity of the eyes is different in the two visual modes (Fig. 2.8).

Only cones sense colour. Cones are unevenly distributed over the retina. Cones can be found only in the central fovea and in the yellow spot. The pigment of the yellow spot is essential for colour vision processes (Figs. 2.9 and 2.10).

Domains of different colours sensed in the visual field depend on the distribution of rods and cones over the retina (Fig. 2.11). No difference can be found between the cones; each one is assumed to contain three kinds of light-sensitive matter. As a physical analogy, three photocells, with red, green and blue sensitivity maxima, are simultaneously operative. Two colours may be considered as identical if photocells emit identical signals in each case. Theory agrees with experience—but the existence of three kinds of photosensitive matter has not yet been proved.

In the late 19th century, the fact that any colour shade can be composed from red, green and blue, prompted Helmholtz to revive the concept of Young (1802), an English physician and physicist, that the retina contains three different systems, all to be found in the conic nerve endings. They are sensitive to lights of different wavelengths, namely to red, green or violet. Nerve endings sensitive to red light are most sensitive to red, less sensitive to green, and the least sensitive to violet. Nerve endings sensitive to green are the sensitive to green light, but to a lesser degree perceive also red and violet. The same is true for the nerve endings sensitive to violet, which are somewhat sensitive to green, but insensitive to red. Whatever the colour of light incident on the three types of nerve endings, it stimulates them at a different level. The colour impression perceived depends primarily on the most excited nerve ending. The excitation process originating from it

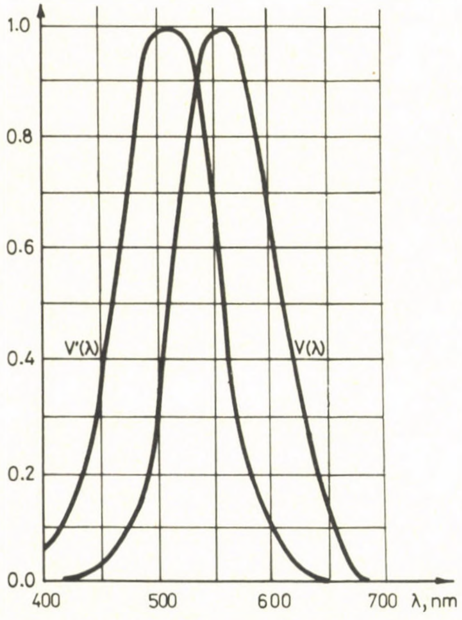


Fig. 2.8. Sensitivity of the eye in scotopic [$V'(\lambda)$] and in photopic [$V(\lambda)$] vision

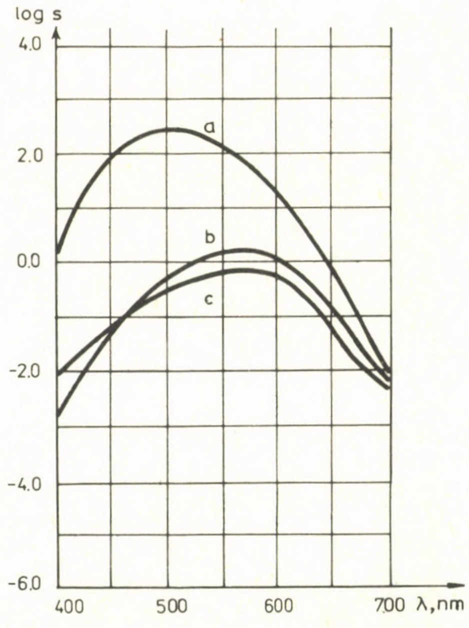


Fig. 2.9. Sensitivity of cones and rods to radiation of various wavelengths after tests by Wald and Judd: a) rods, b) cones at 8° above the fovea, c) foveal domain of cones

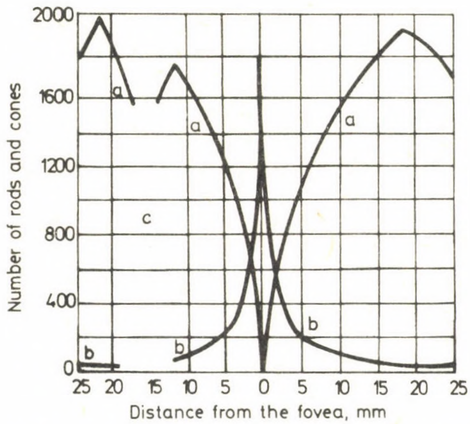


Fig. 2.10. Colour sensitivity of the retina: a) rods, b) cones, c) blind spot

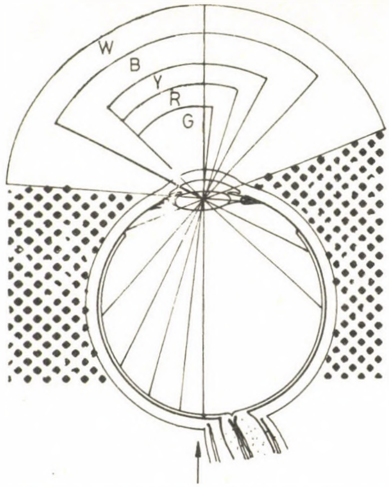


Fig. 2.11. Extension of colour perceptions in the visual fields of the eye. Legend: W white, B blue, Y yellow, R red, G green

dominates colour perception. Equal excitation on all three kinds of nerve endings produces a white light perception.

This ingenious theory not only explains perception of prime colours but also the origin of various shades, as well as of achromatic perceptions. Unfortunately, the *Young–Helmholtz theory* has not been anatomically proved up to the present. It would be a logical conclusion of the theory that the three kinds of nerve endings should differ in their anatomy or physiology.

The Young–Helmholtz theory could not explain several details of colour vision: for instance, why vision in red light is just as sharp as in white light.

According to the theory, in a light consisting of only one of the primary colours, only one type of nerve endings is active, hence vision would be weaker than in white light when all three types of colour sensing nerve endings are active. Eventually, several extensions of this theory have been developed, in order to rationalize phenomena which the original concept failed to explain.

In the '40s an observation by GRANIT (1947) seemed to provide a physiological explanation of the trichromatic theory. When studying various nerve filaments and nerve cells, certain retina elements were found to respond identically to light stimuli of different wavelengths. Part of the rod-type nerve endings—receptors named by him dominators—were found to be equally sensitive to any colour of the spectrum. Perception of achromatic or white light is attributed to the dominator system. In his experiments with radiation of different wavelengths, GRANIT found some nerve cells in the retina to be sensitive only to certain bands of the spectrum, i.e. of different wavelengths. These latter nerve endings, named by GRANIT the modulator system are the ones for which the Young–Helmholtz theory is completely valid. The dominator system may be considered as the resultant of modulators. Cooperation of the two systems produces colour vision.

When light of a given wavelength reaches the retina, excitation of both the dominator system and the modulators—the latter with a specific sensitivity to the light of given wavelength—takes place. Thus, in the eye two simultaneous processes are triggered. On the one hand, perception of achromatic light, and on the other, colour perception corresponding to the wavelength of the radiation. White light sensation, however, is not separated from colour sensation but combines with it in controlling the lightness of the colour.

It has become clear that elements sensitive to different colours according to the Young–Helmholtz theory belong to the modulator system, and also, that more than three types of modulators exist in the retina. GRANIT has found seven kinds of modulators, but this is, however, in no contradiction to the Young–Helmholtz theory, since the seven modulators are the most sensitive to spectrum ranges covering varieties of the three primary colours. Two kinds of modulators are sensitive to long wavelenght light (such as orange and red), another three are the most sensitive to light in the middle band of the spectrum (yellow, green and greenish blue), while the two remaining respond to the short-wavelength end of the spectrum (blue, indigo and violet).

The modulator system is, in fact, more refined and more differentiated than the system of colour sensing elements suggested by the Young–Helmholtz theory. Thus, different modulators respond, fail to respond, or respond differentially to light of a given wavelength. In this way this intricate system of nerve endings so to say selects from the light beam incident on the eye those components which are able to excite various elements of the system, and impulses generated in the different elements produce various colour perceptions, colour sensations on the retina and finally in the cortical visual centre.

GRANIT's assumptions on the functioning of receptors have been recently revised. Doubts arose whether the reactions disclosed by him correspond to elementary receptor functions. By studies by electro-physiological methods of the electric functioning of nerve cells, or investigations on the light absorption features of the retina, receptors with sensitivities more or less similar to that of GRANIT's modulators have been detected. In the current literature, receptors identified by electrophysiological methods by DE VALOIS (1971), GOURAS (1970) and SVAETICHIN (1958), and by light absorption methods by MACNICHOL (1973), MARKS (1964), DOBELLE (1963), RUSHTON (1951) and ALPERN (1964) have been discussed.

Among others, SVAETICHIN and DE VALOIS found some receptors which respond to all four psychological primary colours, i.e. to blue, green, red and yellow. This provided physiological evidence for the opposite colour theory by HERING (1864). According to HERING, complementarity or opposition (red–green, yellow–blue) apparent in the direct colour impressions and in hue contrasts are decisive for perception. Colour sensitivity curves resulting from colour complementarity are the same as in physiological reactions.

Present day investigations on the theory of opponent colours (former "Zone Theory") try to interpret the possibility of a transition from a three receptor system to a four receptor system, which would correctly reflect hue contrast and other phenomena, in other words to opponent colour processes. According to the theory of opponent colours by HURVICH and JAMESON (1960) the opponent colour processes yellow–blue and red–green contribute unequally to colour perception. Beyond that, WALRAVEN (1962) emphasized the independent functioning of the so-called lightness channels (lightness perception) and colour channels (colour receptors). GUTH (1969) in his opponent colour theory model, relying on a similar idea, attributed the phenomenon to the inactivity of the blue receptor in lightness perception. According to TÁNCZOS (1984) transition from three to four receptors is due to an on/off "switching" of the retina peripherals, the rod system in colour vision, modifying thereby first of all the functioning of blue receptors and the blue–yellow opposition.

Existence of colour receptors differently positioned in space has been described by HARTRIDGE (1950). His experiments demonstrated that when a light beam of medium light intensity is incident on the fovea centralis, three kinds of modulators dominate colour vision, and in this case, pure trichromatic colour vision prevails. This so-called foveal colour vision is, however, a special case, and considering colour vision in general, the trichromatic theory is still correct, but it has to be complemented by the so-called *polychromatic theory* of seven receptors.

Within the polychromatic system, three sections may be distinguished. One system of receptors constitutes a trichromatic unit; its elements are most sensitive to orange, green and bluish violet light, i.e. this system is essentially the same as the colour sensing elements envisaged by HELMHOLTZ. This system, however, is activated only by light of medium intensity, while in weak or intensive light, other systems become dominant. Such a system is the so-called dichromatic system, activating at very low light intensity a receptor for red and bluish green. A third dichromatic system situated in the fovea centralis produces, upon intensive light effects, yellow and blue colour impressions. Thus, it can be seen that this system is rather complex, and consists of three interactive sections.

Cooperation between the three systems results in a special correlation between colour vision and illumination intensity. In poor light, cone shaped nerve endings are not activated at all, the process of vision relies entirely on the stimulation of rods, therefore there is no eliminating colour distinction in visual sensation. On the other hand, if the eye is exposed to very intensive light, then only the dichromatic section of colour vision —sensitive to blue and yellow alone—is activated. Consequently, very intensive illumination is inimical to colour vision by impairing the ability of colour differentiation. An optimum for colour vision is offered by light of medium intensity.

Other fundamental rules established for the colour vision process are as follows:

Colour distinction ability of the human eye is different in various colour domains (Fig. 2.12).

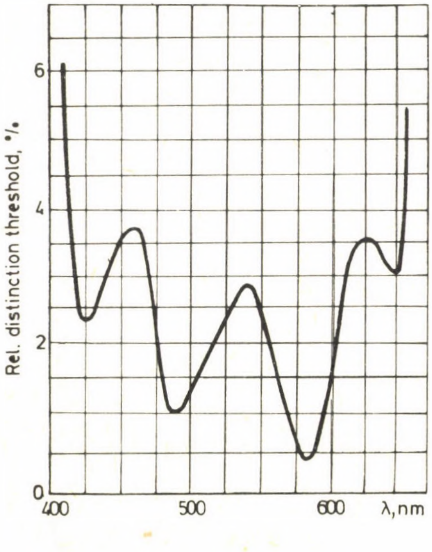


Fig. 2.12. Ability of the human eye to distinguish colours of different wavelengths

There is a definite relation between sensation resulting from the functioning of the visual organ and the brain, and the external stimuli eliciting this sensation. Correlation between the change of sensation and relative change of the external stimulus has been formulated in the *Weber–Fechner law*. This law served as a basis for the authors who created perceptionally equidistant colour systems.

A relative decrease of the lightness of red light as compared to that of blue light where light intensities of both decrease proportionally while their spectral distribution remains unchanged is the so-called *Purkinje phenomenon*.

The qualitative unit of external light stimulus to the eye is defined as the *troland*. For an eye looking at a surface of even light intensity, the numerical value of troland is the product of the area in sq.mm of the natural or artificial pupil intercepting the light by the light intensity on this surface in candelas per sq.m.

Variation of the light stimulus depending on through which part of the pupil the light beam penetrates is known as the *Stiles–Crawford effect*.

The reciprocal of the time lag between the appearance of light stimulus and the sensation elicited is called the light perception velocity.

Variation of colour sensation as a function of light intensity in the domain of vision in light is called the *Bezold–Brücke* phenomenon.

2.3.3. Chromatopsy (The Capacity of Colour Vision)

Normal eyes perceive three colours (trichromatism). The sensitivity curve has its maximum at 555 nm. An abnormal chromatopsy is when spectral tristimuli of an individual observer differ from CIE tristimulus function values. The latter are obtained by averaging spectral tristimulus functions of a large number of individuals having correct chromatopsy.

Minor chromatoptic anomalies for a normal eye include:

— the colour sensitivity curve is shortened toward red (protanomaly);

— maximum of the colour sensitivity curve is shifted toward red (deuteranomaly);

— the colour sensitivity curve is shortened toward blue (tritanomaly).

A more serious deficiency of vision (dyschromatopsia) is dichromatics (two-colour vision), with two alternatives: red and green parachromatism (daltonism), or, blue and yellow parachromatism.

In case of hereditary total colour blindness (achromatopsy) the subject has a colour vision from 380 to max. 500 nm, and for acquired colour blindness, from 380 to max. 556 nm.

2.4. Colour, Colour Stimulus, Colour Perception

In everyday wording, colour is understood both as the radiation penetrating the eye and the resulting content of consciousness. More precisely, however, the former is *colour stimulus* and the latter is *colour perception*.

2.4.1. Colour Stimuli

Physically defined, visible radiation penetrating the eye and causing colour perception is called a *colour stimulus*. Several kinds of colour stimuli can be distinguished.

An *achromatic colour stimulus* is one with zero chroma (white, gray, black).

A *chromatic colour stimulus* is one with non-zero chroma, i.e. to which a *dominant* or *accessory* wavelength can be assigned.

Colour stimuli which elicit the same colour sensation when acting simultaneously on two adjacent parts of the visual field are said to be *isochromatic stimuli.*

Colour stimuli eliciting different colour sensations when acting simultaneously on two adjacent parts of the visual field are said to be *heterochromatic stimuli.*

Pairs of *colour stimuli* can be *complementary*, by additive mixing in proper proportions a definite achromatic light stimulus is produced.

Metameric colour stimuli are defined as spectrally different colour stimuli which elicit the same colour sensation under identical perception circumstances (such as light distribution, geometries of illumination and observation, visual field dimensions).

The *colour space* is a spatial representation of the three dimensional multiplicity of colour stimuli where any colour stimulus is represented by a single point (colour point).

Colour solid is the part of the colour space composed of surface colours.

A *uniform colour space* is one in which the spacing between two colour points is about proportional to the perceptional colour difference, irrespective of the colour domain.

Dominant wavelength is defined as the wavelength of a particular monochromatic colour stimulus that when in a proper proportion to the given achromatic light stimulus, produces a chroma equal to that of the given colour stimulus.

Complementary wavelength is defined as the wavelength of a particular monochromatic light stimulus, that when mixed in a due proportion to the given colour stimulus produces a chroma equal to that of the given achromatic colour stimulus.

Colour stimulus is qualified by *chromaticity*, defined either by its colour coordinates, or by its dominant wavelength and excitation purity (colorimetric purity).

Excitation purity is defined by the ratios:

$$p_e = \frac{y - y_w}{y_d - y_w} \tag{14}$$

or

$$p_e = \frac{x - x_w}{x_d - x_w}, \tag{15}$$

where x and y are colour coordinates of the colour stimulus, x_d and y_d are colour coordinates of the monochromatic light stimulus of the same dominant wavelength as that of the selected colour, while x_w and y_w are colour coordinates of the achromatic light stimulus chosen as reference.

Colorimetric purity is defined as

$$p_c = p_e \frac{y_d}{y}, \tag{16}$$

where notations are the same as before.

Radiance (*luminance*) *factor* β of a non-radiant solid (at a given point, in a given direction and under definite illumination conditions) is the ratio of luminance of the given solid to that of a solid identically illuminated and of perfectly diffuse reflectance.

Three linearly independent, otherwise arbitrary colour stimuli, from which any other colour stimulus can be created by additive mixing, are called the *reference stimuli*. Colour stimuli are linearly independent if additive mixing of two of them cannot produce the third one.

2.4.2. Colour Perception

An element of the content of consciousness elicited by an effect on a sensory organ, which cannot be further analyzed is called *perception*. The concept of *colour perception* is defined as the consciousness content arising when the observer is able to distinguish in the visual field two adjacent parts of equal size, shape and texture, by means of the difference between the spectral distributions of the observed radiations.

Colour perception may vary in three ways: by hue, saturation, and lightness.

Hue is the attribute of colours that permits them to be described as, for example, blue, green, yellow, red, or purple. *Saturation* permits assessment of the position of a colour —among samples of the same lightness and hue—between the spectrum colour of the same hue, and gray as light as the given spectrum colour. The concept of saturation involves the distance of the given colour from the achromatic axis at the same lightness.

Lightness is the attribute of object colours by which the object appears to reflect or transmit more or less of the incident light. Lightness expresses a sensation of an intensity proportional to the luminance or the luminance factor, respectively, of the surface.

Saturation and lightness vary in finite ranges; while hue varies continuously along a closed curve, the colour circle. This is why colour sensations can be geometrically conveniently represented in a cylindrical coordinate system. Colours of identical hues lie in semi-planes confined by the achromatic axis, colours of equal saturation form coaxial cylindrical surfaces, and colours of equal lightness lie in horizontal planes normal to the achromatic axis. The outermost cylinder shell is occupied by the points of the most saturated colours, the spectrum colours (Fig. 2.13).

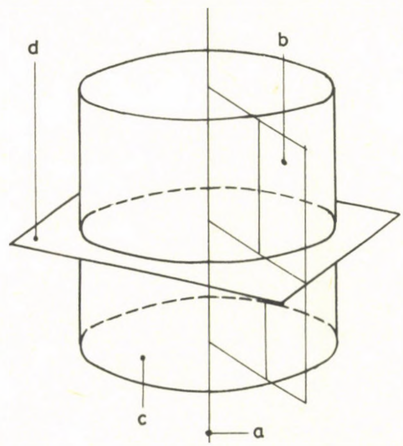


Fig. 2.13. Cylindrical coordinate system illustrating variations of hue, saturation and lightness; a) achromatic axis, b) half-plane of colours of the same hue, c) cylindrical surface of colours of the same saturation, d) plane of colours of equal lightness normal to the achromatic axis

In publications, concepts similar to those defined above such as chromaticness, chroma, colourfulness, brightness and darkness are often encountered. *Chromaticness* is determined both by hue and saturation; it is the perceptional equivalent of chromaticity, a quantity used in colorimetry. *Chroma* is a special case of saturation. The difference in saturation and chroma of colours with identical lightness and hue is the same. Chroma is a quality of colour combining hue and saturation, approximately the perceptional equivalent of the colorimetric magnitude of chrominence. *Colourfulness*, attribute of a visual sensation according to which an area appears to exhibit more or less of its hue. *Brightness*, attribute of a visual sensation according to which an area appears to exhibit more or less light. (Adjectives: bright and dim). *Darkness*, attribute of perceived colour according to which an area appears to absorb a greater or smaller fraction of incident light.

There is a wide variety of colour sensations, such as: *aperture colours* are colour sensations not bound to any material, i.e. they do not refer to any spatial position or structure. Object-bound colour sensations are named *object colours*.

Achromatic colours, i.e. white, black, gray are colour sensations lacking hue. Colour sensations with a hue are *chromatic colours*. *Spectrum colours* are colour sensations elicited by spectral colour stimuli.

Primeval colours are colour sensations which man first identified by names: yellow, red, blue, and green (Fig. C2).

Any colour may be produced from three selected colours by additive or subtractive colour mixing (see under 2.5).

By additive mixing other colours can be most conveniently obtained when selecting blue, green, and red colour sensations as *primary colours*, elicited by radiations of 444 nm, 526 nm, and 645 nm wavelength, respectively.

In Fig. C3 the primary colours are represented in the CIE diagram and in the Coloroid colour circle, respectively. For subtractive colour mixing, in turn, optimum primary colours are the principal colours i.e. yellow, blue, and red colour sensations elicited by radiations of about 570 nm, 509 nm, and 495 nm wavelength, respectively.

Secondary colours are orange, green, and violet colour sensations elicited by radiations of about 591 nm, 509 nm, and 555 nm wavelength, respectively. They can be produced from principal colours by subtractive colour mixing (Fig. C4).

Pure colours are colour sensations elicited by monochromatic light stimuli of a definite wavelength.

A *full colour* is a colour sensation elicited by a light stimulus of high chromaticity, while a *broken colour* by a low one.

A colour sensation with a high lightness is a *light colour*, while that with a low lightness is a *dark colour*.

A *cold colour* is a colour sensation dominated by the short wavelengths, while a *warm colour* by the long wavelengths of the spectrum.

Complementary colours are colour sensations elicited by such monochromatic colour stimuli which when properly mixed pair-wise give a chromaticity equal to a definite achromatic light stimulus.

Determination of complementary colour sensations has been the concern of several researchers. Experimental results by HELMHOLTZ (1925), KOENIG (1889), VON KRIES (1904), DITERICI (1892), as well as by NEMCSICS and PÁLFFY are compared in Fig. 2.14. These results show that perceptional determination of complementarity cannot be

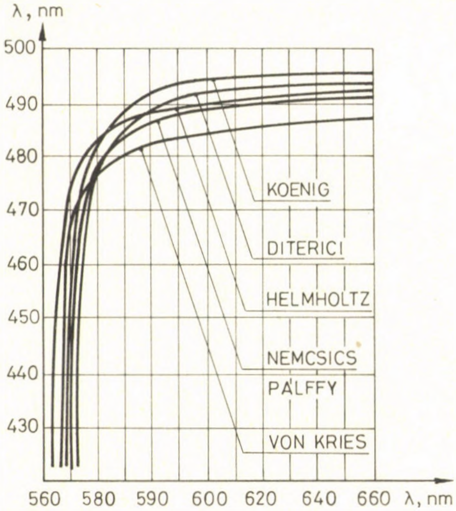


Fig. 2.14. Complementary colour sensations after KOENIG, DITERICI, HELMHOLTZ, NEMCSICS and PÁLFFY, and VON KRIES

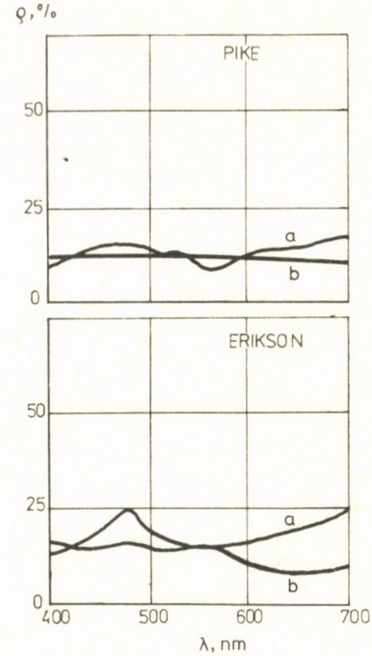


Fig. 2.15. Reflection curves of metameric gray samples of PIKE and ERIKSON. Curves a refer to "living gray", curves b to "dead gray"

other than approximate. In Fig. C5 pairs of complementaries in the CIE diagram and in the Coloroid colour system are shown.

Identical colour sensations elicited under identical conditions of perception by spectrally different colour stimuli are called *metameric*. This term was first applied by OSTWALD for the phenomenon where two or more surface colours seem similar under a given illumination, but differ in another (e.g. daylight vs. incandescent light). A deeper study has become possible with the advent of spectrophotometers and light sources of different spectral energy distributions. Metamerism has a great importance in the paint industry and in finishing, where it is important to avoid metameric coloration. In other words, colours should not change when exposed to different light sources. GRANVILLE (1949) attributed the phenomenon of living and dead grays, distinguished by artists, to metamerism. Reflection curves of some metameric colour samples by PIKE and ERIKSON (1950) are given in Fig. 2.15.

Pure colours varying along a continuous, closed curve constitute the *colour circle* (Fig. C6). Most of the practically applied colour circles are sectional, containing, e.g., 5, 6, 12, 24, 28, 48, 64, 96, or 100 colours of a continuous set of pure colours (Fig. C7).

The *gray scale* is the set of achromatic colours from white to black in which consecutive achromatic colours seem to reflect less light in even grades. Lightness differences between members are felt throughout to be equal. In the gray scale the ratio of the change of lightness perception and reflected light quantity is non-linear.

Based on experiments performed with a large number of observers, NEWHALL (1942), NICKERSON (1943) and JUDD (1975) found that the above relation is approximated to by

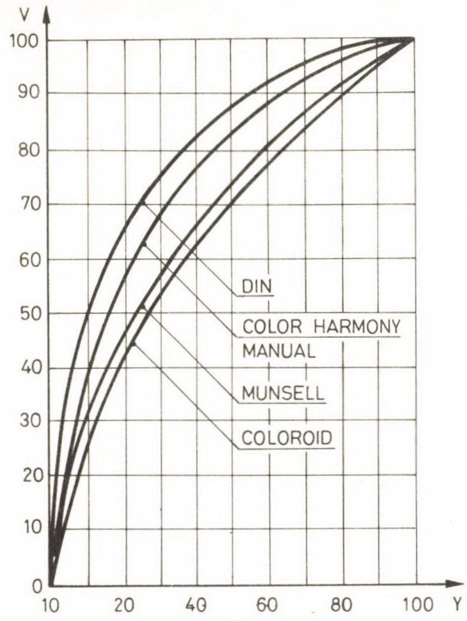


Fig. 2.16. Comparison of gray scales in DIN (RICHTER), Colour Harmony Manual (FOSS), Munsell (NEWHALL, LADD and PINNEY) and Coloroid (NEMCSICS and BÉRES) systems

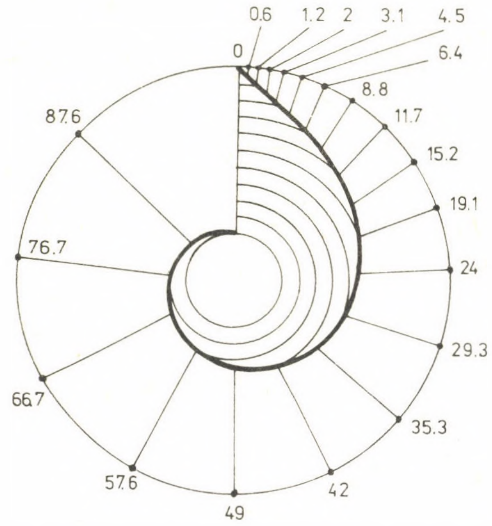


Fig. 2.17. Construction of a logarithmic gray scale by a Maxwell disc. Spinning the disc at 2000 rpm results in an evenly lighted scale

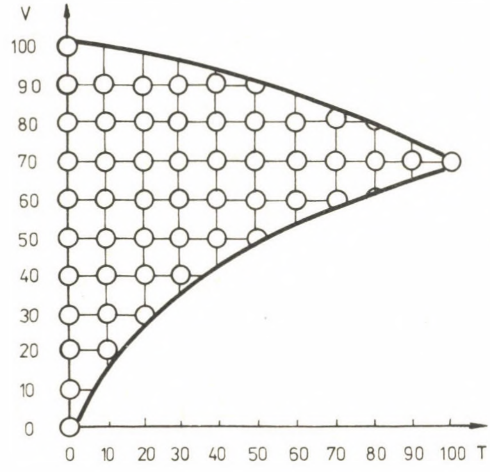


Fig. 2.18. A primary hue in the Coloroid colour system

a logarithmic curve. Figure 2.16 is a comparison of gray scales according to DIN, the Colour Harmony Manual (Ostwald), as well as the Munsell and Coloroid colour order systems. Development of a logarithmic gray scale on the Maxwell disk is illustrated in Fig. 2.17.

The *colour plane* is defined as a half-plane of colours of the same hue. Intermittent variation of colour points in the plane represents e.g. changes of colour, of white and black content, or of saturation and lightness (Fig. 2.18).

The *space of colour sensations* is a spatial representation of a 3D multiplicity of colour sensations, where every colour sensation is represented by a single point. The *solid of colour sensations* is the part of the space of colour sensations made up by surface colours. The part of the colour space containing colours of about the same hue is known as the *colour domain*.

2.5. Colour Mixing

It is known from experience that from any two or more colours other colours may be produced by mixing, and that there is more than one way to produce a particular colour by mixing. As a matter of fact, any colour can be produced by mixing an appropriate number of reference colours in the correct proportion. A certain colour may be produced from reference colours either by additive or by subtractive colour mixing.

Additive colour mixing may be realized in three ways, i.e. by means of a revolving colour disk, by projecting coloured lights onto the same area of a screen, or by printing screen points side by side. Additive colour mixing can be described by simple mathematical expressions; their regularities are simple.

Subtractive colour mixing consists of subtracting certain components of the complex light by mixing pigments of different colours or by superimposing colour filters. Subtractive colour mixing is more difficulty to be expressed mathematically often involving approximations.

2.5.1. Additive Colour Mixing

Adding light to light results in a stronger light. Coloured lights add up, this is why mixing of coloured lights is called additive colour mixing. The simplest way to illustrate additive colour mixing is by placing red, yellowish green and blue glasses before three projectors projecting them on to the same white screen so that the circles partly overlap (Fig. C8).

With the projection made as shown in the figure, each two overlapping colours result in a lighter colour, while all the three add up to white.

In additive colour mixing, not only a mixture of red, green and blue, but also a pair of adequately selected colours may add up to white.

When we may try to find out the rules of additive colour mixing by experiment, we experience the following:

Let two monochromatic colours be mixed by projecting one over the other. If these two mixed colours are not very far apart in the spectrum, then the mixed colour is intermediary between the two (Fig. 2.19). Position of the resulting colour within the spectrum depends on the intensities of colours mixed. By mixing these two colours in due proportions, all the other colours possible between them can be produced. In any case, luminance of the mixed colours will more or less exceed that of any of the components. The closer the two colours (A_1 and A_2) selected from the middle part of the spectrum, the higher will be the luminance of the resulting colour (A_3).

Again, luminance of the mixed colour increases with the distance of the components within the spectrum. Finally, the higher the luminance of the mixed colour A_3, the closer it is to the mean value of the two component colours (A_1+A_2).

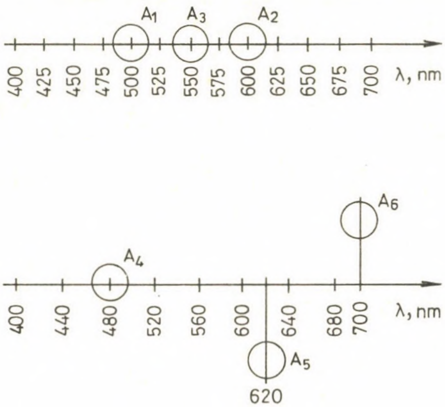


Fig. 2.19. Examples for double additive colour mixing

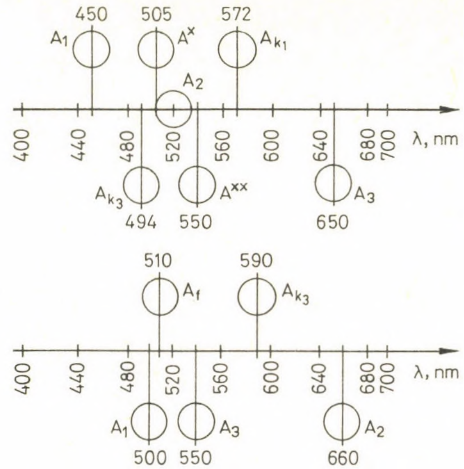


Fig. 2.20. Examples for triple additive colour mixing

With large differences between the two monochromatic colours, there is a special case, that of the complementary colour pairs—the mixture of which appears white. Mixing of complementary colour pairs in different proportions will always result in one of the component colours, only more or less lighter.

Further increasing the distance of monochromatic colours in our experiment results in a colour mix A_6, with a dominant wavelength outside the range between A_4 and A_5, or a purple, a colour missing from the spectrum, will be obtained. This purple will be the most saturated if the two extreme colours of the spectrum, those of 400 nm and 700 nm wavelength are mixed. Possibilities to produce ochre by double colour mixing are illustrated in Fig. C9.

Mainly for stage illumination, in addition to dichromatic mixes, trichromatic mixes have also been applied. In Fig. 2.20, results of trichromatic mixing were plotted. This was done by mixing first two colours e.g. A_1 and A_2, resulting in a colour A^* of higher luminance. This colour is then mixed with a third one, A_3. Thereby, in conformity with the rule for dichromatic mixes, blending of the colour obtained from A_1 and A_2 with A_3 results in a colour corresponding to A^{**}. Upon mixing, luminances of the colours add up.

It is important that the wavelength difference between A_1 and A_3 should exceed that between A_1 and its *complementary colour** A^{k1}, in order to be able to obtain colours outside the range of wavelengths between A_1 and A_3, as well as purples. Also, it is of importance that A_2 should be nearer to A_1 and A_3 than to A^{k3}, its complementary colour. Since by mixing A_1 and A_2, as well as of A_2 and A_3 intermediate colours may be produced, white (A_f) may be mixed from A_1, A_2 and A_3 if A_1 and A_2 are taken in a proportion such that colour mix A^{k3} is the complementary colour of A_3.

Tristimuli A_1, A_2 and A_3 can be additively mixed to any spectrum colour, in addition also to purple, missing from the spectrum, and white. (Creation of certain colours

* See under 2.5.2.

needs a negative quantity of a primary colour, that is, when matching colours, the primary colour has to be added to the colour to be matched.) All the colours may be produced with arbitrary white content.

Lightness of the colour mix may be increased by proportionally increasing the intensities of the reference colours.

In our colour mixing experiments, we find that different monochromatic primary colours may add up to identical colours.

Consequently, a colour eliciting one and the same colour sensation may be composed from different spectral colours, that is, different colour stimuli may elicit the same colour effect (metameric colours).

Regularities in mixing coloured light have been formulated by GRASSMANN (1853)—the first to recognize essential relationships between light and colours—in three theorems since then referred to as *Grassmann's laws*:

I — Any colour obtained by additive colour mixing is determined by its tristimuli, irrespective of their spectral composition.

II — To describe a certain colour, three and only three independent data are required.

III — In the domain of daylight vision, colour sensation does not vary with light intensity.

2.5.2. Subtractive Colour Mixing

In our everyday work we mainly have to do with subtractive colour mixing, named after the fact that a colour mixed to another colour subtracts some radiation from the latter. Stained glass when illuminated by transmitted white light withholds, absorbs radiation of any colour but its own, making the transmitted light appear as having the colour of the glass. When looking at red letters on white paper through red glass, the letters disappear since the glass transmits only the red component of the light reflected by the white paper.

The same is experienced if any other coloured object is viewed through a glass or liquid of the same colour. If, however, a coloured object is viewed through glass of its complementary colour, it looks black, since radiation corresponding to the colour of the object is barred by the complementary colour. Thus, no light from the object is incident on the eye, just as if it reflected no radiation at all, i.e. as if it were black. In additive colour mixing, in turn, the resulting colours are always lighter than the components.

Subtractive colour mixing is illustrated in Fig. C10. From each two colours of the coloured circles, another colour results by subtractive colour mixing. Red arises from yellow and purple, green from blue and yellow. Finally purple and ultramarine result in greenish blue. These three together add up to black, because in combination they subtract or absorb all the radiation, and nothing remains to be reflected.

While additive colour mixing is an optical process involving coloured light, subtractive colour mixing mainly involves the mixing of pigments, coloured liquids, and transparent coloured materials.

While the primary colours used for additive colour mixing are green, red and blue, for subtractive colour mixing mostly yellow, greenish blue and purple are applied. It is interesting that colours resulting from additive colour mixing are just the primary colours used for subtractive colour mixing, and *vice versa*.

Regularities of subtractive colour mixing are much more complex than those for additive colour mixing. Its essentials are as follows:

I — Output of subtractive colour mixing always depends on the actual spectral composition, rather than on the character, of the component colours.

II — In subtractive colour mixing, two colours, which appear quite identical but have different spectral compositions, will yield different colours when mixed with a third colour.

Hence, subtractive colour mixing is antagonistic to additive colour mixing, since the simple laws of the latter follow from independence of spectral composition.

Spectrum colours composing the colour of some surface are called the *dominant colour group*, the other colours being the *compensating colour group*.

Colours of painted surfaces, pigments and other surfaces invariably result from the phenomenon that part of the incident light, composed of light beams of different wavelengths (e.g. daylight) is absorbed and the other part reflected. If only little light is absorbed the coloured surface seems to be faintly coloured, i.e. having a light colour. The colour perceived is always complementary to the colours absorbed by the surface or pigment.

With increasing absorption, the white content decreases, whereby the colour becomes more saturated. At the same time, the colour resulting from reflected rays darkens, and if all the incident light is absorbed, the surface seems black.

The colour produced by subtractive colour mixing depends on the ratio of the dominant group in the incident light to the absorbed compensating colour group. Practically, this can be envisaged as if the illuminating white light contained "all kinds of colours", that is to say as if it were a mix of all the spectrum colours. Apart from a general reduction of intensity affecting all the colours (graying), at some wavelengths there is hardly any reflection, biassing thereby the spectral composition of the light. This gives a coloured impression, marked by the dominant colours.

The resulting new colour is determined by those component colours of the dominant group that outweight the compensating group, in other words, their compensating colour counterpart is missing from the mix.

If some colours are missing from the dominant group, the new mixed colour will be lighter. The more colours are missing, the lighter is the colour; conversely the more complete the group, the more saturated will be the resultant colour. Saturation will be at a maximum when all the colours of the dominant group are present.

As a general rule, in mixing paints, the resulting new colour will be the one which is present in dominant colour groups of all the colours entering the mix. Mixing e.g. a yellow paint with a blue one, gives green since reflected rays, that is, its dominant colour group comprises green, hence the mix will also be green.

It has to be mentioned that in explaining subtractive colour mixing the terms compensating colours and colour groups have been used. The same have been defined as complementary colours in connection with additive colour mixing. By speaking here of compensating instead of complementary colours, we wished to emphasize the spectral aspects of the light reflection and light absorption processes discussed.

In the practice of subtractive colour mixing, mainly when mixing colours light by nature, some colour shift can be observed. For instance, on mixing yellow, shifts toward red, blue to green may occur. The reason for this can best be understood by observing opposite dominant and compensating colour groups of the spectrum. If either the dominant or the compensating colour group lies entirely or partly on a spectrum gap (colours missing from the spectrum), the colour is formed by "deficient" spectral processes responsible for these colour shifts. Thereby spectrally compensating colour pairs are not quite the same as complementary colour pairs of subtractive colour mixing.

2.6. Colour Systems

Man is able to distinguish between an extremely large number of surface colours. Since the earliest times, in order to help orientation, it has been attempted to systematize colours. The modern idea of colour systematization, namely to arrange colours in a 3D space, dates back to the 17th century. Stages in the development of this idea have been colour systems suggested by Forsius (1611), Agulionius (1613), Fludd (1629), Kirchner (1641), Waller (1686), Newton (1704), Mayer (1758), Harris (1766), Lambert (1772), Schiffermüller (1772), Sowerby (1809), Goethe (1810), Runge (1810), Hayter (1826), Chevreul (1839), Field (1846), Maxwell (1860), Benson (1868), Wundt (1874), Hering (1878), Blanc (1879), Rood (1879), Lacouture (1890), Höfler (1897), Ebbinghaus (1902). Colour systems actually applied in present times—to be considered below—are all the achievements of the 20th century, and only these will be discussed here.

Colour solids constructed according to the principles of the given colour system are usually represented by means of colour sample collections. In general, it is attempted to arrange the colour samples within the colour solid approximately uniformly. The reason for this is that by assigning codes to colour samples, the aim of colour collections is to assist in comparative colour determination. Determination or even approximation by interpolation of codes of colours missing from the colour collection is only possible when there is a perceptional equidistance between colour samples.

Codes assigned to colour samples represent either tristimulus values or colour sensation parameters of hue, saturation and lightness. Without colour samples a colour system is only unambiguous if its codes can also be expressed by internationally agreed tristimulus values.

2.6.1. Colour Systems Based on Additive Colour Mixing

In colour systems based on additive colour mixing, colours are considered as additive mixes of a colour in the colour circle, as well as of white, and black. Codes are related to the proportion of additive components. Several of such colour systems are actually used.

Ridgway's colour system

Ridgway published his colour system in 1886, and his Colour Atlas in 1912. Under the title "Color Standards and Color Nomenclature" it is still used in the USA mainly for describing colours of flowers, plants and insects. It uses a colour circle consisting of 36 saturated colours, and a 9-stage achromatic scale including white and black. The double cone-shaped colour solid contains 1115 colours, each marked by a letter and number code. Names are assigned to some colours. This colour collection includes a disproportionately high number of very dark colours and its colour space is discontinuous and not uniform enough, and also disregards the specific lightness of colours. Codes do not follow perceptional variations.

Ostwald's colour system

OSTWALD, the famous physicist and chemist published his system in 1915. Every colour is described by its chroma, and its white and black content. Graduations of its gray scale follow the Weber–Fechner law. Among the many possible ways of arranging gray shades, those with ten degrees each between 1 and 10, then between 10 and 100 are applied. In decreasing proportions the series is as follows:

100	79	63	50	40	32	25	20	16	12	6
10	7.9	6.3	5.0	4.0	3.2	2.5	2.0	1.6	1.2	0.6.

In his system, the mean value of two adjacent numbers is the white content of a shade in the gray scale:

89	71	56	45	36	28	22	18	14	11
a	b	c	d	e	f	g	h	i	k
8.9	7.1	5.6	4.5	3.6	2.8	2.2	1.8	1.4	1.1
l	m	n	o	p	q	r	s	t	u
0.89	0.71	0.56	0.45	0.36					
v	w	x	y	z					

Letters mark gray scale tones.

In recently published Ostwald colour collections, the gray scale consists only of eight shades: a, c, e, g, i, l, n, p. Initially, the colour system comprised a colour circle of 100 units, reduced in subsequent editions to 24 colours (Fig. C11).

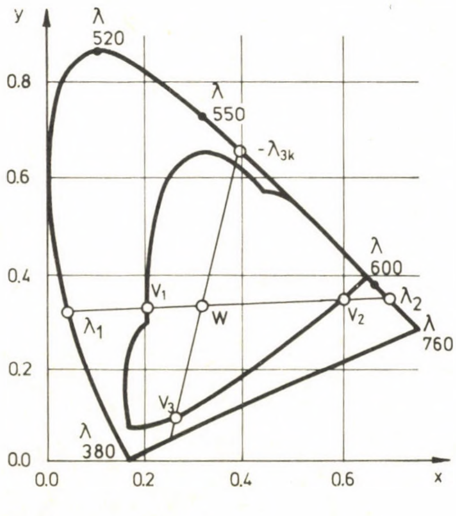


Fig. 2.21. Arrangement of ideally saturated colours making up the primary colour circle of the Ostwald colour system in the CIE 1931 diagram. Dominant wavelength of V_1 is λ_1, that of V_2 is λ_2, while the dominant wavelength of V_3 is dominant wavelength $-\lambda_{3k}$ of its complementary colour

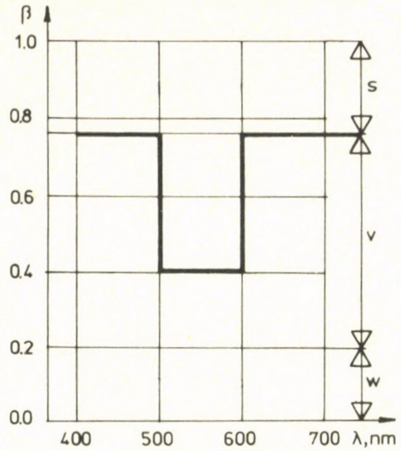


Fig. 2.22. Description of solid colours similar to that of optimum colours after OSTWALD. β luminance factor; s black content; v chroma; w white content

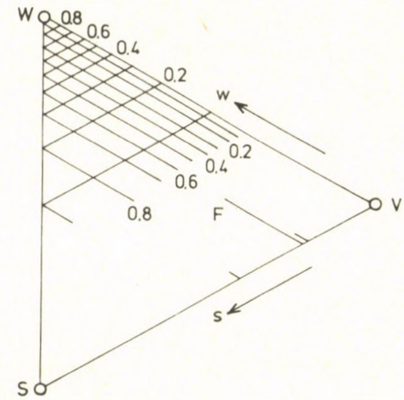


Fig. 2.23. Perceptionally equal distances in a colour plane of the Ostwald colour system. W white, V pure colour, S black

In the CIE diagram, points of the colour circle form a closed curve. A straight line laid across any point on the curve and the white point cuts out from the curve the complementary of the starting colour (Fig. 2.21). OSTWALD represented also existing colours of the solid by curves similar to the characteristic curves of optimum colours (Fig. 2.22). Here wavelengths of the optimum colour representing the colour content define its characteristics referred to the horizontal axis of the curve, while the corresponding sections on the ordinate axis are obtained from:

$$s+v+w=1 \tag{17}$$

where s is the black content, v the chroma, and w the white content, respectively.

In this system, possible shades are grouped as:

— reference colours;
— light colours (reference colour + white content only);
— dark colours (reference colour + black content only);
— dull colours (reference colours + white and black = gray content).

OSTWALD's colour solid is a double circular cone, with white and black at the vertices. Colours of the same hue reside in isosceles triangles (Fig. C12).

The best practical realization of OSTWALD's principle of colour systematization is the colour sample collection entitled "Colour Harmony Manual" and published in the USA, indicating also colour sample coordinates in the CIE *XYZ* system.

In spite of OSTWALD's efforts, a deficiency of the system is lack of perceptional equidistance (Fig. 2.23).

Also the idea known as the internal symmetry principle of the system is erroneous. In spite of different saturations of the colours in the colour circle, it is stated that a 1 : 1 additive mix of each two adjacent saturated colours results in the perceptional average of the two colours. His endeavour to include only complementary pairs in the colour circle implies that in the blue and cold green colour domains, perceptional hue steps are smaller than e.g. in domains of yellow or orange.

The Baumann–Prase colour system

Based on ideas forwarded by Prase (1941) this system was published by Baumann and Prase in 1942. Its drawback is its ambiguity inasmuch as some pure light and pure dark shades occur repeatedly. It also lacks clarity since colours have been marked by continuous numerals. Its colour card collection is hardly in use today.

Rabkin's colour system

The Soviet Rabkin's colour system, relying on nine primary colours, appeared in 1950. Every primary colour is further divided into five parts, thus the colour circle consists of a total of 45 pure colours. Its gray scale is graduated in smaller steps from medium gray to light gray, and in larger steps toward darker shades. Codes do not suit perceptional description; the system is not uniform from the perceptional point of view.

2.6.2. Colour Systems Based on Subtractive Colour Mixing

In these systems, colours are described as being mixtures of various pigments.

Plochère's colour system

Plochère published his colour system and colour sample collection in the USA in 1946. It is noteworthy from the point of view of colour harmony correlations. Colours are described in terms of chroma, and of white and black content. The colour collection includes 1248 colours. Every colour in the collection is named, and mixing recipes are provided for their preparation by subtractive mixing from primary colours, and black or white. Colour space of the system is not continuous and perceptionally not uniform.

The Colorizer colour system

This was developed in the USA for colour reproduction. Every colour is described as a subtractive mix from any of twelve primary colours and white and black. Its colour system is not continuous and perceptionally not equidistant.

The tintometer colour system

Originally this was developed in 1887 by Lovibond for beer colorimetry and improved by Schofield in 1943. Colours are described as subtractive mixes from a red, a blue and a yellow. Visual colorimeters based on these relationships, applying superimposed coloured glass filters are still in use in several fields of industry.

2.6.3. Printed Screen Systems

Colour systems for the printing industry rely on the size and overlapping of screen points obeying laws of additive or subtractive colour mixing.

Hickethier's colour system

Hickethier's colour system (1963), first published in 1940, is primarily of importance for colour photography and trichromatic printing. The collection of the system containing 1000 colour cards finds increasing use in practice.

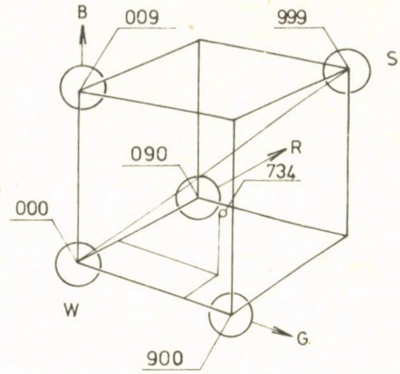


Fig. 2.24. Scheme of HICKETHIER's system based on three-colour printing

Ordering and descriptive magnitudes of the system are numbers indicating screen size of the three superprinted primary colours in trichromatic printing (Fig. 2.24). These magnitudes do not correspond to colour perception, therefore the system does not suit colour design practice.

Villalobos' colour system

This colour system, published in 1947 by VILLALOBOS brothers in Argentina, relies on a 38-part colour circle, and a gray scale of 21 steps. Colours in the colour circle are approximately complementary. Every hue section of the system comprises 191 colours i.e. the collection contains a total of 7279 colours. Colour description magnitudes are: colour tone, lightness degree, and hue step. Every colour is produced as a mix from a pure colour and white or black. Its colour space is not uniform and has no relation to the CIE colorimetry system.

Wilson's colour system

WILSON's colour system was published in 1942 in England as a common publication of the British Colour Council and the Royal Horticultural Society. The collection contains 800 colour samples. Characteristic magnitudes are: chromaticness, grayness, lightness. Its colour space is perceptionally not uniform.

Küppers' colour system

This was intended for the printing industry and published in 1976. Its colour collection of 25 000 shades appeared in 1987. Inherently, most of the samples are very dark shades. It is in no tabular, graphic or transformational relationship to the CIE *XYZ* system and unsuitable for environment colour design.

2.6.4. Perceptionally Equidistant Colour Systems

These systems strive to equidistance between adjacent colour points in the model of the system. Distances express differences between colours represented by the points. All these systems except the Munsell system were worked out in recent times. They differ partly by the degree of perceptional equidistance of their colour space and their continuity and partly by their relation to the CIE colour order system.

Munsell's colour system

The foundations for the most up-to-date idea of colour systems were first laid down by MUNSELL, who published his "Book of Color" and the pertinent colour sample collection in 1915. This system has been further developed in 1943 and correlated to the CIE 1931 colorimetry system. In 1956 it was extended to include very dark colours. Later the Munsell Color Company was founded for re-editing at regular intervals, in the original quality, the colour collection of the system. Since 1979, it is also published in Japan under the title "Chroma Cosmos 5000".

The Munsell System is still one of the most popular colour systems. Its codes are up to this day the most common colour identification numbers in the international literature. Colours are identified by three data: hue H, chroma C, and value V (lightness). These data are the three coordinates of the Munsell colour solid, characterized by cylindrical coordinates and correspond to the three characteristics of visual perception.

Colour circle of the colour solid, the hue scale, is divided into 100 perceptionally equal parts according to ten shades each of the following five reference and five mixed colours: red (R), yellow–red (YR), yellow (Y), green–yellow (GY), green (G), blue–green (BG), blue (B), purple–blue (PB), purple (P) and red–purple (RP) (Fig. C13).

The axis of the Munsell colour solid accommodates gray (neutral, N) colours. The achromatic scale is divided in a perceptionally equidistant manner from 0 to 10. Munsell lightness of a perfectly absorbing surface (ideal black) is 0, that of a perfectly and diffusely reflecting (ideal white) surface is 10.

The correlation between Y tristimulus percentage referred to CIE ray distribution C, MgO surface and the Munsell lightness V is:

$$Y = \sqrt{1.2219\,V - 0.23111\,V^2 + 0.23951\,V^3 - 0.021009\,V^4 + 0.0008404\,V^5}\,. \qquad (18)$$

The Munsell chroma increases with the distance from the achromatic axis. The maximum of the chroma scale is between 10 and 38 depending on the hue (Fig. C14).

In the Munsell colour system, colours are marked as:

$$H, \quad V/C$$
$$10\ \mathrm{RP}, \quad 5/6.$$

The shape of the Munsell colour solid is shown in Fig. 2.25.

Relationship between the Munsell colour system and CIE has been tabulated.

The OSA colour system

On commission by the Optical Society of America, this system was elaborated under the guidance of JUDD between 1947 and 1977. Colours are described in terms of lightness L, yellowness y, and greenness g. In this system, lightness may range from -17 to $+5$. Gray of 30% reflection has been chosen for zero lightness. Yellowness ranges from -6 to $+11$. Numbers with a negative sign mean blues, positive numbers mean yellows. Greenness varies from -9 to $+9$. Here negative numbers are red, positive ones are green. Also in these latter cases, 0 refers to gray. Because of the geometric arrangement of colours this system is also called the rhombohedron lattice colour system. Each colour has twelve, about perceptionally equidistant, neighbours. Its colour collection contains 645 samples defining also the corresponding CIE XYZ identifiers. The system itself is in no transformational relation to the CIE XYZ system.

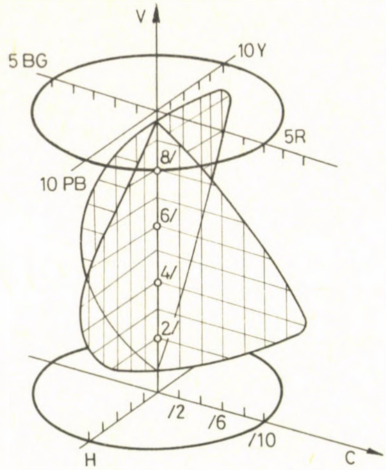


Fig. 2.25. The Munsell colour solid

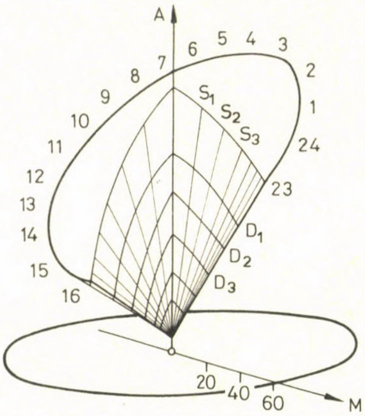


Fig. 2.26. Colour solid of the DIN colour system: $M=\sqrt{(Y-X)^2+(Y-Z)^2}$.

The Hunter LAB colour system

This was set up by Billmeyer and Saltzmann in 1981. Colours are distributed in a geometrical arrangement similar to the OSA colour system. Perceptional equidistance is given up in order to enable transformation to the CIE XYZ system by the following formulae:

$$L=10\sqrt{Y},$$
$$a=\frac{17.5\,(1.02X-Y)}{\sqrt{Y}}, \tag{19}$$
$$b=\frac{7.0\,(Y-0.847Z)}{\sqrt{Y}},$$

where L indicates colour lightness, a redness and greenness, b yellowness and blueness.

The DIN colour system

It was in 1944 that the first report on Richter's colour system—to become German standard in 1953—was published. Colours are described by perceptional characteristics.

DIN-Farbton (T) corresponds to hue. In this system, the colour circle is divided into 24 perceptionally nearly equal sections. DIN shades thus defined are numbered from 1 to 24 (Fig. C15).

DIN-Sättigungsstufe (S) is the degree of saturation. The achromatic point has a saturation $S=0$. DIN hue and DIN saturation jointly describe chroma (Farbart). In the CIE colorimetry system these data are expressed by colour coordinates x, y (Fig. 2.26).

DIN-Dunkelstufe, i.e. darkness degree (D) is a lightness characteristic of solid colours. With the luminance factor concept defined by the CIE tristimulus value Y it is mathematically related as:

$$D=10-6.1723\log\left(40.7\frac{A}{A_0}+1\right), \tag{20}$$

where A and A_0 are tristimuli Y of the given colour, and of the optimum colour of dominant wavelength corresponding to the given colour, respectively. The ratio A/A_0 stands for relative lightness.

In the DIN colour system, colours are identified as:

$$T:S:D$$

$$12:7:9\,.$$

Relationship between the DIN and the CIE XYZ colour systems has been tabulated. An axial section of the DIN colour solid is seen in Fig. C16.

The NCS colour system

One of the latest ideas on colour systematization relies on the *Hering–Johansson theory*, materialized as the colour atlas by HESSELGREN issued in 1953. Based on this atlas, in 1972 HÅRD and SIVIK have developed the Natural Colour System (NCS) adopted as Swedish Standard in 1979.

The authors of this system started from HERING's idea about six elementary colour perceptions, i.e. white (W), black (S), yellow (Y), red (R), blue (B), and green (G)—all the other colour perceptions being more or less related to them. In the NCS colour system every colour is described by the degree of its similarity to the six selected colours.

A colour cannot be similar to more than two hues. Yellow and blue exclude each other, and so do red and green. Sum of the colour variables defines the NCS chromaticness (c) of the perceived colour, and their ratio its hue (Φ).

In the NCS colour system, colours are marked as:

$$sc-\Phi\,,$$

for instance:

$$2040-\mathrm{G40Y}\,,$$

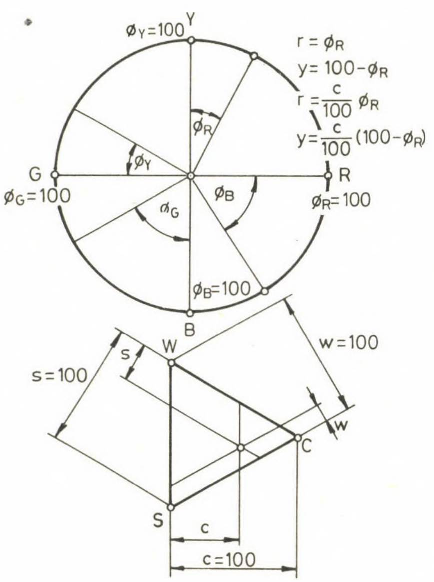


Fig. 2.27. Two projections of the colour solid of the NCS colour system

where s is whiteness (a magnitude associated with lightness), c is chromaticness (a magnitude associated with saturation), and Φ is the hue of the colour. In colour marking, s and c values—both of two digits—are written without space and separated from Φ by a hyphen. The hue of the colour in the example above is intermediary between green (G) and yellow (Y) in a ratio of 40 to 60.

The geometric form that the NCS system assumes is a regular symmetric double cone with white and black at the vertices, while the other four preferential hues are on the circle of full colours, at corners of a square touching this circle (Fig. 2.27). This colour solid is of the same shape as that of the Ostwald system. Also the basic principle of some variables was adopted from the Ostwald system, but with a modified definition and scale. Similarities and differences between CIE and NCS colour spaces have been tabulated but no exact mathematical correlations were established.

The significance of this system is that it operates with a tetrachromatic colour description as a possible way of visual colour description. From other aspects it exhibits most of the deficiencies associated with the Ostwald system.

The TGL colour system

This was published by ADAM in the German Democratic Republic in 1963. Colours are ordered according to different scales utilizing the ideas of the Baumann–Prase and Ostwald systems. It is in no transformational relation to CIE. Its colour collection was named as FARAU.

The Coloroid colour system

A new idea in colour systematization is a colour space relying on colour harmony intervals, developed by the Author at the Technical University of Budapest. Psychometric scales of the system were based on experiments conducted between 1965 and 1980. It was published in a final form in 1979 (NEMCSICS, 1979b).

It has been adopted as standard by the Hungarian Standards Bureau in 1982 (MHSZ, 1982).

By virtue of its aesthetically uniform colour space, convenient symbol system and simple, two-way unambiguous correlation with the CIE *XYZ* system it suits environment colour design, colour education and various other creative activities concerned with colour. Colour sensation characteristics are Coloroid hue, Coloroid saturation and Coloroid lightness. The first, hand-painted colour collection was issued in 1972. In 1988, the "Coloroid Atlas" (NEMCSICS, 1988) comprising 1647 colour samples was published. In addition to Coloroid characteristics, the collection also indicated those according to the CIE *XYZ*, Munsell, DIN, and NCS systems. The Coloroid colour system is described in detail in Chapter 3.

2.6.5. Colour Collections

Acceptance of a colour system by practitioners also depends on the quality of its colour collection. Practice requires ever more of colour collections. These mostly rely on ordering principles of one of the colour systems outlined above, but there exist collections following other principles. The table below contains more or less popular colour collections applied in environment colour design.

Year of publication	Title	Publisher	Colour system	Number of samples
1929	Munsell Book of Color	Munsell Color Co., Baltimore	Munsell	850
1933	Ostwald Color Album	Winsor–Newton, London	Ostwald	900
1934	Dictionary of Colour Standards	British Colour Council, London		240
1938	Wilson Colour Charts	British Colour Council, London	Wilson	800
1938	Historical Color Guide	Helburn, New York		150
1946	Swiss Colour Atlas	Edition Chromos, Winterthur	Müller	1090
1946	Color and Color Names	Edition Plochère, Los Angeles	Plochère	1248
1947	Atlas de los Colores	Molyn Homes, Buenos Aires	Villalobos	7279
1948	Baumanns Farbtonkarte	Aue i Sa., Stuttgart	Baumann	1359
1948	Color Harmony Manual	Container Corp. of America, Chicago	Ostwald	900
1949	Dictionary of Colours for Interior Decoration	British Colour Council, London		378
1950	Designer's Color Guide	E. I. du Pont de Nemours, Wilmington		1600
1950	Dictionary of Color	Maerz-Paul, McGraw-Hill, New York		7000
1952	DIN Farbenkarte	Deutsches Institut für Normung, Berlin	DIN	240
1952	Hesselgren's Colour Atlas	Palmer, Stockholm	Hesselgren	507
1952	Farbenordnung Hickethier	Osterwald, Hannover	Hickethier	999
1953	Der Mobile Farbkörper 743	Edition Chromos, Winterthur	Müller	743
1955	Colorizer Paint System	F. Birren, Stamford, CT	Colorizer	1342
1955	RAL Farbregister 840R	Musterschmidt-Verlag, Göttingen		94
1956	Scandinavian Colour Book	Nordisk Textile Unions, Copenhagen		1728
1958	Munsell Book of Color	Glossy Edition, Munsell Color Co., Baltimore	Munsell	1500
1961	Kornerup Farver i Farver	Politikens Forlag, Copenhagen		1440
1962	DIN 6164 Matte Farbmuster	Beuth-Verlag, Berlin	DIN	507
1962	Swiss Color Atlas 2541	Edition Chromos, Winterthur	Müller	2541
1963	Colors for Interiors, Historical and Modern	Whitney, New York		248
1963	Pantone Color Specifier	Moonachie, New Jersey		563
1964	Design Color for Architecture	Japan Color Res. Inst.-Nihon Shikiken Enterprise, Tokyo		400
1970	ICI Colour Atlas	Imperial Chemical Industries, Butterworths, London		1379

Year of publication	Title	Publisher	Colour system	Number of samples
1971	JIS Color Code for Investigation	Japan Color Res. Inst., Tokyo		600
1971	Farau Farbenkarten	PGH Farbe und Raum–Aue i Sa., Berlin	TGL	1080
1972	Magyar színdinamikai színsor (Hungarian Colour Dynamic Colour Series)	OMFB, Budapest	Coloroid	214
1973	Aesthetics of Colour in Natural Harmonies	Edition Chromos, Winterthur	Müller	200
1974	Chart System of Color Names	Japan Color Res. Inst., Tokyo		286
1974	Manual of Color Names (ISCC-NBS)	Japan Color Res. Inst., Tokyo		400
1974	Uniform Color Scales Samples	Opt. Soc. Amer., Washington	OSA	552
1977	Color Arrangements for Interiors	Japan Color Res. Inst., Tokyo		108
1978	Chroma Cosmos 5000	Japan Color Res. Inst., Tokyo	Munsell	5000
1978	Farbenkatalog für die Gestaltung	Bauakademie der DDR, Berlin	TGL	652
1978	Acoat Color Codification	Akzo Coatings, Amstelveen		2021
1978	Color Range Manual 100	Japan Color Res. Inst., Tokyo		65
1979	Colour Atlas SS 01 91 02	Swedish Standards Inst., Stockholm	NCS	1412
1980	Color Tone Manual	Japan Color Res. Inst.-Nihon Shikiken Enterprise, Tokyo		400
1981	Chromaton 707	Japan Color Res. Inst., Tokyo		2215
1982	Coloroid színatlasz. E. minta (Coloroid Colour Atlas. Sample E.)	Technical University, Budapest	Coloroid	982
1983	DIN 6164. Glänzende Farbmuster	Beuth-Verlag, Berlin	DIN	571
1986	Eurocolor Farbenatlas	Schwabenmuster, Gaildorf		1100
1987	Der Grosse Küppers Farbenatlas	Callwey, München	Küppers	25000
1988	Coloroid Colour Atlas	Innofinance, Budapest	Coloroid	1647

The proliferation of colour collections highlights the problem of standardizing colour notations, requiring, in turn, to test the practical value of colour systems. In 1977, an International Working Committee headed by WYSZECKI was set up to test various current colour systems and colour collections. In 1985, BILLMEYER reported about the activity of the Committee at the Monte Carlo Congress of AIC (Association Internationale de la Couleur). Definitions have been adopted for advisable requirements for colour systems and colour collections to be used in international practice. Results of investigations concerning current colour systems and collections have been recapitulated in an annotational bibliography of 435 entries compiled by BILLMEYER and published by AIC in 1986. This publication devotes separate chapters to Coloroid, DIN, ISCC–NBS (colour catalogue of Inter-Society Color Council), Munsell, NCS, OSA, and Ostwald colour systems.

2.7. Colorimetry

Colorimetry is a rather complex domain of metrology. Origins of its theory date back to NEWTON (1704), then to GRASSMANN (1853), MAXWELL (1860), HELMHOLTZ (1925), and SCHRÖDINGER (1925). Contributions to up-to-date colorimetry are due to GUILD (1926), JUDD (1933), MACADAM (1955), RICHTER (1952), STILES (1959), WYSZECKI (1968) and WRIGHT (1969).

Colorimetry is strictly speaking a tool to predict whether or not under given conditions two visual stimuli of different spectral distributions raise the same visual sensation. Prediction is made by locating the two visual stimuli in a given colour space. If coordinates in the colour space of one stimulus are the same as those of the other, a person with a normal colour vision will find them indistinguishable.

That is why in the theory of colorimetry, it is first necessary to define circumstances of colour perception.

In addition to the spectral composition and intensity of light energy, texture of the chromophoric surface, and individual features of the colour perception mechanism, perception of a colour is also markedly affected by such factors as physical or psychical fatigue at perception, preceding colour sensations, ambience of the perceived colour, direction of observation. Therefore in colorimetry, colour sensations by an observer of normal colour vision, with his/her eyes adapted to light, are always assumed. Further restrictions are as follows:

1) the visual field of the observer's eyes should be 1.5 to 2° in order to avoid the disturbance of effects of retina unevenness,
2) luminance of the visual field should exceed 3 $\mathrm{cd\,m^{-2}}$ but by not so much as to elicit dazzling,
3) the observer's eyes should be neutrally adapted, that is, not tired, and not exposed to a different colour stimulus directly before perception of the colour. It is also necessary that the texture of the chromophore should be imperceptible and it should have uniformly clear and achromatic surrounding.

Standard Colorimetric Observer was defined by CIE in 1931, and Standard Supplementary Colorimetric Observer was defined in 1964.

When several monochromatic colour stimuli of different wavelengths reach the eye simultaneously, lightnesses due to each component add up to:

$$L = \sum_{i=1}^{n} L_i \,, \tag{21}$$

where L_i is lightness due to monochromatic radiation of wavelength λ_i. This additivity fails only at a very high luminance.

Spectral sensitivity of the human eye changes below a given illumination level. Thereby, with diminishing luminance, visual fields of different colours, which previously seemed of identical lightness, may be perceived as of unequal lightnesses. This fact made it necessary to settle the minimum luminance (about 3 cd m^{-2}) of the colour stimulus eliciting perception, below which general relationships do not hold.

After these premises, let us consider the possiblities of colorimetry. There are two main lines to follow. Either, under fixed conditions of colour perception, sensing properties of man are only reckoned with according to the internationally accepted average (basic colorimetry), or, colours are examined within the everyday complex environment (higher colorimetry).

In the first case, colour stimuli creating colour sensations are related, while in the second case direct relations between colour sensations are sought for, or relationships between colour stimuli are transformed so as to express relationships between colour sensations.

It is an empirical fact that by mixing the necessary number of primary colours in correct proportions, any colour may be produced. The human eye being rather sensitive to colour differences, colorimetry may rely on the method of mixing some primary colours into a colour which is visually identical to the colour to be measured. A given colour may be produced from primary colours either by additive or by subtractive mixing. By either method, the set of colours may be assembled to a colour space. The measured colour may also be defined by coordinates locating it in the colour space.

2.7.1. Colour Space Based on Additive Colour Mixing

Essential correlations for additive colour mixing have been recapitulated by GRASSMANN (1853), a German mathematician (see under 2.5.1).

The first, and second Grassmann laws are formulated mathematically as follows: Let A_1, A_2 and A_3 be three independent reference stimuli applied in additive colour mixing, resulting in an arbitrary colour F:

$$F \equiv a_1 A_1 + a_2 A_2 + a_3 A_3 \,, \tag{22}$$

where a_1, a_2, a_3 are primary colour quantities, or else, tristimuli needed to mix colour F. In visual observation, these three characteristics are invariant. Fatigue and accommodation of the eye do not affect colour agreement. The sign of equality is replaced in the above equation by a sign of identity, expressing that an additive colour mix looking identical to colour F has been produced.

It is an experimental fact that colour mixing series are continuous, that is, a slight variation of reference stimuli results in a proportionately slight variation of the colour mix.

The equation expressing the summation of monochromatic light stimuli simultaneously acting on the eye leads to a rather enlightening analogy: colour F defined thereby may be identified to the position vector $\bar{F}$ in the three-dimensional space.

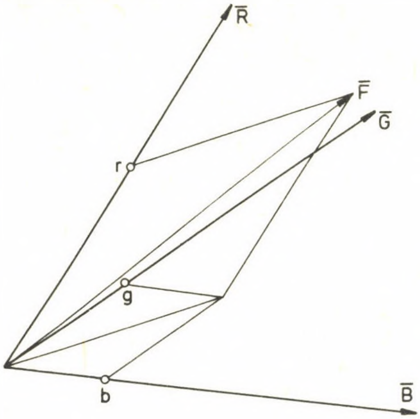


Fig. 2.28. Vectorial representation of colours

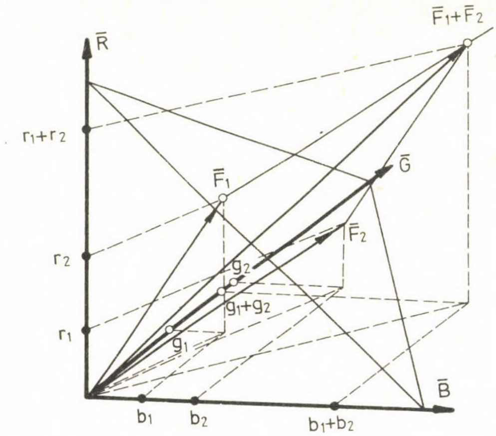


Fig. 2.29. Vectorial summation of colours

Unambiguous description of both concepts—colour stimulus and position vector—requires three data (vector coordinates or tristimuli). Transformation in either case is subject to the same regularities.

In publications colour stimuli are often represented by vectors, and so will be here. Reference stimulus vectors define axes of the 30 coordinate system. Be $\bar{R}$, $\bar{G}$ and $\bar{B}$ unit vectors of coordinate axes each. Colour equality is described in vectorial form:

$$\bar{F} = r\bar{R} + g\bar{G} + b\bar{B}\,, \tag{23}$$

where r, g and b are tristimuli (Fig. 2.28). In summing up two colour stimuli, vectorial addition rules are valid:

$$\begin{aligned} \bar{F}_1 &= r_1\bar{R} + g_1\bar{G} + b_1\bar{B}\,, \\ \bar{F}_2 &= r_2\bar{R} + g_2\bar{G} + b_2\bar{B}\,, \\ \bar{F} = \bar{F}_1 + \bar{F}_2 &= (r_1 + r_2)\bar{R} + (g_1 + g_2)\bar{G} + (b_1 + b_2)\bar{B}\,. \end{aligned} \tag{24}$$

Spatial position of colour stimulus $\bar{F}$ resulting from vectorial summation of colour stimuli $\bar{F}_1$ and $\bar{F}_2$ is seen in Fig. 2.29. Summation may involve any number of colours.

In cases described by the equation which mathematically expresses GRASSMANN's first and second laws, the colour stimulus of F can be directly mixed from three reference stimulus values. Geometrically this means that vector $\bar{F}$ is inside the pyramid defined by vectors $\bar{R}$, $\bar{G}$, and $\bar{B}$.

There are cases where visual colour identity cannot be achieved by mixing the three reference colours. Now, the two colour mixes may be equalized by mixing the proper amount of some reference stimulus to the colour to be measured. This indirect colour mixing is mathematically expressed as:

$$\begin{aligned} \bar{F} + g\bar{G} &= r\bar{R} + b\bar{B}\,, \\ \bar{F} &= r\bar{R} - g\bar{G} + b\bar{B}\,. \end{aligned} \tag{25}$$

Vector $\bar{F}$ corresponding to colour F expressed by this equation is outside the pyramid defined by vectors $\bar{R}$, $\bar{G}$, and $\bar{B}$.

2.7.2. The CIE 1931 Colorimetric System

The CIE colorimetric system accepted in 1931 by international agreement permits the unambiguous and objective description of colours. It relies on the assumption that colours of primary or secondary light sources are unambiguously defined by their spectral distribution. To spectral distributions three colour characteristics based on additive colour mixing are assigned in the following way:

Composition of relative spectral power distribution of an arbitrary colour stimulus:

$$\Phi(\lambda) = \begin{cases} S(\lambda) & \text{for illuminants;} \\ \varrho(\lambda)\, S_i(\lambda) & \text{for reflective surfaces;} \\ \tau(\lambda)\, S_i(\lambda) & \text{for transilluminated materials,} \end{cases} \tag{26}$$

where $S(\lambda)$ is the relative spectral power distribution of the radiant, $\varrho(\lambda)$ or $\tau(\lambda)$ the spectral reflection or transmission coefficient, and $S_i(\lambda)$ the relative spectral power distribution of any of the standard colorimetric light sources (A, B or C) (Fig. 2.30). CIE Standard Illuminants: Distribution A means the spectral distribution of a Planckian radiator at a correlated colour temperature of 2856 K. Distribution B means the spectral distribution of a Planckian radiator at a correlated colour temperature of 4900 K. Distribution C means the spectral distribution of daylight at a correlated colour temperature of 6800 K. Distribution D65 means the spectral distribution of daylight at a correlated colour temperature of 6500 K.

Colour stimulus $\Phi(\lambda)$ may be considered as sum of a definite number of elementary spectral colour stimuli $\Phi(\lambda_i)\Delta\lambda$. Because of the additivity of the colour stimuli, resultant colour codes may be produced as a sum of colour codes for spectral colour stimuli.

As the first step in establishing the system, measurements by a sufficient number of observers with normal colour vision were averaged to determine—for three given reference stimuli—tristimulus values assigned to monochromatic components of the visible domain of the isoenergic spectrum. Such experiments were made first by MAXWELL (1890), later by KÖNIG and DITERICI (1892), as well as by GUILD (1925) and WRIGHT

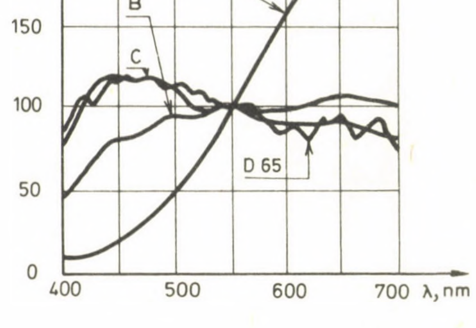


Fig. 2.30. Relative spectral power distributions of standard light sources

(1928). The internationally agreed values are the averages of the results by GUILD and WRIGHT.

In the CIE 1931 decision, monochromatic radiations with wavelengths $\lambda_R = 700.0$ nm (red), $\lambda_G = 546.1$ nm (green), and $\lambda_B = 435.8$ nm (blue) have been accepted as reference stimuli of the international colorimetric system. As a definition it has been agreed that in the isoenergic spectrum, all three tristimuli of the colour white are equal, and their luminance ratio was set as: $L_R : L_G : L_B = 1.000 : 4.5907 : 0.0601$. As "white" the absolute diffuse reflecting surface deriveable from the NPL (National Physical Laboratory) white standard has been accepted.

Spectral tristimuli for the reference stimuli above were tabulated. The respective curves are shown in Fig. 2.31.

Tristimuli for colours in the RGB system are:

$$\begin{aligned} R &= \Sigma\Phi(\lambda_i)\,\bar{r}(\lambda_i)\,\Delta\lambda\,, \\ G &= \Sigma\Phi(\lambda_i)\,\bar{g}(\lambda_i)\,\Delta\lambda\,, \\ B &= \Sigma\Phi(\lambda_i)\,\bar{b}(\lambda_i)\,\Delta\lambda\,, \end{aligned} \tag{27}$$

where $\bar{r}(\lambda_i)$, $\bar{g}(\lambda_i)$, and $\bar{b}(\lambda_i)$ are distribution coefficients for monochromatic radiation of wavelength λ_i (spectral tristimulus functions). Knowing the distribution coefficients, determination of colour characteristics requires only spectral distribution measurements and calculations.

Chromatic values interpreted by additive colour mixing can be represented in 3D space by vectors—the so-called colour vectors. The space defined by colour vectors is the colour space. It could be imagined that colour vectors might occur in the complete 4π range of steric angles. In fact, however, tests showed real colour vectors not to occur outside the boundaries set by real spectral colour vectors.

That part of the colour space which incorporates vectors of all the solid colours arising at a given illumination is called a colour solid. A "colour cone" confined by spectrum

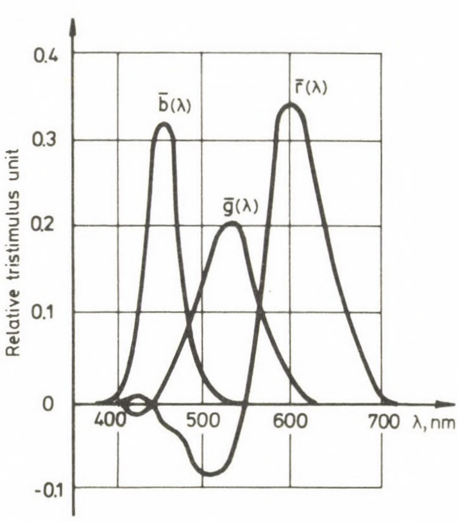


Fig. 2.31. Spectral tristimuli of the CIE *RGB* system

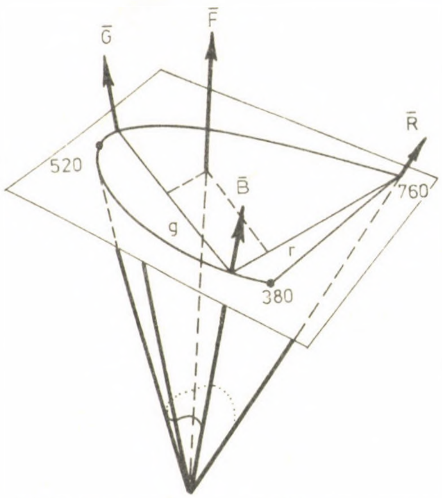


Fig. 2.32. Colour solid stretched between monochrome primary colours $\bar{R}$, $\bar{G}$, $\bar{B}$

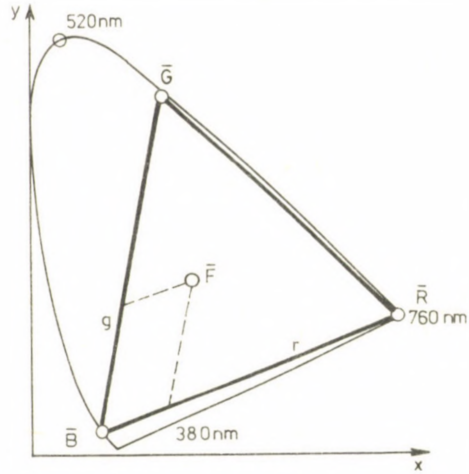


Fig. 2.33. Colour triangle, the plane section of the colour solid

colour vectors and the purple plane in the space stretching between primary colour vectors $\bar{R}$, $\bar{G}$, and $\bar{B}$ is seen in Fig. 2.32.

Three dimensional representation is rather complex and may be confusing for several colour vectors. Information on hue and lightness of colours can be, however, separated. Hue may be defined in plane by not more than two coordinates. The so-called *CIE chromaticity diagram* or *colour triangle* is a plane intersecting the colour cone.

For the plane in Fig. 2.33 the three reference stimuli are equivalent. In the colour triangle, every colour vector is represented by a point. Thus, in planar representation, colour points for colours of the same hue and saturation but different lightness are coincident. Intersection points of reference stimuli define a triangle. Colour points may also be located by triangle coordinates.

Within the colour triangle, the chromaticity point of the colour resulting from additive colour mixing may be determined by methods of centroid determination, hence, obviously, in determining the colours, proportion, rather than absolute values of tristimuli is decisive.

Therefore colours are described—rather than by the tristimuli above—by so-called chromaticity coordinates, derived from the former as

$$r=\frac{R}{R+G+B}$$

$$g=\frac{G}{R+G+B} \qquad (28)$$

$$b=\frac{B}{R+G+B}.$$

Obviously, for the coordinates: $r+g+b=1$.

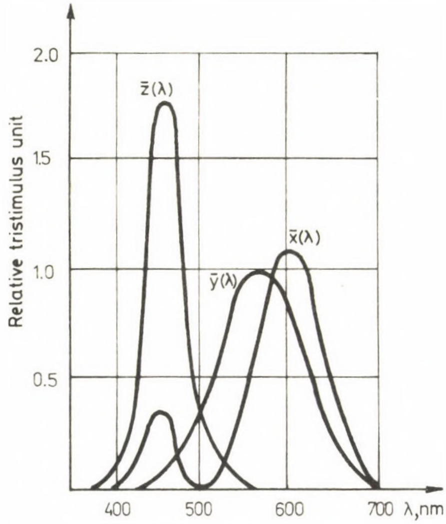


Fig. 2.34. Distribution coefficients of the CIE *XYZ* colorimetric system

Hue and saturation being perceptional values, unambiguous colorimetric description of chroma needs but two data.

As shown before, some spectrum colours could only be mixed from reference stimuli if one or the other reference stimulus was a negative quantity in the summation—that is, the given reference colour stimulus value was added to the colour to be metered.

For convenience, a linear transformation of the outlined reference colour value system was carried out whereby distribution coefficients of all three reference colour values became positive.

The transformational equations are as follows:

$$\begin{aligned}\bar{X} &= +2.36460\,\bar{R} - 0.51515\,\bar{G} + 0.00520\,\bar{B},\\ \bar{Y} &= -0.89653\,\bar{R} + 1.42640\,\bar{G} - 0.01441\,\bar{B},\\ \bar{Z} &= -0.46807\,\bar{R} + 0.08875\,\bar{G} + 1.00921\,\bar{B}.\end{aligned} \tag{29}$$

The resulting reference stimuli $\bar{X}$, $\bar{Y}$ and $\bar{Z}$ are imaginary, i.e. cannot be realized and serve for calculations alone. CIE distribution coefficients ($\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$) for the isoenergy spectrum calculated in the primary colour value system above are seen in Fig. 2.34.

According to the curves, tristimuli of monochromatic radiations are proportional to ordinate values corresponding to the abscissa of the radiation.

Knowing the spectral composition of an arbitrary colour stimulus, tristimuli may be calculated also in the *XYZ* system as described above:

$$\begin{aligned}X &= k \int \Phi(\lambda)\,\bar{x}(\lambda)\mathrm{d}\lambda\,,\\ Y &= k \int \Phi(\lambda)\,\bar{y}(\lambda)\mathrm{d}\lambda\,,\\ Z &= k \int \Phi(\lambda)\,\bar{z}(\lambda)\mathrm{d}\lambda\,.\end{aligned} \tag{30}$$

with notations as above; interpretation of *k* see below.

Colour coordinates may be derived from tristimuli as for the *RGB* system:

$$x=\frac{X}{X+Y+Z}$$

$$y=\frac{Y}{X+Y+Z} \qquad (31)$$

$$z=\frac{Z}{X+Y+Z}.$$

Figure C17 shows the colour triangle x, y represented in an orthogonal coordinate system. In planar representation, only chromaticity (hue and saturation) differences appear. By convention, in the colour triangle, point $x=y=z=0.333$ is the "achromatic colour". All the white-gray-black line is at this point.

In the CIE colorimetric system, function y_λ has been chosen to agree with the eye sensitivity function V multiplied by a constant. Accordingly, tristimulus Y is proportional to the luminance of the colour stimulus. In calculating tristimulus values, proper selection of the proportionality factor k permits that Y numerically agrees with the luminance of the colour stimulus. In describing the colour of reference radiants, x, y values are calculated from the determined X, Y, Z values (here $k=1$), indicating luminance values as the third characteristic of the colour stimulus.

In describing solid colours, k is determined for an ideal white solid taking $\tau(\lambda)=1$ or $\varrho(\lambda)=1$, $Y=100$, that is taking (26) and (30) into consideration as follows:

$$100=k\int 1\cdot S_i(\lambda)\,\bar{y}(\lambda)\,\mathrm{d}\lambda\,, \qquad (32)$$

thence the value of k can be calculated.

Since it is thus apparent that the proportionality factors depend on the spectral energy distribution of the illuminating light source, k values for various normal illuminations have been tabulated.

Thus, for describing solid colours, x, y and Y values have to be given. These characteristics of the CIE colour system, however, cannot be directly used for environment colour design, since they are not directly and sensibly related to the perceptional distribution of colours.

Perceptional description of colours is possible by means of hue, saturation and lightness parameters. Their counterparts among colour stimuli are the Helmholtz characteristics, such as dominant wavelengths, in case of purples the corresponding complementary wavelength, tristimulus Y, and the CIE excitation purity p_e.

Lightness sensation and tristimulus Y are in no linear interrelation. Although excitation purity p_e is akin to the concept of saturation, this relation is more complex and cannot be related to the concepts of black and white content often applied for the description of pigment colours. Among the three concepts, it is the dominant wavelength which is the nearest to the perceptional hue, although this relation is not free from ambiguities either. Dominant wavelength is invariant for any hue if lightness or saturation are altered.

2.7.3. Colour Space Relying on Subtractive Colour Mixing

Also for subtractive colour mixing, a colour (visually) similar to that to be measured has to be produced from known reference colours. Colour mix may be produced by such means as superimposing coloured filters, mixing pigments, or by printing coloured screen points on one another. Simple mathematical handling is only possible when subtractive colour mixing is carried out by means of colour filters. Obviously, transmission values of consecutive filters $\tau_1(\lambda)$ and $\tau_2(\lambda)$ have to be multiplied:

$$\tau_{1-2}(\lambda)=\tau_1(\lambda)\tau_2(\lambda)\,. \tag{33}$$

Filter transmission being exponentially dependent on filter thickness x, filter material concentration c and molar extinction d, therefore:

$$\tau=\exp(-cdx)\,. \tag{34}$$

Here we can introduce the concept of density to describe a filter of unit thickness:

$$D=-\log\tau\,. \tag{35}$$

Hence:

$$D_{1-2}(\lambda)=D_1(\lambda)+D_2(\lambda)\,. \tag{36}$$

Superimposing n similar filters, overall density of the filter is:

$$D_e(\lambda)=nD(\lambda)\,. \tag{37}$$

Separating pigment concentration from the above product, for mixing different pigments of different concentrations:

$$D_e(\lambda)=c_1D_1(\lambda)+c_2D_2(\lambda)+\ldots+c_nD_n(\lambda)=\sum_{i=1}^{n}c_iD_i(\lambda)\,. \tag{38}$$

As for additive colour mixing, a colour solid confined by three reference colours can be constructed.

Variable concentrations of reference colours give rise to a 3D solid colour population. Subtractive colour solid in the colour space confined by the normal colour values $\bar{X}$, $\bar{Y}$, $\bar{Z}$ is seen in Fig. 2.35.

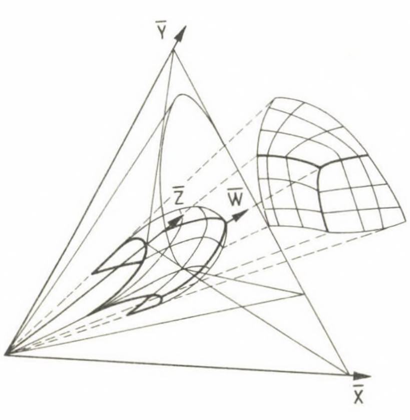


Fig. 2.35. Colour solid defined by subtractive colour mixing

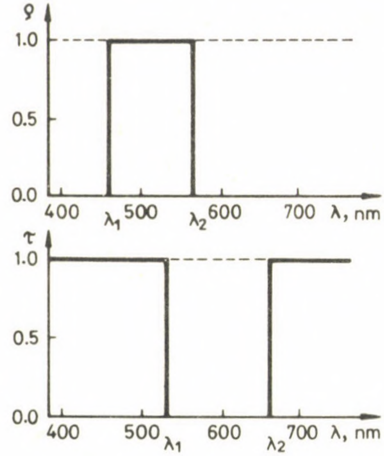


Fig. 2.36. Spectral reflection curves of two types of optimum colours

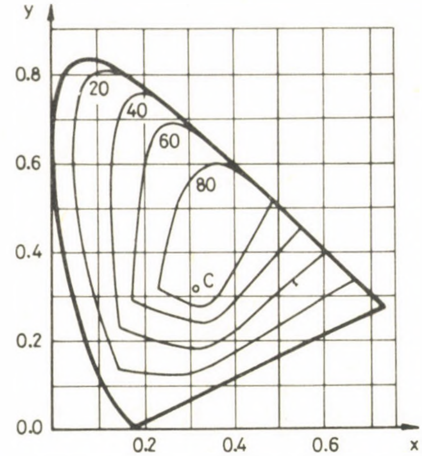


Fig. 2.37. Loci of optimum colours of equal lightness in the CIE 1931 diagram after MacAdam

Shape, internal structure and extension of the subtractive colour solid depend essentially on spectral compositions of the reference colours involved. This is the most important difference between additive and subtractive colour mixing. Accordingly, in the first case, conversion to new reference colours is simply a homogeneous linear transformation of the existing system, while in subtractive colour mixing, it is mostly impossible to determine by simple mathematical methods tristimuli valid in the new system of reference colours.

It is not easy to find reference colours defining a subtractive colour solid containing the points of all the possible solid colours. Based on research in this field the pigments showing respectively the most convenient spectral transmission and reflection distribution, can be selected. With such so-called optimum colours, the curve of reflection or transmission exhibits only one or two jumps, otherwise $\tau(\lambda)$ or $\varrho(\lambda)$ have values of only 0 or 1. Optimum colour means the lightest one among those of the same hue, and the most saturated one among those of equal relative lightnesses.

Reflection curves of optimum colours are characterized by the location of the jump. In Fig. 2.36 curves of two types of optimum colours are seen. Figure 2.37 shows curves of optimum colours of different lightnesses in the CIE diagram for CIE ray distribution C. It is apparent that the more saturated colours can be produced only with very low lightness.

Subtractive colour solids composed of surface colours are always inside the optimum colour solid.

Other systems of surface colours are the Luther–Nyberg and the Rösch colour solids. The Luther–Nyberg space (M_1, M_2, S) is the affine image of the trichromatic colour space, related to it as:

$$M_1 = -X + Y,$$
$$M_2 = -Z - Y, \qquad (39)$$
$$S = X + Y + Z.$$

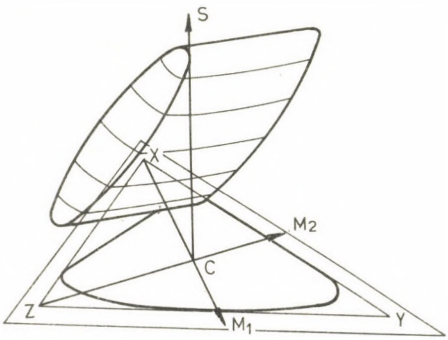


Fig. 2.38. Representation of a colour solid of surface colours in the Luther–Nyberg space

M_1 and M_2 are called colour moments, and S the colour weight. A colour solid of surface colours in the Luther–Nyberg space is seen in Fig. 2.38. The Rösch space is not an affine transformation of the trichromatic colour space.

2.7.4. Transformations of CIE 1931 Aiming at Perceptional Equidistance

Increasing fields of industry require the determination of so-called colour differences. Prompted by this need the CIE system has been reviewed for the homogeneity of its colour space, that is, how closely variations in colour coordinates in different parts of the colour space correspond to changes of colour sensations.

To achieve visual uniformity of the colour space is also a problem of the theory of environment colour design, namely it is advantageous for the practice if psychophysical and psychometric scales expressing the relations of man, colour and environment may be assigned to points of a visually homogeneous colour space.

Demand for constructing a colour space based on perceptional equidistance is as old as systematic colour research itself. As early as in 1896, HELMHOLTZ pointed out the importance of an unambiguous definition of the so-called "visually homogeneous colour space". Ever since, several researchers have devoted themselves to solve this problem. Theoreticians endeavoured to find a function unambiguously determining the perceptional difference between two arbitrary points U_i and U_k of the colour space. The first step was to define the line elements ds for the distance between two, just distinguishable points of the colour space.

Systems relying on line elements defined by different assumptions by individual researchers such as HELMHOLTZ (1896), SCHRÖDINGER (1920), SILBERSTEIN (1943), and STILES (1959) showed a fair agreement with experiments by MACADAM (1969) and BROWN (1965). Length variation of the line element along the line of spectrum colours vs. wavelength is presented in Fig. 2.39 based on experiments by BEDFORD and WYSZECZKI (1958), WRIGHT and PITT (1934), and STILES (1939). STILES has determined the length of his line elements at different locations in the CIE diagram by means of Gaussian curves (Fig. 2.40). CIE diagram in Fig. 2.41 shows distances for equal colour differences. STILES also applied the line elements to construct curves of locations for colours of equal hue and saturation (Fig. 2.42).

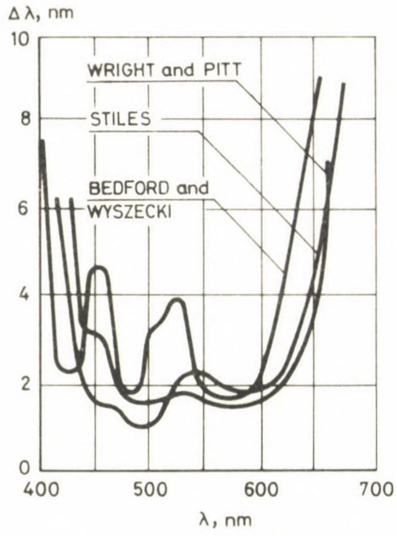


Fig. 2.39. Length variation of the line element along the colour track after BEDFORD and WYSZECKI, STILES, and WRIGHT and PITT

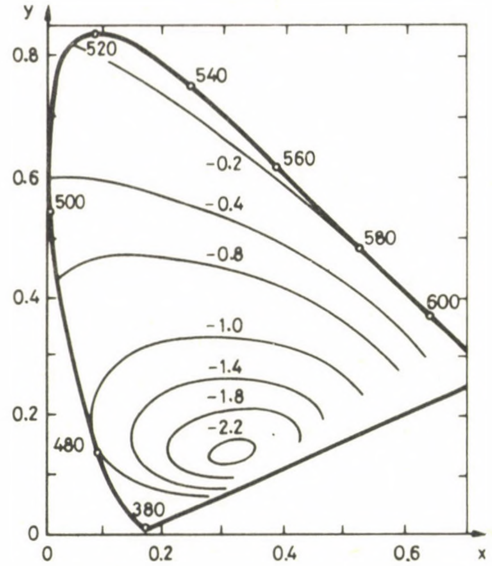


Fig. 2.40. Gaussian curves defining STILES' line elements in the CIE diagram

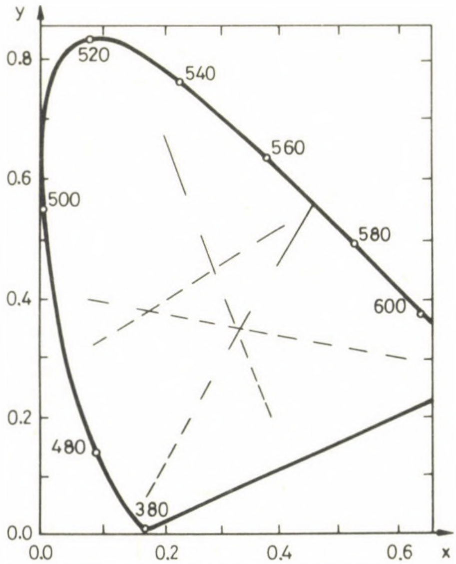


Fig. 2.41. Line elements in the CIE diagram after JUDD and WYSZECKI

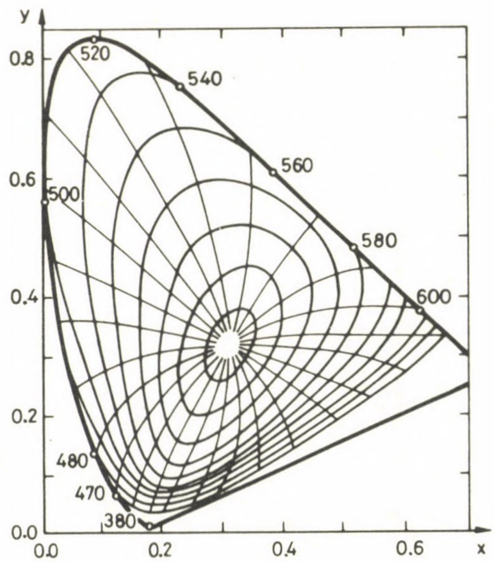


Fig. 2.42. Equal hues and saturations in the CIE diagram after STILES

Experiments by MacAdam (1955) were mainly concerned with the just perceptible colour differences at different points of the colour space. He determined the standard deviation of colour intensity determinations for a large number of colours of the same light density. He postulated that the just perceptible colour differences at various parts of the colour diagram are proportional to the standard deviation in measurements of the incident colours. In this way he recorded threshold ellipses at different points of the colour diagram. The colour in the centre of the ellipse is at a perceptionally equal, so-called unit distance from colours on the perimeter. In the CIE system this unit distance varies from one location to the other (Fig. 2.43).

Although MacAdam recognized later that it is impossible to create a system of equidistance throughout the colour space by projective transformation from the XYZ system, this idea was underlying the first, approximately uniform colour space (UCS = = Uniform Chromaticity Scale) recommended by CIE.

The first UCS transformation was made back in 1935 by Judd, in which, however, the distance between two colour points only at certain points of the colour space was proportional to the perceptional difference. Two years later, in 1937, MacAdam developed the UCS transformation which became the starting point for subsequent transformations (Fig. 2.44). MacAdam's transformational equations are:

$$u = \frac{2x}{6y - x + 1.5}, \qquad v = \frac{3y}{6y - x + 1.5}. \tag{40}$$

UCS transformation by Breckendrige and Schaub (1939) arose by bipartite transformation. In practice, it has become clear that even this transformation could not solve the problem of perceptional equidistance, nor did UCS colour spaces by Hunter completed in 1941, and by Fransworth dating from 1944.

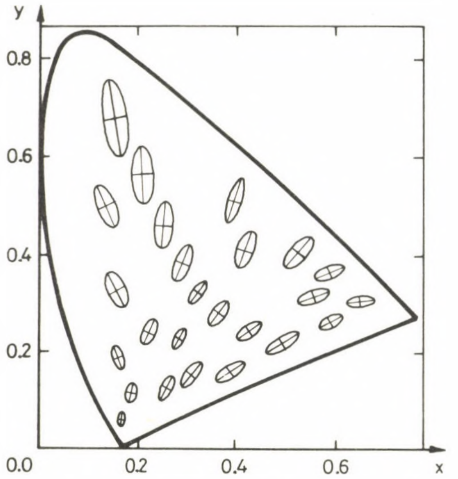


Fig. 2.43. MacAdam ellipses in the CIE diagram

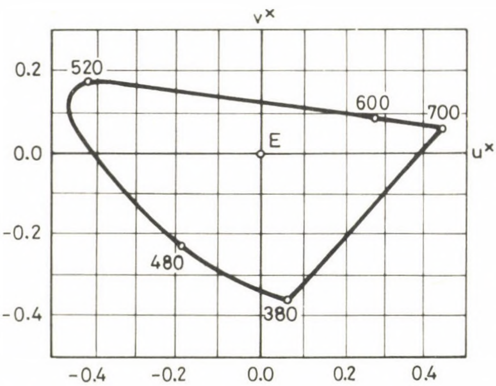


Fig. 2.44. UCS diagram by MacAdam

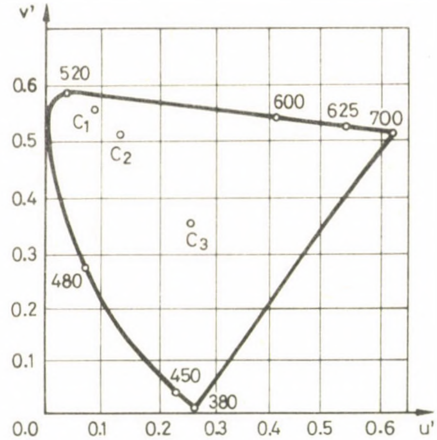


Fig. 2.45. The CIE 1976 UCS diagram

Proliferation of UCS colour spaces resulted in an increasingly confused situation concerning perceptionally equidistant colour space, which called for an international agreement. This was the CIE 1960 UCS transformation. A colour space was built upon this colour diagram in 1964, in which lightness W^x resulted from the cubic root transform of tristimulus value Y. The other two coordinates of the space—U^x and V^x—are also functions of W^x. Practice of the last fifteen years revealed several deficiencies of the system, primarily, perceptional inequalities in the domains of red, yellowish green and violet. Therefore in 1976, CIE has agreed upon another so-called $u'v'$ UCS transformation, presented in Fig. 2.45. Here $u' = u$, $v' = 1.5v$. This new colour diagram was also used to construct a corresponding colour space.

The CIE 1976 $L^x u^x v^x$ colour space is a modification of CIE 1964. The colour space comprises the (u', v') colour diagram relying on projective transformation of the (x, y) diagram. In the new diagram, products of additive colour mixing fall on a straight line, just as in the (x, y) diagram.

Coordinates for hue u^x, v^x include the differences $u' - u'_0$, $v' - v'_0$ where zero subscript refers to the coordinates of the light source.

To describe lightness, a magnitude L^x proportional to the cubic root of tristimulus value Y has been introduced, namely lightness differences of sample pairs with the same numerical difference were deemed to seem equal after this transformation. Since in dim light, the cubic root formula yielded a poorer approximation, for low Y/Y_0 values a different transformation has been introduced.

In the $L^x u^x v^x$ or CIELUV space, each $u^x v^x$ plane assigned to a L^x value accommodates colours of the same lightness, but with different hues and saturations. Achromatic (gray) colours are on the $u^x = 0$, $v^x = 0$ axis of the colour solid. Hue may also be described by the so-called metric hue angle h_{uv} defined by direction $u^x = 0$ and the arbitrarily chosen plane $v^x = 0$, $L^x = \text{const}$. In plane $u^x v^x$ the colour point may be located by this angle and the distance from the achromatic axis, a magnitude similar to chroma, called also metric chromaticity C^x_{uv}. It differs from saturation by depending also on the lightness value.

The relationships involved are:

$$
\begin{aligned}
L^x &= \sqrt[3]{116\frac{Y}{Y_0} - 16}, \quad \frac{Y}{Y_0} > 0.008856\,, \\
s_{uv} &= 13\sqrt{(u'-u'_0)^2 + (v'-v'_0)^2}\,, \\
C^x_{uv} &= \sqrt{(u^x)^2 + (v^x)^2} = L^x s_{uv}\,, \\
h_{uv} &= \operatorname{arc\,tg}\frac{v'-v'_0}{u'-u'_0} = \operatorname{arc\,tg}\frac{v^x}{u^x}\,, \\
\Delta H_{uv} &= \sqrt{(\Delta E^x_{uv})^2 - (\Delta L^x)^2 - (\Delta C^x_{uv})^2}\,.
\end{aligned} \tag{41}
$$

In 1976, CIE has suggested the introduction of an additional colour space—the so-called CIELAB. Colour space $L^x a^x b^x$ is a simplified cubic root form of that applied for developing the Adams–Nickerson colour difference formula.

Concerning the elucidation of the mechanism of colour vision, two theories, Helmholtz's trichromatic additive theory and Hering's opponent colour theories have been wrestling with each other for decades. Colour diagram by ADAMS (1959) adopted the latter, and since at that time no precise information on the reference colour stimuli of vision was available, he reckoned simply with XYZ reference colours, using their transforms, for the elaboration of his opponent model. To that end, he chose characteristics relying on $(X-Y)$ and $(Y-Z)$ and referred to the "white point" i.e. the light source to tristimuli X_0, Y_0, Z_0. He assumed that the eye perceived stimuli as the cubic root of Y.

The original Adams colour diagram has been complemented with lightness information by NICKERSON (1960). This was simplified by CIE in 1976 choosing the same L^x value as for the $L^x u^x v^x$ space. It was attempted to assign them hue coordinates so as to be perceptionally equidistant in directions of hue and lightness corresponding to equal distances in the colour space.

For the constant L^x, representation by polar coordinates in the $a^x b^x$ plane becomes valid again. Metric hue angle and metric chromaticity are:

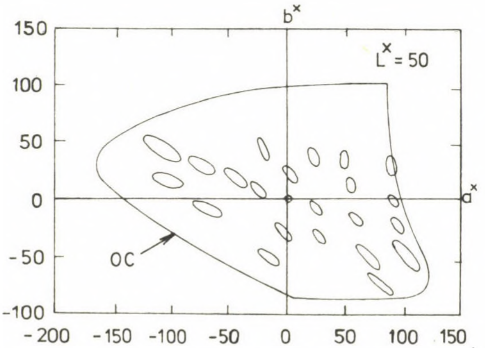


Fig. 2.46. MacAdam ellipses in the CIE 1976 $L^x a^x b^x$ diagram (OC is the line of optimum colours)

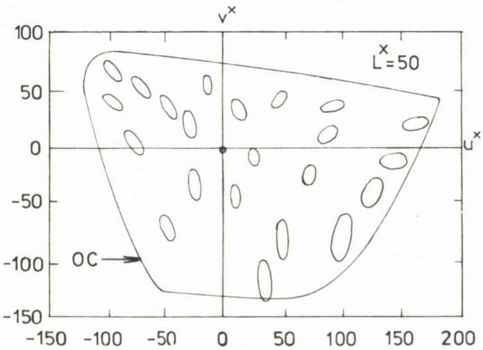


Fig. 2.47. MacAdam ellipses in the CIE 1976 $L^x u^x v^x$ diagram (OC is the line of optimum colours)

$$h_{ab}^{x} = \operatorname{arc\,tg} \frac{b^{x}}{a^{x}},$$

$$C_{ab}^{x} = \sqrt{(a^{x})^2 + (b^{x})^2}\,. \tag{42}$$

Plotting MacAdam ellipses in CIELUV and CIELAB colour spaces is a solution for perceptionally equidistant mapping (Figs 2.46, 2.47). Since coordinates of these colour spaces do not refer to colour sensations, they hardly suit environment colour design.

2.7.5. Colorimeters

Under the outlined conditions of observation, three indices are necessary and sufficient to describe the appearance of each colour. These three indices may be determined by any of the following three colorimetric methods:

— Visual comparison. The colour to be measured is compared to another colour of known indices. The reference colour is either taken from a colour sample collection or produced by optical mixing from known components by means of a proper device.

— The spectral method where the relative spectral composition of the radiant, or the radiation reflected from or transmitted by the surface is determined, and colour indices are derived therefrom.

— Using tristimulus devices with sensors simulating spectral tristimulus curves, either directly providing colour indices, or the radiance (luminance) factor and colour coordinates.

The first procedure is the so-called subjective colorimetry, the other two are objective colorimetries.

In the case of radiants, the colour can be determined unambiguously, while for surface colours, only in association with the illumination.

Among the several theoretical possibilities of exactly defining colour by three values, in colorimetric practice three procedures are being applied. One can establish 1) the quantities of internationally agreed reference colour stimuli (tristimuli) required to produce the given colour, 2) two colour coordinates and the radiance (luminance) factor, and 3) the indices of hue, saturation and lightness.

For the practical requirements of environment colour design, an instrument with the following features would be ideal:

1. Mobile, small-size.
2. Permitting direct field colorimetry without sampling of buildings and parts thereof.
3. Suitable for colorimetry of any sample, irrespective of surface appearance.
4. Suitable for colorimetry of a surface in any spatial position.
5. Accuracy of 0.01 trichromatic unit, and independence of the accuracy from environmental impacts.
6. Suitable for the determination of Coloroid indices.
7. Suitable to determine CIE colour coordinates.
8. Visual display for the colour of any surface based on CIE colour coordinates and colour sensation parameters.
9. Easy handling.

3. Relations between Colour Sensations

The realm of colours is a realm of colour sensations. Laws of colour composition are based upon relations between colour sensations. In addition to being oriented in this realm of colours, these relations permit development of a method to document our visual colour message, to describe unambiguously this method, to learn ourselves and to impart to others regularities of colour composition.

Relations between colour sensations are essentially the same for anybody; they result primarily from the process of colour perception, and may be explained by essential psychophysical processes. These relations express interactions between colour sensations, to be described, in turn, by relations between colour sensation parameters and laws of colour composition. In this chapter, colour sensations will be integrated into a new system of relationships suitable to describe the laws of colour composition in a simple form.

3.1. The Concept of Aesthetically Uniform Colour Space

In an aesthetically uniform colour space, colour sensation differences between adjacent colours are equal, and not less than the harmony colour differences.

Harmony colour difference is defined as the smallest difference between two colours permitting their coexistence in the same harmonic composition. Here the two colours are not only distinguishable but also aesthetically appreciable next to each other.

Before expounding these statements, let us have a closer look at the perceptionally uniform colour space based on experiments of threshold measurements, to permit a safe distinction from the aesthetically uniform colour space.

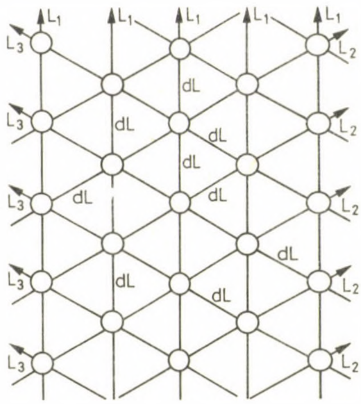
3.1.1. Colour Space Based on Threshold Measurements

The term "threshold" (L), and its Latin counterpart "limes" mean essentially a limit between stimuli eliciting the same, and a different, response, respectively. The difference threshold ($\mathrm{d}L$ = difference limit) means the just perceptible stimulus increase, or by another term the just noticeable difference (JND).

Threshold measurement experiments aim at empirically dividing a set of stimuli to $\mathrm{d}L$ units. In general, the observed regularity is simplest described as: the given stimulus has to be increased by a constant fraction of its value to be just perceptible. This fraction (Weber's constant) is often written as $\mathrm{d}I/I$, where I is intensity, and $\mathrm{d}I$ its increment just sufficient to let test persons state: this is a more intense stimulus.

The situation is somewhat different for colour stimuli. Since each colour stimulus is described by three parameters, the quality of colour stimulus may vary in three ways. That is, the colour sensation elicited by a colour stimulus may vary in lightness, saturation and hue. Lightness variation being a quantitative entity, it is more or less

Fig. 3.1. Scheme of an ideally equidistant space of colour stimuli built up of dL units. Directions L_1, L_2, L_3 represent three normal spatial dimensions. From every intersection point of the theoretically infinite space mesh the neighbouring six intersection points are at a distance of one dL unit each



subject to WEBER's statement. On the other hand, variations of saturation and hue being definitely qualitative, are subject to other relationships.

Let us carry out the following threshold measurement test with colour stimuli. Take a rectangular place illuminated by colour light. Upon illumination, the surface as a secondary radiant is perceived as e.g. being of orange colour. Let us change the composition of the colour incident on half of the surface delimited by a straight line. Variation may affect either of three parameters. By increasing or decreasing the dominant wavelength of the light, the colour is seen either more reddish or more yellow. By increasing or reducing the light density factor of the surface, the colour will be perceived as darker or lighter. Lastly, by increasing or reducing the ratio of dominant to compensating radiation, the colour will appear as more saturated or duller. Each kind of variation must be performed separately. For instance, leaving lightness and saturation of one half-plane unchanged, the dominant wavelength is altered until two different colours appear as divided by a sharp border line. The magnitude variation grade is marked on the scale of stimuli by a dL unit. Thereafter the unchanged field is adjusted to the colour of the changed field and the test is repeated until the appearance of the boundary, permitting to mark the second dL unit on the scale of stimuli.*

This test has to be performed not only in all three dimensions of the colour space (space of colour stimuli) but must be repeated several times in every direction, for different hues, saturations and lightnesses. By completing the test for all the possible scales of the space of colour stimuli, an ideal colour space built up of dL units is created (Fig. 3.1). Thereafter the scales are uniformly divided in all three directions of the ideal colour space. In the resulting ideal, perceptionally uniform colour space, every scale interval comprises the same number of dL units (Fig. 3.2).

Colour space of the Munsell renotation colour order system approximates to the concept of the outlined perceptionally uniform colour space, where differences between scale units are products of the smallest perceptible colour differences by the same factor. Because of this feature, codes of a colour system based on such a colour space are suitable to quantify small colour differences, essential in colour rating. Laws of colour

* This test is continued until all the scale of stimuli—from the beginning to the end point—for the hue scale, for the whole cycle is graded in dL units.

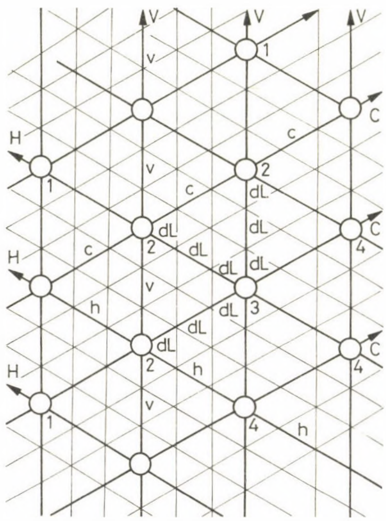


Fig. 3.2. Scheme of an ideal perceptually uniform colour space. This space is differently confined in the direction of the three dimensions corresponding to three colour sensation parameters i.e. hue (*H*), saturation (*C*) and lightness (*V*). The number of d*L* units between scale divisions are equal throughout

composition involved in environment colour design rely, however, on other than these properties. In thise case relationships between quite different colours of the colour space have to be established. In setting such relationships, all the colour space has to be kept in mind, involving large—rather than small—colour differences. A colour space built up on such relationships is called an aesthetically uniform colour space—to distinguish it from the perceptionally uniform colour space.

3.1.2. Aesthetically Uniform Colour Space

A colour complex created for an aesthetic purpose, causing a pleasant feeling in the observer, is called a harmonic composition. The question may arise whether a relationship can be found which would enable a decision to be made over colours admitted to, or excluded from, such a composition.

To decide this question, let us make a test. First we prepare colour scales by painting tens of thousands of colour samples of a few sq.cm surfaces. One set of samples should differ only by hue, another by saturation, and a third by lightness, the other two parameters being the same. Single variable parameters of adjacent colour samples in the scales should differ not more than by one d*L* unit, i.e. they are distinguishable only when in juxtaposition.

Now, let us make compositions using 50 to 80 pieces of the samples of 15 to 20 different colours. Some of the samples should be quite different, others differing by only a few d*L* units. Colours just distinguishable under the conditions outlined above will be felt in the composition to be identical. Also we will find that the number of d*L* units necessary to be able to discern neighbouring samples in the composition, i.e. to appreciate them as independent colours are not the same for colours at different positions in the colour space.

In subsequent parts of our experiment, let us proceed as consistently as in the test described under 3.1.1. On the proper, perceptionally uniform d*L* scale, colours with

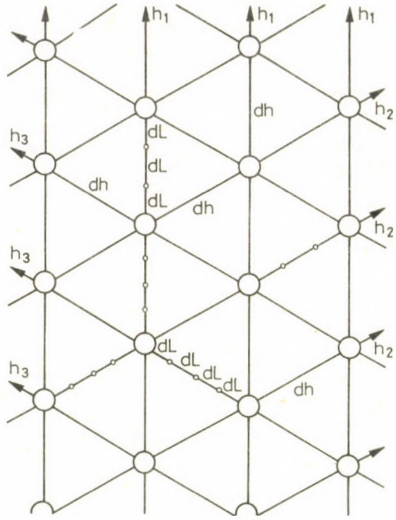


Fig. 3.3. Scheme of an ideally equidistant colour sensation space built up of dh units. Directions h_1, h_2, h_3 represent the three normal directions of the space. From every intersection point of the theoretically infinite space mesh, neighbouring intersection points are at a distance of one dh unit each. At different sites of the space, one dh unit contains different numbers of dL units

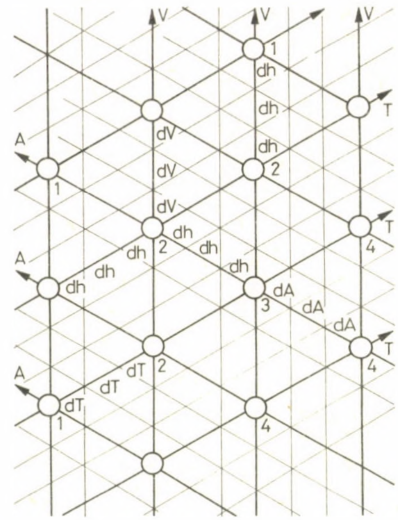


Fig. 3.4. Scheme of an aesthetically uniform colour space. There are definite numbers of divisions between starting and end points of psychometric scales in directions of three colour sensation parameters, i.e. hue (A), saturation (T), and lightness (V). Divisions represent equal numbers of dh units but different numbers of dL units

different hues, saturations and lightnesses, which are clearly distinguishable from our starting colour and are aesthetically appreciable in the composition, are marked. The perceptional differences in all three directions between each two colours are defined as harmony intervals (dh) (Fig. 3.3). Thereafter the resulting new colours should be taken as starting colours for new compositions, and we determine for each the neighbouring colours spaced at a harmony interval. This should be continued until all dh units are marked in all three directions of the space of colour sensation, between beginning and end points on as many scales as possible.

On juxtaposing scales of colours spaced at dh units it appears when looking at the whole scale with its beginning and end points, that its colours make up a uniformly varying set, i.e. in relation to large colour differences they are perceived as having a perfectly uniform spacing, in spite of differing by different numbers of dL units (Fig. 3.4).

3.1.3. Comparison of Colour Spaces Based on ds and dh Units

In respect of small colour differences involving a single colour parameter, differences between adjacent colours in the perceptionally uniform colour space are denoted as elementary spacings between adjacent points of the colours space by ds.

Such a colour space composed of ds units is approximated to by the colour space of the Munsell colour order system, as well as by relevant transformations of the CIE XYZ system, such as CIELAB and CIELUV.

In the perceptionally uniform colour space for large colour differences, i.e. in the space considered as aesthetically uniform, colour difference referring to a given colour sensation parameter, i.e. the elementary spacing between adjacent points of the colour space is denoted by dh.

Such a colour space made up of dh units is approximated to by the colour space of the Coloroid colour system, to be discussed in detail later.

Perceptional differences between the two kinds of colour spaces will be illustrated by comparing Munsell and Coloroid colour spaces. A set of colour sensations composed of colours uniformly varying in respect to a given colour sensation parameter is expressed by different colour codes in each of the two colour systems. Consecutive colour codes have intervals representing about the same number of elementary spacings ds and dh, respectively. Parameters of the two kinds of colour sensations may only be compared by recording on the scale of stimuli the stimuli eliciting the sensations associated with the parameters of both systems, that is, by establishing a relationship between codes of colour sensations elicited by definite stimuli. In this context, lightnesses and saturations in the two colour systems are related as:

$$V_C = 10\sqrt{1.2219\,V_M - 0.23111\,V_M^2 + 0.23951\,V_M^3 - 0.021009\,V_M^4 + 0.000840\,V_M^5}$$

$$T = \sqrt[3]{C^2\,(\mathrm{ab})}\,, \tag{43}$$

where V_C and V_M are Coloroid and Munsell lightnesses, respectively; T is Coloroid saturation, and C is Munsell chroma. Letters a and b in the second formula mean that expression of a sensed colour saturation by either Munsell or Coloroid codes also depends on lightness and hue of the colour. Formulae reflect that in each system, to sensations elicited by uniformly varying stimuli sets of codes are assigned varying according to different relationships. Therefore the two colour systems make different suggestions for measuring colour sensations.

In tests to be described below, it was found that in the Munsell system, the lightness scale of colours was denser for dark colours than required for aesthetic uniformity. In spite of about the same colour differences (ds units), again, saturation steps were felt to be aesthetically denser in dark, than in light domains of the system. Further observations showed the Munsell chroma steps to be aesthetically too large in very saturated, and, in turn, too small in unsaturated domains.

To point out differences, a set of sensations elicited by a set of stimuli will be recorded in both systems. Munsell and Coloroid colour systems will be compared below for all the three colour sensation parameters. Comparison for hue is seen in Figs 3.5, 3.6, 3.7 and 3.8. Figure 3.5 shows axial sections 5RP, 5G and 5GY of the Munsell colour system containing colours of the same hue; Fig. 3.6 shows surfaces with colours of these axial sections in the Coloroid colour solid. Also surfaces in Figs 3.7 and 3.8 show identical colours, colours of the same hue of Coloroid sections 35, 65 and 75. The same colours lie in planar surfaces in one colour solid and in curved surfaces in the other. Also the shapes of the surfaces differ. Part of these differences are explained by the fact that in the Coloroid colour system, colours of the same hue have the same dominant wavelengths, irrespective of their lightnesses and saturations, whereas in the Munsell colour

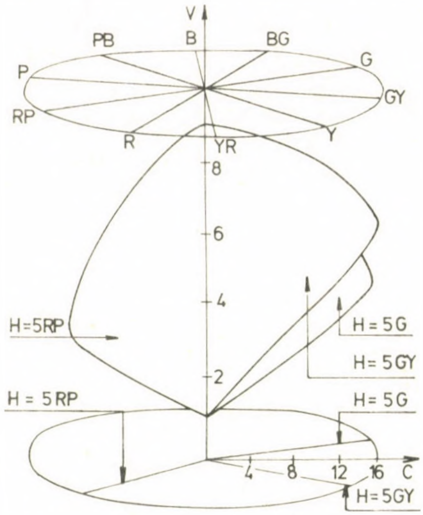


Fig. 3.5. Surfaces with colours of Munsell hues $H=5G$, 5GY, 5RP in the Munsell colour solid

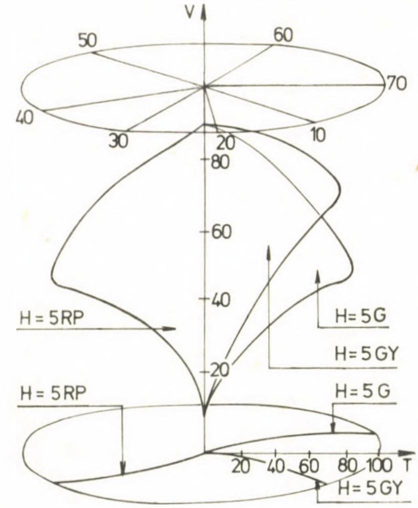


Fig. 3.6. Surfaces with colours of Munsell hues $H=5G$, 5GY, 5RP in the Coloroid colour solid

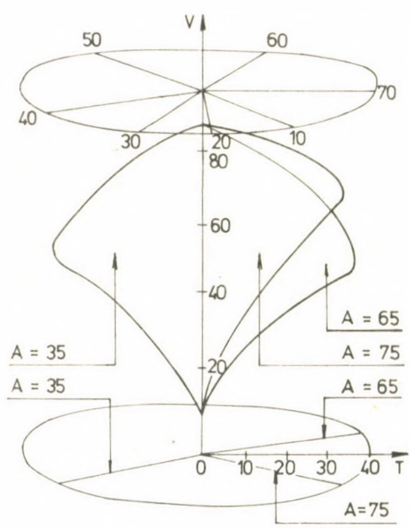


Fig. 3.7. Surfaces with colours of Coloroid hues $A=35$, 65, 75 in the Coloroid colour solid

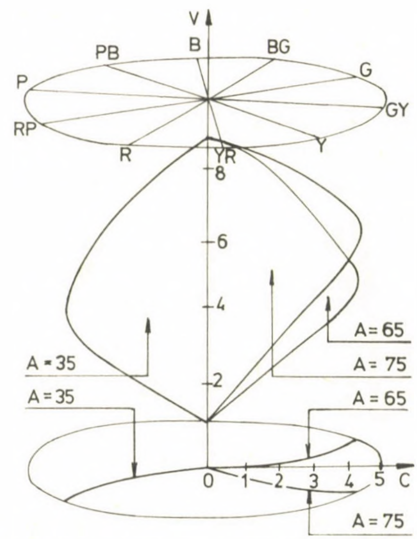


Fig. 3.8. Surfaces with colours of Coloroid hues $A=35$, 65, 75 in the Munsell colour solid

system, dominant wavelengths of colours of the same hue depend on their lightness (light density factor of eliciting stimuli) and saturation (proportion of complementary radiation in eliciting stimuli). Other differences are due to the fact that dh units include different numbers of ds units at different points of the colour space.

The two colour systems are compared for saturations in Figs 3.9, 3.10, 3.11 and 3.12. Cylindrical surfaces of the Munsell colour system including colours of chromas 4, 8 and

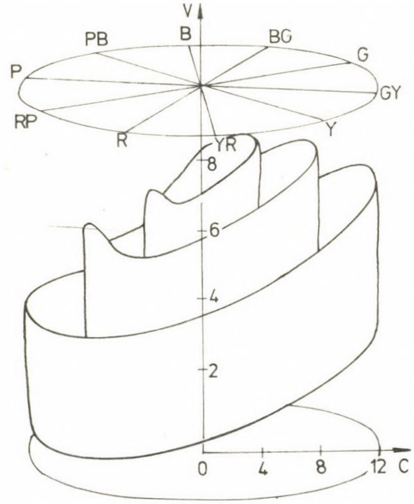


Fig. 3.9. Circular cylindrical surfaces with colours of Munsell saturations $C=4, 8, 12$ in the Munsell colour solid

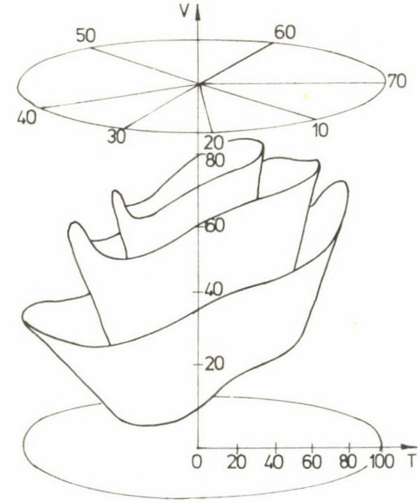


Fig. 3.10. Conical surfaces with colours of Munsell saturations $C=4, 8, 12$ in the Coloroid colour solid

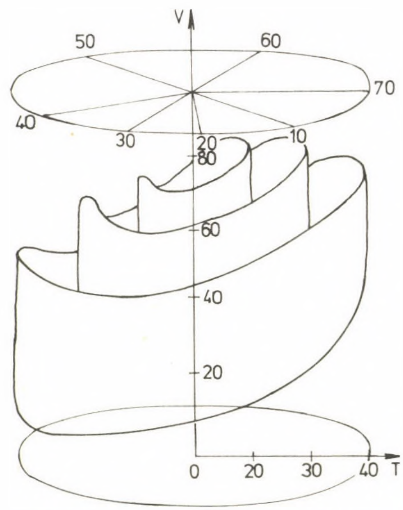


Fig. 3.11. Circular cylindrical surfaces with colours of Coloroid saturations $T=20, 30, 40$ in the Coloroid colour solid

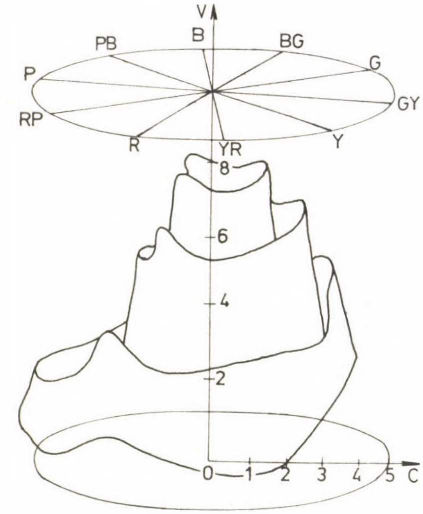


Fig. 3.12. Conical surfaces with colours of Coloroid saturations $T=20, 30, 40$ in the Munsell colour solid

12 are seen in Fig. 3.9, and the same colours are seen in Fig. 3.10 on conical surfaces in the Coloroid colour system. Figure 3.11 shows cylindrical surfaces bearing Coloroid colours of saturations *T*20, *T*30 and *T*40 in the Coloroid system. In conformity with Fig. 3.12, in the Munsell system these colours form conic surfaces opposite to those in Fig. 3.9. These diagrams point out that in dark domains of the colour space, one d*h* unit comprises more of d*s* units than in clear domains. The Munsell and the Coloroid

colour systems are compared from the aspect of lightness in Figs 3.13, 3.14, 3.15 and 3.16.

Now in a few figures (Figs 3.17 through 3.28) we compare the Coloroid, CIE XYZ, CIELUV and CIELAB colour spaces. It can be stated that both nature and trend of differences between colour spaces of CIE transformations and of Coloroid are similar to those between Coloroid and Munsell colour spaces. This is not surprising, since for all these transformations striving to perceptional equidistance, the colour space of the

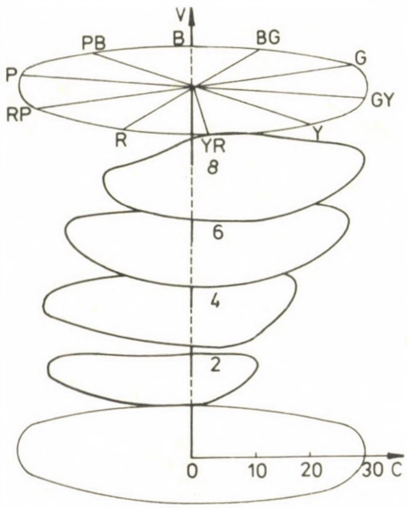


Fig. 3.13. Surfaces with colours of Munsell lightnesses $V = 2, 4, 8$ in the Munsell colour solid

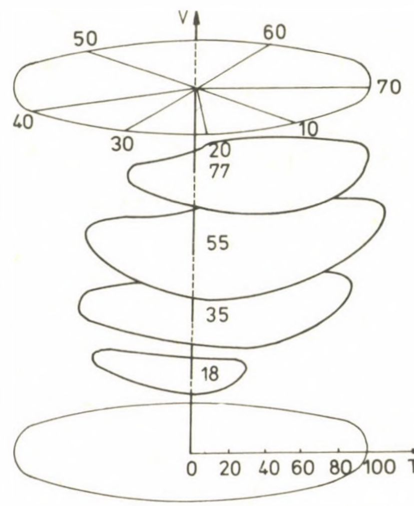


Fig. 3.14. Surfaces with colours of Munsell lightnesses $V = 2, 4, 6, 8$ in the Coloroid colour solid

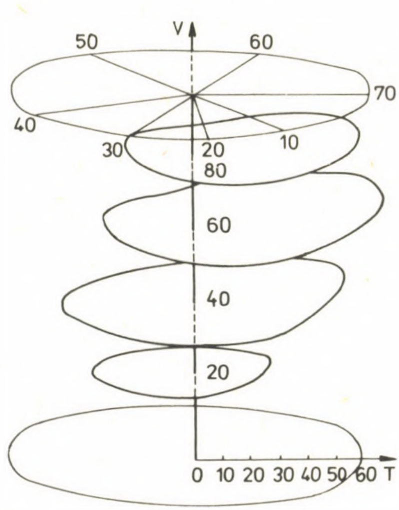


Fig. 3.15. Surfaces with colours of Coloroid lightnesses $V = 20, 40, 60, 80$ in the Coloroid colour solid

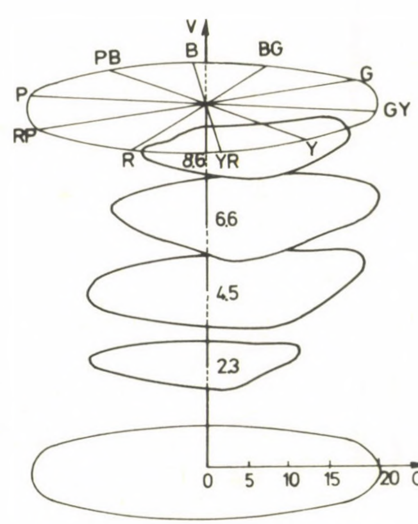


Fig. 3.16. Surfaces with colours of Coloroid lightnesses $V = 20, 40, 60, 80$ in the Munsell colour solid

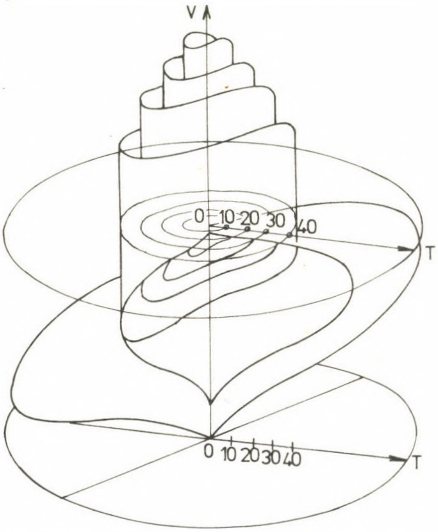


Fig. 3.17. Circular cylindrical surfaces with colours of Coloroid saturations $T=10$, 20, 30, 40 in the colour space of the Coloroid system

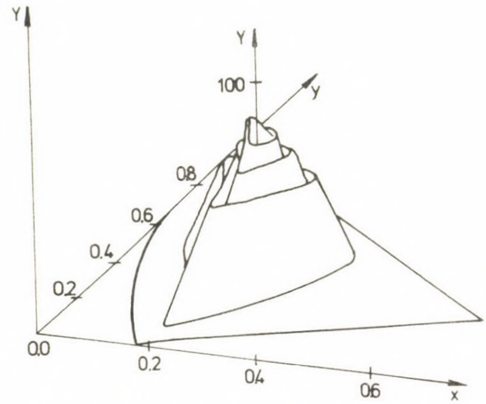


Fig. 3.18. Conic surfaces with colours of Coloroid saturations $T=20$, 30, 40 in the colour space of the CIE 1931 system

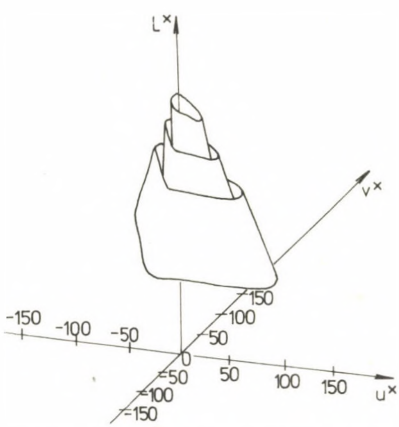


Fig. 3.19. Conic surfaces with colours of Coloroid saturations $T=20$, 30, 40 in the CIELUV colour space

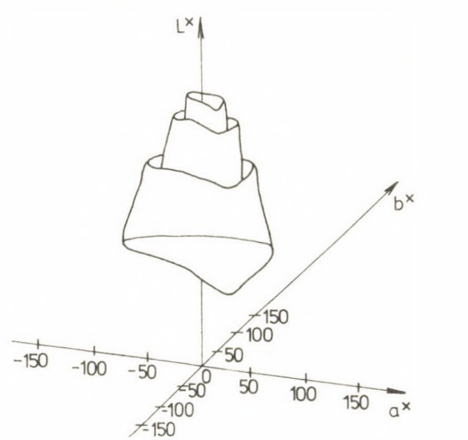


Fig. 3.20. Conic surfaces with colours of Coloroid saturations $T=20$, 30, 40 in the CIELAB colour space

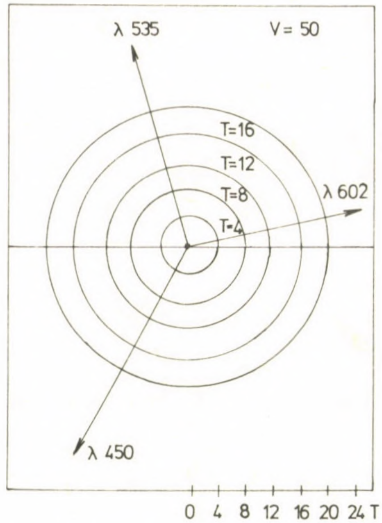


Fig. 3.21. Circles for colours of Coloroid saturations $T=4, 8, 12, 16$ in the Coloroid diagram

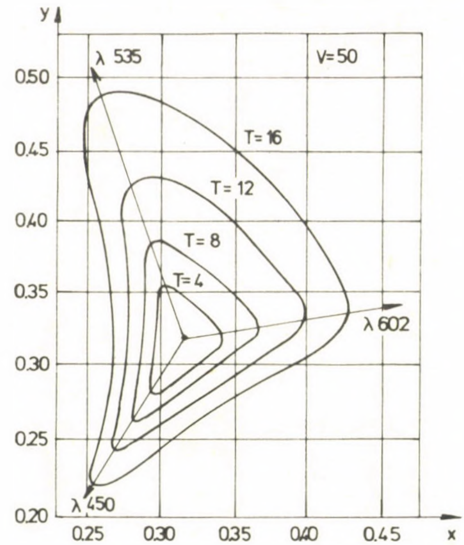


Fig. 3.22. Curves for colours of Coloroid saturations $T=4, 8, 12, 16$ in the CIE 1931 diagram

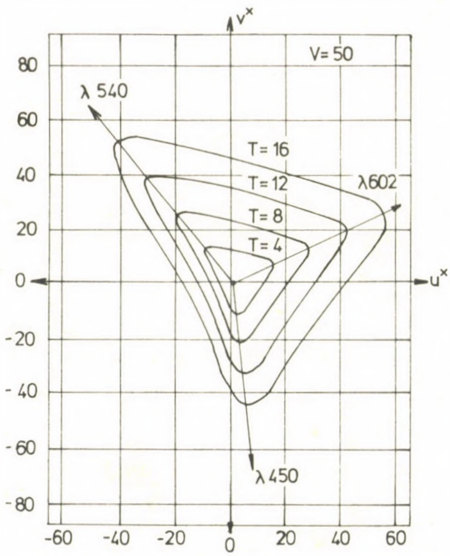


Fig. 3.23. Curves for colours of Coloroid saturations $T=4, 8, 12, 16$ in the CIE 1976 $u^x v^x$ diagram

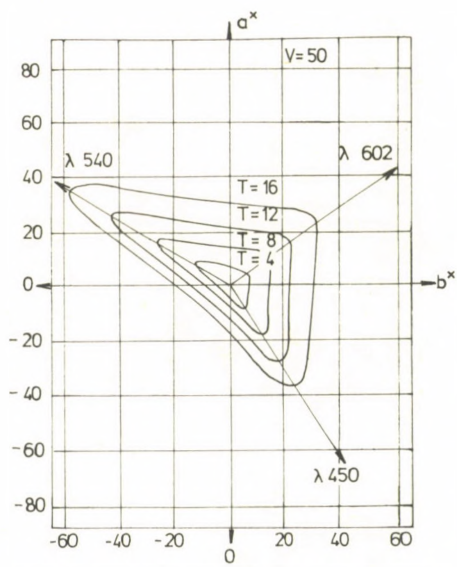


Fig. 3.24. Curves for colours of Coloroid saturations $T=4, 8, 12, 16$ in the CIE 1976 $a^x b^x$ diagram

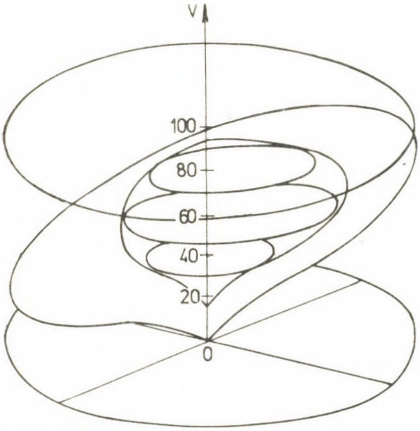


Fig. 3.25. Surfaces with colours of Coloroid lightnesses $V=20$, 40, 60, 80 in the Coloroid colour solid

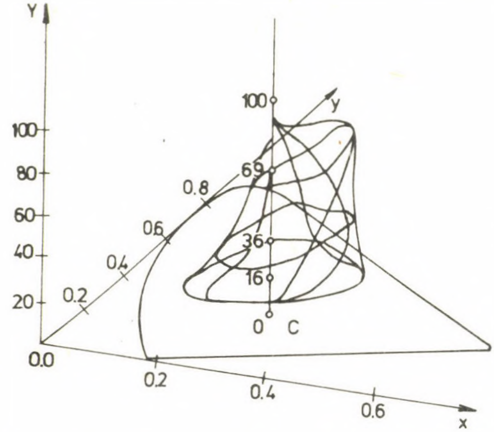


Fig. 3.26. Surfaces with colours of Coloroid lightnesses $V=20$, 40, 60, 80 of the Coloroid colour solid in the colour space of the CIE XYZ system

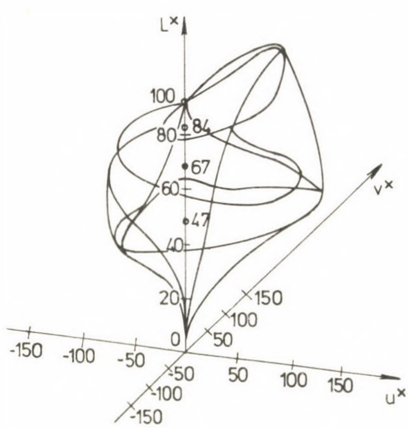


Fig. 3.27. Coloroid colour solid surfaces with colours of Coloroid lightnesses $V=40$, 60, 80 in the colour space of the CIELUV system

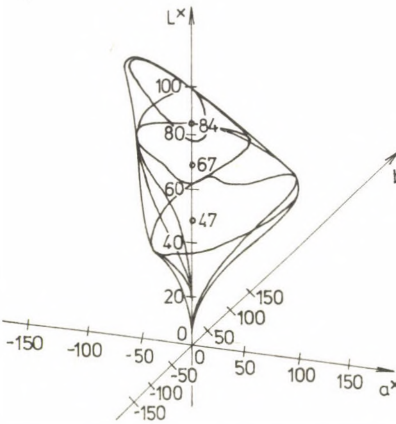


Fig. 3.28. Coloroid colour solid surfaces with colours of Coloroid lightnesses $V=40$, 60, 80 in the colour space of the CIELAB system

Munsell colour system served as model. Also these comparisons lead to the same conclusion as that between the Coloroid and the Munsell colour systems, namely that in different positions within the colour space, dh units comprise different numbers of ds units. It may be concluded that colour codes of colour systems created for colorimetry comprising ds units are hardly suitable for establishing colour compositional relationships valid for the whole colour space or even for its major domains, assuming an aesthetic appreciation.

3.2. Experiments to Establish the Aesthetically Uniform Psychometric Scales of the Coloroid Colour System

The Coloroid colour system has been developed at the Technical University of Budapest, as a result of investigations extending over a period of 16 years and is intended for colour design in construction (Nemcsics, 1978*c*). Like the colour codes of the Munsell colour system, coordinates of this new system refer to colour perceptions. Nevertheless, it is essentially different from the former inasmuch as its psychometric scales are based on human judgement concerning the uniformity of these series, rather than on the ability of human eye to distinguish individual members in hue, saturation and lightness series (Nemcsics, 1979). In the new colour system—as in the Ostwald system—every colour is also expressed as an additive mix of a saturated colour, white, and black. It is, however, essentially different from the Ostwald system in that these tristimuli are in an unambiguous correlation with the CIE *XYZ* system, and permit a numerical description of the quality of our colour sensation (Nemcsics, 1982). The colour space of the Coloroid system was built up on votes of thousands of observers (Nemcsics, 1980).

3.2.1. Experimental Conditions

Our experiments were aimed at creating a colour space suitable for describing colour harmony relationships.

Coloured surfaces in our environment display simultaneously a wide range of colours of different hues, saturations and lightnesses. These colours have to be asserted by the designer to be in an aesthetically valuable relation, that is to form a beautiful combination. Selection is easier if the change of colour codes parallels that of the aesthetic content of colours. An aesthetically uniform variation of colours is where the colour scale as a whole is found to be uniformly varying. Such scales constitute an aesthetically uniform colour system, in which a colour sensation difference between two adjacent colour samples is an integral multiple of the harmony colour difference.

Earlier experiments served to determine harmony colour difference as the least difference between two adjacent colours permitting their combination in the same harmonic composition. The separation of adjacent colours in scales composed on the basis of harmony colour differences is not uniform when using the scale of the least, just appreciable colour differences, as perceived by a CIE 1931 colorimetric sensor.

Experiments to establish scales of the Coloroid colour space based on aesthetically uniform variation were performed under the following conditions.

Statistical surveys for creating psychometric scales were made near the window of a room illuminated by skylight from the north at 1600 to 1800 lx illumination. Test persons (observers) were students aged 19 to 23, numbering about 2500 per test. Some tests involved primary school pupils or older age groups. Colour samples of 15 to 18 sq.cm were presented on a horizontal gray plane of uniform CIE tristimulus $Y=30$, illuminated by light incident at about 45° across the window. Observation was at 90° from a distance of 100 cm.

Care was taken not to have reflective coloured surfaces in the test room, and to provide an achromatic surrounding. Colour blind persons were eliminated in preliminary tests. Before the tests started, subjects spent at least five minutes in the test environment to let their eyes accommodate to the illumination level and the achromatic surrounding. The time available for selection among the presented colour samples, and to arrange them was not limited.

3.2.2. Tests on the Correlation of Hue and Dominant Wavelength

The statement found in publications and underlying the Munsell system, that with the variation of saturation and lightness also the dominant wavelength of the colour varies, has been reexamined in two test series.

In the first series, observers had to assess the hue of the presented colour samples. Our tests involved hues 2.5G, 2.5Y, 2.5R, 2.5P and 2.5B of the Munsell colour system. As original Munsell colour samples were not available, about a thousand colour samples were prepared for each of the five hues mentioned and Munsell scales assembled by selecting among colorimetered samples. The widest band (526 to 540 nm) was represented by samples of hue 2.5G, so that the problem could be best described in the light of tests carried out with this hue.

Observers were given a set of 15 green colours. The central colour had Munsell parameters $H=2.5G$, $V/C=4/4$, and dominant wavelength of 533 nm. Colours on either

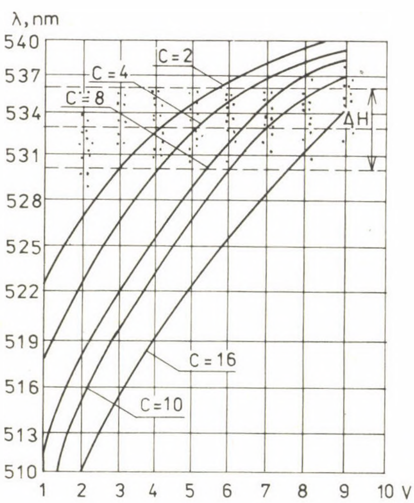


Fig. 3.29. Result of a test series on Munsell samples of hue 2.5G concerning the relation between hue and dominant wavelength, plotted for dominant wavelength and Munsell lightness V of the colour. The curves illustrate Munsell's wavelength dependence of colours of the same Munsell hue, different lightnesses, and Munsell chroma $C=2, 4, 8, 10, 16$. Contrary to Munsell's suggestion, votes of observers fell almost exclusively into the range ΔH (one point stands for 8 to 10 votes)

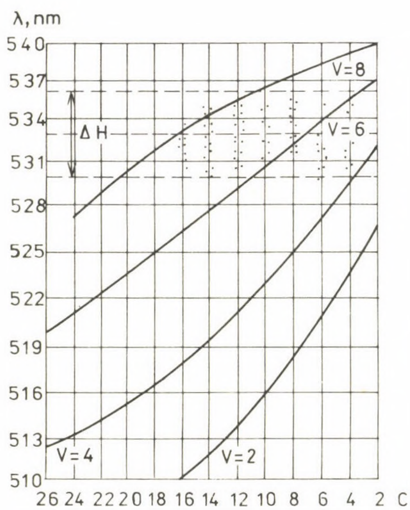


Fig. 3.30. Results of a test series on Munsell samples of hue 2.5G concerning the relation between hue and dominant wavelength, plotted for dominant wavelength and Munsell chroma (C). Curves illustrate Munsell's wavelength dependence of colours of the same Munsell hue, different chromas, and Munsell lightnesses $V=2, 4, 6, 8$. Contrary to Munsell's suggestion, votes of test subjects fell almost exclusively into the range ΔH (one point stands for 8 to 10 votes)

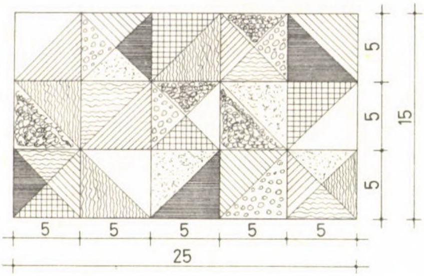


Fig. 3.31. Scheme of colour compositions of the second test on the correlation of hue and dominant wavelength. Identically shaded areas mean identical colours. Dimensions are in cm

side of this colour had the same chroma and lightness, but the hue tended to yellowish on the right, and to bluish on the left. Hue difference between adjacent colours was described as 2 nm of dominant wavelength variation each. Observers had to state for each of the seventy colours differing by chroma and lightness, which colour in the sample series had a hue identical to that of the colour set. Test results were plotted in Figs 3.29 and 3.30 referring to dominant wavelength vs. Munsell lightness, and to dominant wavelength vs. Munsell chroma, resp. One point represents 8 to 10 votes. Smooth curves in the figures correspond to Munsell's suggestion. The results can be summarized as follows:

— None of the observers gave a completely correct answer concerning the arrangement of all the colours according to the Munsell colour system;
— 5% of observers answered correctly for more than 50% of the colour points;
— 75% of observers placed 80% of the samples within the middle third of the available wavelength band. It was within this third where the correct order of Munsell samples and that according to the answers had the worst correlation.

In the second test, two compositions were presented to the observers who were asked to select the more harmonic one. By previously showing them various colour compositions it was explained that a harmonic composition is understood to be a colour complex of harmonizing members created for an aesthetic purpose. They were also asked to indicate if they did not find harmony differences between two compositions. Both compositions comprised ten colours. In test "A" the composition consisted of colours 8/4, 8/2, 6/8, 6/6, 4/6, 4/4, 4/2, 2/2, of the Munsell hue 2.5G, with dominant wavelengths ranging from 526 to 540 nm, while in test "B" colours were selected exclusively from colours of 533 nm dominant wavelength, i.e. from the centre of the band. Lightness and chroma of the colours were the same in both test, and so was the arrangement and the frequency of occurrence of the colours within the compositions (Fig. 3.31). In a similar way the tests were repeated for Munsell hues 2.5Y, 2.5R, 2.5P and 2.5B. Our conclusion was that

— 68% of observers did not find any aesthetic difference between the two compositions and that
— 17% of observers preferred composition "B", while 15% preferred composition "A".

The results of the two test series suggest that in developing our hue scale it is aesthetically irrelevant to consider Munsell's proposal, that for the same dominant wavelength, with varying saturation and lightness, the hue sensation also varies. An unambiguous perception of this variation is problematic even for the average observer.

3.2.3. Tests on the Aesthetic Uniformity of the Hue Scale

A test collection of 160 colour samples of Munsell lightness and chroma $V/C = 6/12$, but of different hues, was assorted from our colour samples. Using this collection, observers had to compile a colour circle by selecting 50 colour samples and arranging them to form a closed colour scale, which when looked at as a whole should appear to vary uniformly.

Differences between each two adjacent colours of the completed colour circles were defined as aesthetically equal hue intervals (ΔA). According to earlier tests (NEMCSICS, 1978), if the closed hue scale looked at as a whole appears as uniform, then colour differences between scale members are minimum harmony colour differences. These differences are denoted here as aesthetically equal hue intervals, in order to emphasize its deviation from Munsell scales based on threshold measurements and characterized by NICKERSON (1950) as "perceptionally uniform". The relationship of "harmony differences" (dh) and "just perceptible" differences (ds) closely related to WEBER's dI, varies at different points of the colour space. Deviations reveal differences between Munsell and Coloroid colour spaces.

Giving a summary of our test, the number of ΔA values between colours characterized by dominant wavelengths in the range of 400 to 700 nm, and of −490 to −570 nm, have been determined within each 10 nm interval. The equation of the summarizing curve describes the correlation of wavelength and the aesthetically uniform hue scale (Fig. 3.32).

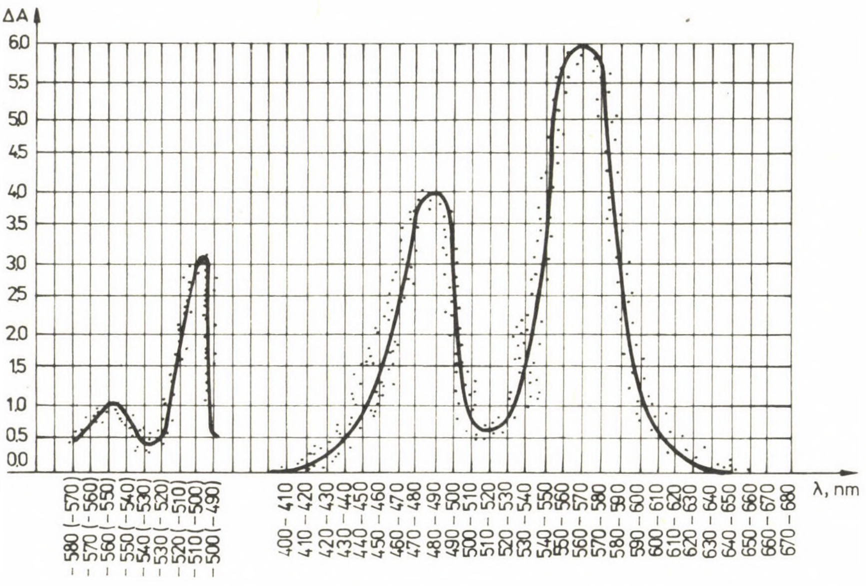


Fig. 3.32. Diagram of the test results on the aesthetic uniformity of the hue scale concerning colour samples of different Munsell hues with $V/C = 6/12$ lightness and chroma. The curve averaging the votes (points in the diagram) represents the relation between the aesthetically uniform hue difference (ΔA) and the dominant wavelength

3.2.4. Tests on the Aesthetic Uniformity of the Saturation Scale

Again, the first step was to perform tests using Munsell colour samples. 6 to 10 additional shades were painted between each two Munsell samples, such as:

2.5Y 8/18, 16, 14, 12, 10, 8, 6, 4, 2
2.5Y 6/14, 12, 10, 8, 6, 4, 2
2.5B 8/12, 10, 8, 6, 4, 2,
2.5B 6/16, 14, 12, 10, 8, 6, 4, 2,
2.5G 8/16, 14, 12, 10, 8, 6, 4, 2,
2.5G 6/26, 24, 22, 20, 18, 16, 14, 12, 10, 8, 6, 4, 2,
2.5R 8/10, 8, 6, 4, 2,
2.5R 6/18, 16, 14, 12, 10, 8, 6, 4, 2.

Eight colour sets averaging 60 samples of eight colours of equal hue and lightness but of different chroma were presented to observers. Using an arbitrary number of colour set, they had to compile from each set a saturation series showing uniformly increasing saturation when looked at as a whole. For the aesthetically uniform saturation differences between each two adjacent colours in the saturation series composed in this way the symbol ΔT was introduced. According to earlier tests, if when a scale including its terminals is looked at as a whole, it appears to be uniform, then colour differences between its members conform to harmony colour differences. These minimum harmony colour differences where here called—in conformity with those said above—aesthetically uniform saturation differences.

As a result of our experiments, the importance of ΔT among members of the Munsell chroma scale, according to scales composed by different observers (Fig. 3.33) could be evaluated. After processing of the results we arrived at

$$\sqrt{(\Sigma \Delta T)^3} = C\,(\mathrm{ab})\,, \tag{44}$$

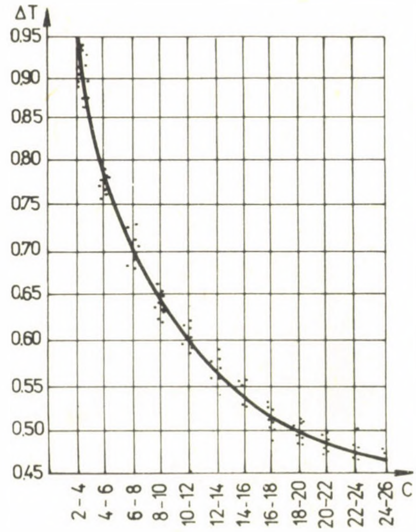


Fig. 3.33. Graphical representation of tests on Munsell samples, concerning aesthetic uniformity of the saturation scale. The curve averaging the votes (points in the diagram) represents the relation between aesthetically uniform perceptional saturation difference (ΔT) and Munsell chroma (C)

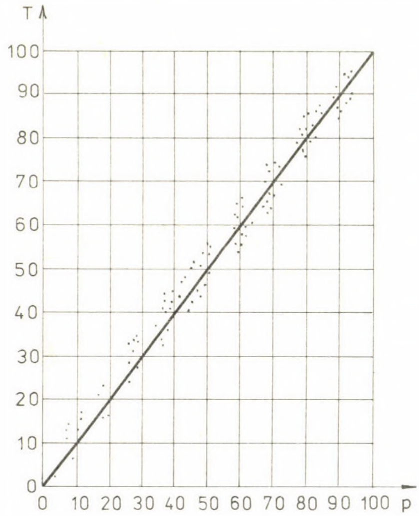


Fig. 3.34. Diagram of results of test on samples of equal Coloroid colour content differences, concerning the aesthetic uniformity of the saturation scale. The straight line averaging the votes (points in the diagram) represents the relation between the Coloroid saturation scale (T) corresponding to aesthetically uniform perceptional saturation differences and the Coloroid colour content (p)

where a and b indicate the lightness and hue dependence of both Coloroid saturation and Munsell chroma. After it was established that the Munsell scale of chroma was not aesthetically uniform, a new test series was undertaken. Colour sets were prepared for the new tests in conformity with the concept of saturation based on additive colour mixing. Samples were additively mixed from a saturated blue of 484 nm, a green of 520 n, a saturated warm yellow of 579 nm, and a saturated red of 610 nm dominant wavelengths, as well as from black and white. These colours were fitted on Maxwell discs so that the surface was covered by different percentages of the colour, and black and white. The discs were spun and the resulting colours of additive mixes of tristimuli were copied by tempera painting. In this way thousands of colours were composed, which were colorimetered, and then the colours with CIE tristimuli $Y=60$ and $Y=30$ were picked out.

These colour sets in which hue and lightness was constant but saturation varied were presented to the observers who were invited to select ten colours each, which, when arranged properly and looked at as a whole constituted a uniformly varying series ranging from least unsaturated to most saturated. Answers have led to the conclusion that the mix differences between colour quantities, needed to each two adjacent colours of the scales arranged by our observers, are on the average nearly constant (Fig. 3.34):

$$p_{i+1}-p_i=q\,. \tag{45}$$

Therefore in the Coloroid colour system the concept of saturation has been defined by assuming that colours produced by additively mixing the same quantities of a saturated colour of the same dominant wavelength, and white and black, are equally saturated.

3.2.5. Tests on the Aesthetic Uniformity of the Lightness Scale

Colours of various lightnesses and of two different saturations were produced by means of the Maxwell discs, as additive mixes of a saturated colour, and white and black, and then copied by tempera painting, as usual.

Mixing involved the following saturated colours:

red	$x=0.5675$,	$y=0.3221$,	$Y=20.32$,
yellow	$x=0.4627$,	$y=0.4685$,	$Y=66.32$,
green	$x=0.2649$,	$y=0.4622$,	$Y=32.21$
blue	$x=0.1768$,	$y=0.2465$,	$Y=17.81$.

The saturated colour entered the mix in two proportions, either 15% or 50% of the disc surface. This gave eight sets comprising colours of equal hues and saturations but different lightnesses. Set members were measured and tristimuli Y recorded, which varied in the range $Y=80$ to $Y=2$. Each set contained about 250 samples.

Observers had to select twenty samples from each set and arrange them according to decreasing lightness, so that the resulting scale looked at as a whole seemed to darken evenly. Differences between each two colours in these scales, i.e., harmony colour differences, were considered as aesthetically equal lightness intervals ΔV. The tests were evaluated by determining the number of ΔV values in steps of $5Y$ between $Y=5$ and $Y=80$. Processing the results has led to the relationship (Fig. 3.35):

$$\left(\frac{\Sigma \Delta V}{10}\right)^2 = Y. \tag{46}$$

Finally CIE XYZ data of all the colours involved in the tests have been recorded. The tabulated data have been included in the final reports of the experiments.

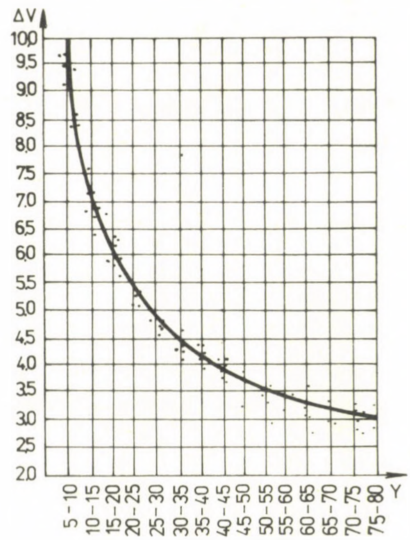


Fig. 3.35. Diagram of results of tests on colour samples of different CIE tristimuli Y. The curve averaging the votes (points in the diagram) represents the relation between aesthetically uniform perceptional lightness differences (V) and CIE tristimulus Y

3.3. The Coloroid Colour System

For the architect concerned with environment colour design, colour is a tool serving both technical and artistic purposes. Unambiguous distinction by codes of every member of the set of colours is required, in the first case, in order to be able to assign technical parameters to colours, and in the second case, to quantify compositional relations between colours.

In addition, the colour designer is expected not only to be safely oriented between colours, but also, to define perceptional interrelations by measurement or estimation, just as for distances or volumes. This requires a measuring system directly or indirectly using international units. Codes of various colour systems are not perfectly suitable for this purpose, since either they are discontinuous, or their colour space is aesthetically not uniform, or even, they are in no exact correlation with the CIE *XYZ* system. This is why a new system—the Coloroid colour system—has been developed specifically for environment colour design.

In the Coloroid colour system colours are arranged in space so that for the average observer their correlation appears to be aesthetically uniform, i.e. it is built up from about equal harmony intervals (d*h* units), which are, at the same time in an exact relation with physical parameters and colour stimuli. That is, it closely approximates the structure of an aesthetically uniform colour system, and is at the same time in a perfect, mutually unambiguous relation to the CIE *XYZ* colour system. Its codes have been derived directly from tristimuli obtained by instrumental measurements.

The concepts of hue, saturation and lightness defined thereby closely approximate to our colour sensations. It involves approximation only where approximation is an inherent feature of the concept introduced, while it provides for an exact relationship whenever this can be secured instrumentally. Coloroid hue, Coloroid saturation, and Coloroid lightness are the perceptional characteristics of the Coloroid system.

It follows from its direct relation to the CIE *XYZ* colour system that the Coloroid system relies on additive colour mixing. Colours are treated as being mixed from tristimuli of boundary colour, black and white. Coordinates of a colour point in the Coloroid colour system can be determined from the components and their proportions.

3.3.1. Essentials of the Coloroid Colour System

According to the principle of colour systems relying on perceptional characteristics, in the Coloroid colour system, the three dimensional array of colour perceptions is accommodated inside an orthogonal circular cylinder so that hue varies along the cylinder shell, saturation along the radius, and lightness along the axis (Fig. 3.36).

Hence, achromatic colours from absolute white to absolute black lie on the axis of the cylinder. Planes normal to the axis accommodate colours of the same lightness. Saturation of colours increases with the distance from the axis. Colours of equal saturation each form a cylinder shell. Colours of the same hue lie in half-planes of vertical axial sections of the cylinder (Fig. 3.37).

An approximately elliptic perimeter of an inclined plane section of the cylinder shell accommodates the spectrum colours and purples, which are the *boundary colours of Coloroid* (Fig. 3.38).

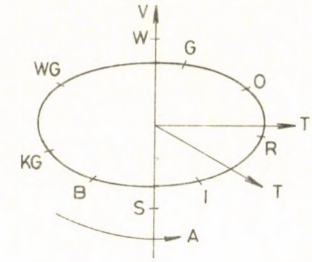


Fig. 3.36. Perceptional dimensions of the Coloroid colour system: Coloroid hue (*A*), Coloroid saturation (*T*), and Coloroid lightness (*V*). Other letters in the diagram denote: W white, S black, G yellow, O orange, R red, I violet, B blue, KG cold green, WG warm green

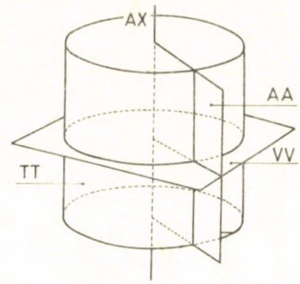


Fig. 3.37. In the Coloroid system, achromatic colours lie in the achromatic axis (AX), colours of equal saturations on coaxial cylindrical surfaces (TT), colours of the same lightness on surfaces normal to the achromatic axis (VV), colours of the same hue in half-planes (AA) crossing the achromatic axis

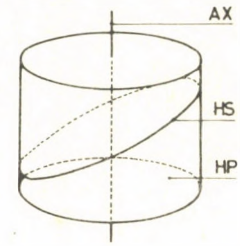


Fig. 3.38. The Coloroid colour space is confined by the shell of a circular cylinder (*HP*) coaxial with the achromatic axis (AX). Curve (*HS*) of Coloroid boundary colours is in the shell of this circular cylinder

Among boundary colours of the Coloroid system, 48 approximately aesthetically equidistant colours with integer codes, have been adopted as *Coloroid basic colours* (Fig. 3.39).

Absolute white and absolute black are at the two end points of the achromatic axis (Fig. 3.40).

Every Coloroid boundary colour is related to absolute white and absolute black by a curve in the common plane of achromatic axis and boundary colour, the so-called *boundary curve* (Fig. 3.41). Surfaces made up by the array of boundary curves confine the Coloroid colour space (Fig. 3.42). *Coloroid colour space* is a confined part of the space including all perceptible colours in an arrangement according to Coloroid perceptional parameters. In the Coloroid colour space, the achromatic axis from absolute white to absolute black, as well as radii normal to the achromatic axis, reaching to the cylinder shell accommodating boundary colours, have been divided into 100 equal parts.

The *Coloroid colour solid* is the part of the Coloroid colour space containing surface colours (Fig. 3.43). The most saturated colours of the Coloroid colour solid lie along a curve on the shell of a cylindroid which is however no longer circular (Fig. 3.44).

Half-planes intersecting the Coloroid colour space are called Coloroid colour planes. A *Coloroid colour plane* is confined by a straight line, the achromatic axis, and two curves, the boundary curves. Similar to, and inside of, the boundary curves are curves cut out of the Coloroid colour solid by half-planes, these are the boundary curves of the surface colours (Fig. 3.45). Colours in the same Coloroid colour plane have the same

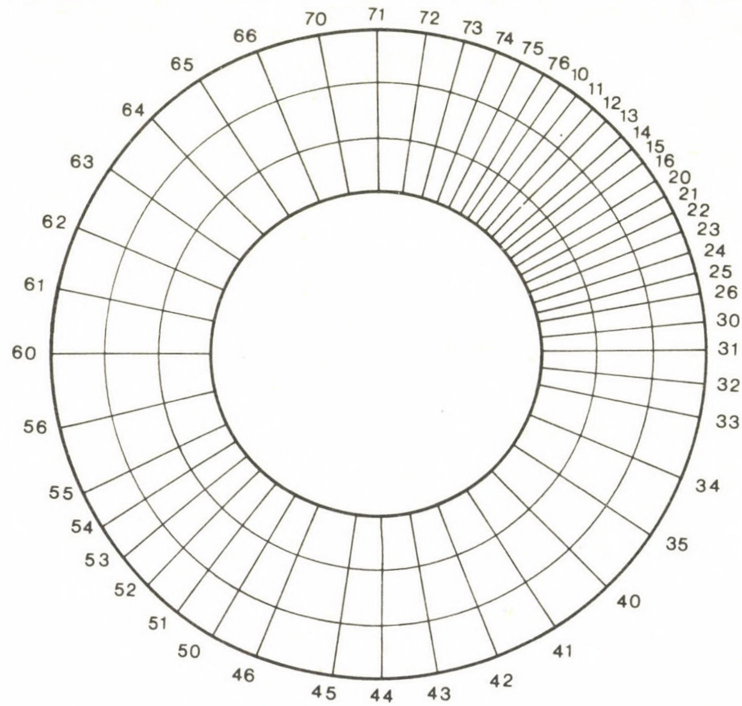


Fig. 3.39. 48 aesthetically equidistant colours selected from Coloroid boundary colours are the basic colours of the Coloroid system. Complementary colours are at 180°. Basic colours and their basic hues have integer codes. Basic colours are not uniformly distributed on the colour circle

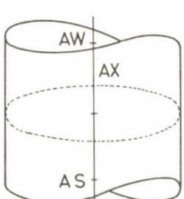


Fig. 3.40. Absolute white (AW) and absolute black (AS) are at end points of the Coloroid achromatic axis (AX)

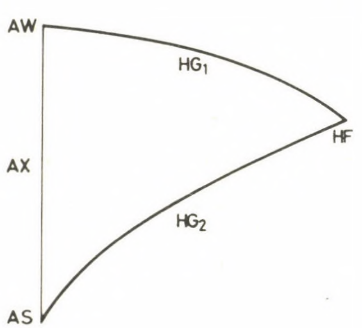


Fig. 3.41. Absolute white (AW) and absolute black (AS) points at the terminals of the achromatic axis are connected to every boundary colour (HF) by two boundary curves (HG_1 and HG_2) each. Boundary curves lie in the common plane of the achromatic axis and the given boundary colour

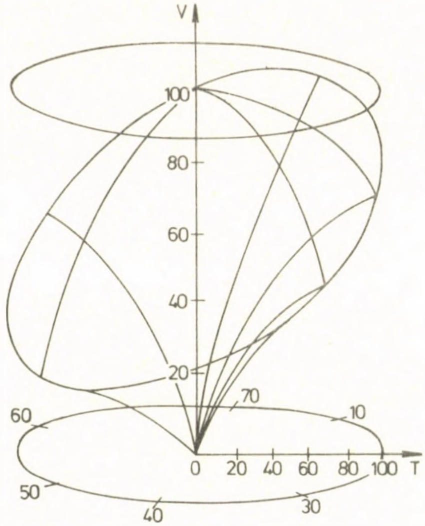


Fig. 3.42. The Coloroid colour space is a confined part of the space including all perceptible colours in an arrangement according to Coloroid perceptional characteristics

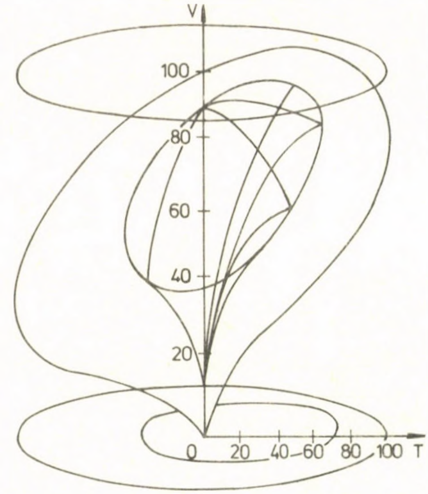


Fig. 3.43. The Coloroid colour solid is part of the Coloroid colour space comprising surface colours

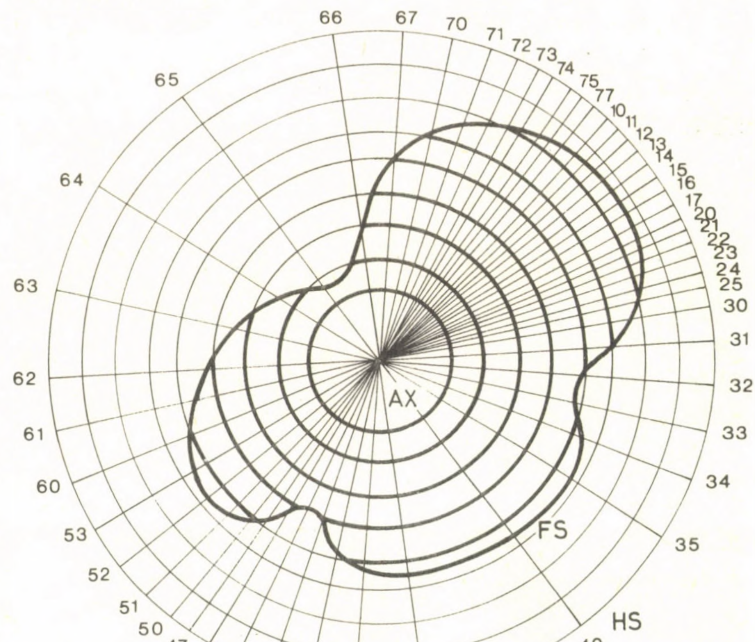


Fig. 3.44. Projection of the Coloroid colour space and solid normal to the achromatic axis (AX). Geometric site of the projection of boundary colours outlining the colour space is a circle (HS), geometric site of the projection of the most saturated pigment colours outlining the colour solid is an irregular curve (FS). Concentric circles in the figure are generatrices of cylindrical surfaces coaxial with the achromatic axis, containing colours of identical saturation

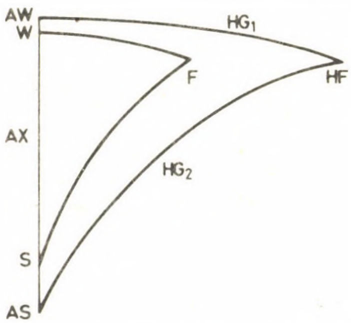


Fig. 3.45. Every Coloroid colour plane outlined by the achromatic axis (AX), and two boundary curves (HG_1, HG_2) connecting absolute white (AW) and absolute black (AS) to a boundary colour (HF), includes all the colours having the wavelength of the boundary colour. The Coloroid colour plane surface confined by lines connecting points of the lightest surface white (W), the darkest surface black (S), and the most saturated surface colour having the same wavelength as the boundary colour includes all surface colours of the wavelength of the given boundary colour

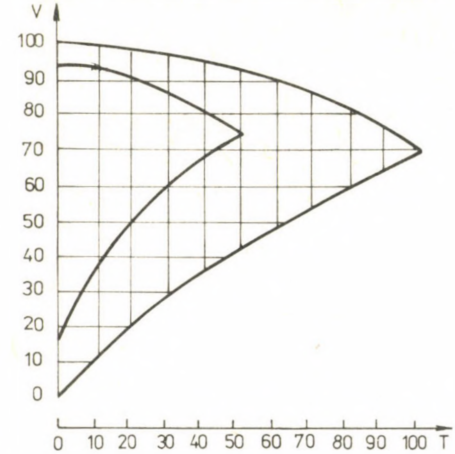


Fig. 3.46. Sites of colours of equal Coloroid saturation (T) and equal Coloroid lightness (V) in a Coloroid colour plane

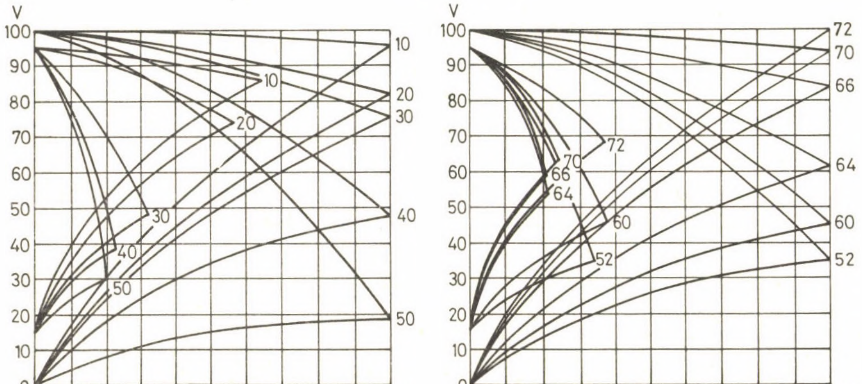


Fig. 3.47. Coloroid colour planes including Coloroid basic colours $A = 10, 20, 30, 40, 50, 52, 60, 64, 66, 70, 72$. The surface part within each colour plane contains surface colours cut out from the Coloroid colour solid by the colour plane. It can be seen that Coloroid basic colours are of different lightnesses but of equal saturation, but the most saturated pigment colours differ not only by lightness but also by saturation

Coloroid hue. On each page of the "Coloroid Colour Atlas" (Nemcsics, 1988) such colours are shown.

Colours in the Coloroid colour solid along straight lines parallel to the achromatic axis have the same Coloroid saturation. Colours along normals to the achromatic axis have the same Coloroid lightness (Fig. 3.46). While the shape of a section of the Coloroid colour space depends only on the Coloroid lightness of the spectrum colour or purple at the vertex of that section; the shape of the section of the Coloroid colour solid depends both on the Coloroid lightness and on the Coloroid saturation of the most saturated surface colour in that plane (Fig. 3.47).

3.3.2. Coordinates of the Coloroid Colour System

Within the Coloroid colour space, every colour is located by its Coloroid coordinates, i.e., by perceptional colour parameters, or colour codes of the Coloroid system. Colours are identified by three correlated numbers, referring to Coloroid hue, Coloroid saturation, and Coloroid lightness, in this order, i.e.: *A–T–V* (hue–saturation–lightness).

Code for a colour of Coloroid hue 13, Coloroid saturation 22, and Coloroid lightness 56 is thus 13–22–56,

compared to this, a colour coded
- 12–22–56 tends to green,
- 14–22–56 tends to orange,
- 13–21–56 is less saturated,
- 13–23–56 is more saturated,
- 13–22–55 is darker, and
- 13–22–57 is lighter (Fig. C18).

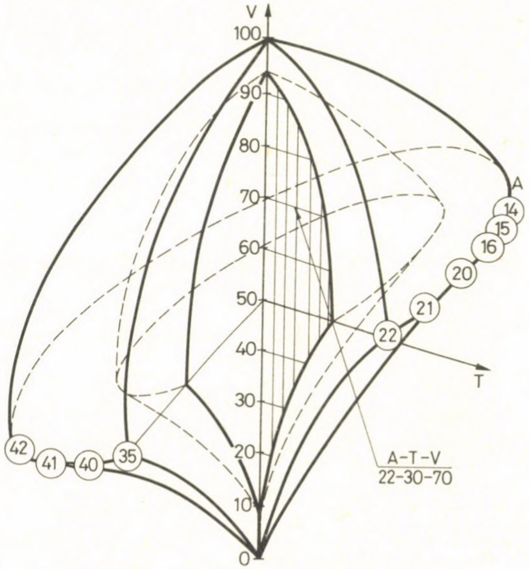


Fig. 3.48. Colour codes of the Coloroid colour system locate the colour inside the Coloroid colour space. These codes are the coordinates of the given colour in the Coloroid system. The first group of numbers corresponds to the angular coordinate, the second to the radial coordinate, and the third to the axial coordinate

These colour codes are Coloroid coordinates which help to indicate the specific colour by locating it inside the Coloroid colour space. The first number indicates the hue of the colour, that is, the accommodating colour plane. The second number reveals on which coaxial cylindrical surface between the achromatic axis and the cylindrical surface of the most saturated, i.e., spectrum colours our colour is situated. The third number refers to the plane normal to the achromatic axis, accommodating the given colour (Fig. 3.48).

Coloroid hue is a characteristic of the colour on a scale having 48 aesthetically uniform divisions. In conformity with the 48 Coloroid basic colours, the Coloroid system comprises 48 basic hues, with integer codes:

*A*10–*A*16 yellows,
*A*20–*A*26 oranges,
*A*30–*A*35 reds,
*A*40–*A*46 purples, violets,
*A*50–*A*56 blues,
*A*60–*A*66 cold greens,
*A*70–*A*76 warm greens.

Some numbers are missing from the Coloroid hue scale, so that the highest code for a Coloroid hue is 76 rather than 48 (Fig. 3.49).

The integral part of the numerical value of the Coloroid hue of an arbitrary colour is the number of the next lower Coloroid basic hue coded by an integer, while its fractional

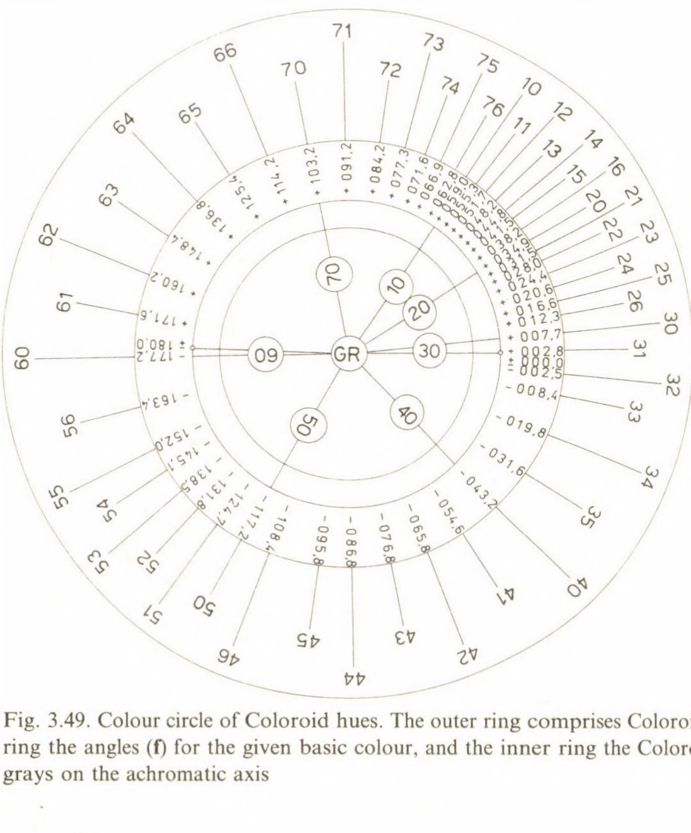


Fig. 3.49. Colour circle of Coloroid hues. The outer ring comprises Coloroid basic hue codes (*A*), the middle ring the angles (f) for the given basic colour, and the inner ring the Coloroid colour domains. GR refers to grays on the achromatic axis

part is ϑ. ϑ is a factor involved in the definition of hue. A hue coded $A=A_i+\vartheta$ is obtained by additively mixing ϑ parts of the Coloroid boundary colour of hue A with $(1-\vartheta)$ parts of the Coloroid boundary colour of hue A_i. Complementary hues are in planes at about 180° relative inclination in the Coloroid colour space. As basic hues are generally aesthetically equivalent, basic colours are in a geometrical sense unevenly distributed on the colour circle, thus not all the basic colours have a basic colour as complementary. Basic hues may be visually represented by a Coloroid colour circle painted with the most saturated pigments available (Fig. C19). Colours of the colour circle shown are about the most saturated colours of the Coloroid colour solid.

Coloroid hue of a colour is defined by its dominant wavelength. In the Coloroid colour space, colours of the same Coloroid hue are in Coloroid colour planes. Figures C20, C21 and C22 show colours of the same hue each in a Coloroid colour plane. In the rectangular mesh of the figures, colours in the same column are of the same saturation. In Fig. C20, from left to right, colour saturations in a column are 8, 16, 24, 32, 40, 48, 56, while in Fig. C21, they are 4, 8, 12, 16, 20, 24, 32. In these figures, columns of equal saturation have different spacings, since for different Coloroid axial sections the most saturated colours of the Coloroid colour solid are at different distances from the achromatic axis; nevertheless we wished to fill up each section with the same number of colours.

Let us have a closer look at Figs C20 and C21. In Fig. C20, among colours of equal hue in Coloroid colour plane no. 10, those of lightnesses 90, 80, 70, 60, 50, 40, and of saturations 8, 16, 24, 32, 40, 48, 56 are depicted. Coloroid saturation of the most saturated pigment colour with this hue is 63. This colour is missing from the figure since its saturation is intermediate between Coloroid saturations 56 and 64. The most saturated pigment colour in the Coloroid colour plane in Fig. C21 has a saturation of 30, intermediate between $T57$ and $T32$ of saturation columns spaced at $T4$. The last in this figure is the column for colours of Coloroid saturation $T57$. The last saturation column in Fig. C22 for colours of Coloroid hue 51 is the column for Coloroid saturation 40. The most saturated pigment colour belonging to this section has a saturation $T41$, causing it to be omitted.

In all of the three figures, horizontal rows contain different numbers of colours with Coloroid lightnesses of 90, 80, 70, 60, 50, 40, in this order. Differences are due to the fact that for different lightnesses of different hues, Coloroid saturations of the existing most saturated colours are different. This fact is also reflected by the shape of the Coloroid colour solid, to be explained later.

Coloroid saturation is the second colour characteristic or coordinate. Coloroid saturation indicates the saturation of a colour, i.e., its distance from an achromatic colour of the same Coloroid lightness, on an aesthetically uniform scale. Coloroid boundary colours have a saturation of 100. Absolute white and absolute black of the Coloroid system, and gray as an achromatic mixture of pure white and pure black, have a saturation of 0. Thus:

$$\begin{aligned} T_\lambda &= 100 \\ T_w &= 0 \\ T_s &= 0\,, \end{aligned} \tag{47}$$

where T_λ, T_w, and T_s are saturations of the spectrum colour, absolute white, and absolute black, respectively.

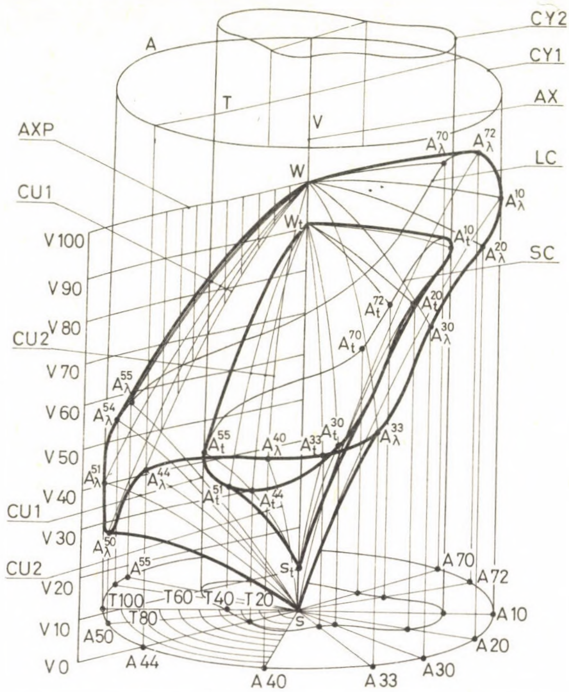


Fig. 3.50. Axonometric view of the 3D model of the Coloroid color system. Legend: CY1 and CY2 are the circular, and irregular generatrices, respectively, of the orthogonal cylinder containing the Coloroid colour space, and the colour solid for surface colours, respectively; AX is the Coloroid achromatic axis; LC is a curve for geometric sites of Coloroid boundary colours (spectrum colours and purples) lying on the shell of the orthogonal circular cylinder confining the Coloroid colour space; SC is the curve of geometric sites of the most saturated surface colours of the Coloroid colour solid, lying on the shell of a cylinder of irregular generatrix, containing the Coloroid colour solid; AXP is an axial section of the Coloroid colour space. Half-planes crossing the achromatic axis cut out so-called Coloroid half-planes of the Coloroid colour solid. CU and CUS are boundary curves which confine colours, and surface colours, respectively, in Coloroid half-planes; W is absolute white in the Coloroid colour system, the upper end of the achromatic axis; W_t is the site of the lightest achromatic surface colour on the achromatic axis; S is absolute black in the Coloroid colour system, at the lower end of the achromatic axis; S_t is the site of the darkest achromatic surface colour on the achromatic axis. *A* is Coloroid hue (there are 48 Coloroid basic hues numbered from 10 to 76, with number omissions). A hue is indicated by *A* followed by the hue number. For instance, *A*10 is for colours of 570.83 nm dominant wavelength. Colours with the same hue lie in axial sections. A_λ is Coloroid boundary colour. There are 48 basic colours denoted like the basic hues. A_t denotes the most saturated surface colours belonging to the individual hues. *T* is Coloroid saturation, gradually and linearly increasing along normals to the achromatic axis to the cylinder shell for Coloroid boundary colours. Numerical value of saturation is 0 at the achromatic axis, and 100 at the cylinder shell. Colours of equal saturation form coaxial cylindrical surfaces. *V* is Coloroid lightness, increasing gradually and linearly across planes normal to the achromatic axis from its absolute black point. Numerical value of lightness in the plane including the point for absolute black is 0, and 100 for absolute white. Colours of equal lightnesses form parallel planes normal to the achromatic axis

In the Coloroid colour space colours of equal Coloroid saturations are on cylindrical surfaces coaxial with the achromatic axis of this space.

Figures C23 and C24 are spreads in plane of the circular cylinder containing colours with Coloroid saturations 16 and 24, showing discrete colours pertinent to hues and lightnesses on the spread of the cylinder section of the Coloroid colour solid. Colours in a column have the same Coloroid hue, colours in a row have equal Coloroid lightnesses. Individual columns contain different numbers of colours, because for each Coloroid hue the cylinder shell bearing colours of the same Coloroid saturation cuts out different parts from the Coloroid colour solid. In fact, the generatrix of the "cylindrical" surface bearing the most saturated colours of the solid is not a circle, so that it cannot be concentrical to generatrices describing cylindrical surfaces containing colours of equal Coloroid saturations (Fig. 3.44).

Coloroid lightness is the third colour characteristic, or coordinate. Coloroid lightness of a colour is expressed as its distance from the Coloroid absolute black, on a scale having aesthetically uniform divisions.

Lightness of Coloroid absolute black is 0, and that of absolute white is 100, hence:

$$\begin{aligned} V_s &= 0 \\ V_w &= 100\,. \end{aligned} \tag{48}$$

The section of achromatic axis within the Coloroid colour solid is seen in Fig. C25. Coloroid lightnesses of grays in the figure range from black (Coloroid lightness 05) to white (Coloroid lightness 95), uniformly varying by steps of 5 units.

Sections cut out from the Coloroid colour solid by planes normal to the achromatic axis, containing colours of Coloroid lightnesses 75 and 45, are seen in Figs C26, and C27, respectively, showing some discrete colours of the section. Colour saturations increase with the distance from gray placed in the centre. Colours of the same Coloroid saturation lie on concentric circles. Colours of the same hue are on a radius each. Due to the asymmetry of the Coloroid colour solid, the number of colours on radii are not equal.

Figure 3.50 is axonometric view of the 3D model of the Coloroid colour system summarizing all that has been discussed above.

3.3.3. Colour Components in the Coloroid Colour System

In the Coloroid colour system, any colour is considered as an additive mix of the proper Coloroid boundary colour, and of Coloroid absolute white and black, in proportions p, w, and s, respectively. Numerical values of p, w, and s are Coloroid colour components, of which p is colour content, w white content, and s black content. The total of Coloroid colour components of any Coloroid colour point is one, that is:

$$p+w+s=1\,. \tag{49}$$

Since in everyday practice, Coloroid boundary colour, absolute white, and absolute black are not available for additive colour mixing, colour components entering colour mixing will be:

— a colour of the same hue but of higher saturation than the wanted colour (in a proportion p_t);

— white lighter than the wanted colour (in a proportion w_t);
— black darker than the wanted colour (in a proportion s_t).
Also in this case, the total of Coloroid colour components is one, that is:

$$p_t + w_t + s_t = 1 \,. \tag{50}$$

Coloroid colour components are the simplest to illustrate on a Maxwell disc. In the disc in Fig. 3.51, the shaded area is for the field occupied by the Coloroid boundary colour p, or by a colour p_t of the same hue but more saturated than the wanted colour, the empty area is for Coloroid absolute white w, or for an achromatic colour w_t lighter than the wanted colour, and the dotted area is for Coloroid absolute black s, or an achromatic colour darker than the wanted colour. The colour appearing upon spinning the disc will have Coloroid colour components with numerical values equal to percentages of areas for p, w, s or p_t, w_t, s_t.

Coloroid hue of the appearing colour will be identical to that of the Coloroid boundary colour on area p, or of the saturated colour of area p_t, that is:

$$\begin{aligned} A &= A_\lambda \,, \\ A &= A_{t\lambda} \,. \end{aligned} \tag{51}$$

Not perfectly achromatic white and black modify in proportion to their percentage in the mix the hue of the mixed colour as compared to the chromatic colour on the disc. Tendency and degree of this modification will be considered later.

Numerical value of the Coloroid saturation of a colour is the product of saturation T_λ of the Coloroid boundary colour having the same wavelength as the Coloroid hue of the colour and its Coloroid colour component value p. For a more saturated colour the corresponding parameters are $T_{t\lambda}$ and p_t. Thus:

$$\begin{aligned} T &= pT_\lambda \,, \\ T &= p_t T_{t\lambda} \,. \end{aligned} \tag{52}$$

Accordingly, colours considered to be mixed from a Coloroid boundary colour, absolute white and absolute black are said to be of equal Coloroid saturation if the percentage of the boundary colour in both is the same.

Lastly, the Coloroid lightness of the appearing colour depends on the numerical values of lightnesses of the boundary colour, absolute white, and absolute black making up

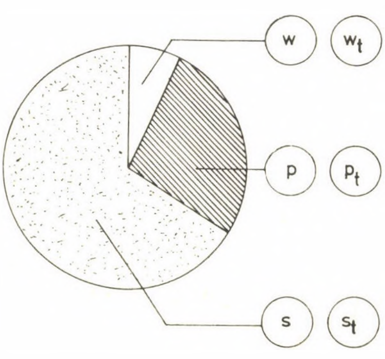
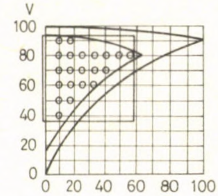


Fig. 3.51. Coloroid colour components: w white content, p colour content, s black content. Percentages of white (w_t), saturated colour (p_t) and black (s_t) surfaces needed to display the given colour on a Maxwell disc differ from those of Coloroid colour components, namely lightness of a white surface, and saturation of the coloured surface is less than 100

Fig. 3.52. Coloroid coordinates, and p_t, w_t, s_t values needed to display by additive mixing of some discrete colours in the axial section containing colours of basic $A=11$ of the Coloroid colour solid



A=11

V \ T	8	16	24	32	40	48	56
90	11-08-90 11.38 86.51 2.11	11-16-90 22.76 76.37 0.87					
80	11-08-80 11.38 65.65 22.97	11-16-80 22.76 55.51 21.73	11-24-80 34.14 45.37 20.49	11-32-80 45.53 35.23 19.25	11-40-80 56.91 25.09 18.01	11-48-80 68.29 14.95 16.76	11-56-80 79.67 4.81 15.52
70	11-08-70 11.38 47.24 41.38	11-16-70 22.76 37.10 40.14	11-24-70 34.14 26.96 38.90	11-32-70 45.53 16.82 37.66	11-40-70 56.91 6.68 36.42		
60	11-08-60 11.38 31.28 57.34	11-16-60 22.76 21.14 56.10	11-24-60 34.14 11.00 54.85	11-32-60 45.53 0.86 53.61			
50	11-08-50 11.38 17.78 70.84	11-16-50 22.76 7.64 69.60					
40	11-08-40 11.38 6.74 81.88						

areas p, w, and s, respectively, or of the saturated colour, white and black making up areas p_t, w_t and s_t, respectively, such as:

$$V=10\sqrt{0.01\,pV_\lambda^2+100\,w}\,,$$
$$V=10\sqrt{0.01\,p_tV_{t\lambda}^2+0.01\,w_tV_{tw}^2+0.01\,s_tV_{ts}^2}\,. \tag{53}$$

Coloroid colour components also permit a colour to be displayed by its Coloroid coordinates. Figure 3.52 is a section containing colours of Coloroid hue $A11$, indicating, however, only Coloroid coordinates and colour components, rather than the colours themselves. Strings of numbers printed with larger characters are Coloroid coordinates of the colour of the given field, while strings in smaller print denote percentages p_t, w_t and s_t of Coloroid colour, white and black, respectively. By looking at the numbers it can be seen that tristimuli p_t of colours of the same saturation are equal; for instance, for colours of Coloroid saturation $T8$ $p_t=11.38\%$ while for saturation $T16$ $p_t=22.76\%$. Coloroid saturations and colour contents p_t of colours in the section were equal only if colours were to be produced by mixing Coloroid boundary colour of hue $A11$, absolute white, and absolute black. Colour components for colours in this figure refer to the case of additively mixing a yellow surface of Coloroid hue $A11$, Coloroid saturation 70, and Coloroid lightness 86, a white surface of Coloroid lightness 95, and a black surface of Coloroid lightness 15. Thus, numerical values of Coloroid colour components of a colour always depend on data of the colour surface of the same hue but more saturated than it is, a lighter white surface, and a darker black surface to be mixed.

When we wish to display a colour indicated with its Coloroid A–T–V colour coordinates, i.e. to replace numbers in the table fields by painted colours, and a more saturated colour of the same hue, as well as white, and black are available, then Coloroid colour components for the display are obtained as:

$$p_t = \frac{T}{T_t}$$

$$w_t = \frac{V^2 - p_t V_t^2 - (1 - p_t) V_s^2}{V_w^2 - V_s^2} \tag{54}$$

$$s_t = 1 - p_t - w_t \, ,$$

where T and V are Coloroid colour coordinates of the colour to be displayed, T_t the saturation of the colour surface entering the mix, of the same hue as the wanted colour, V_t, V_w and V_s are Coloroid lightnesses of the colour surface of the same hue as the wanted colour, and of white and black surfaces, respectively, entering the mix.

3.3.4. Relation between Coloroid and CIE *XYZ* Colour Systems

For establishing a link between the Coloroid and CIE XYZ colour systems a fundamental condition was to define Coloroid boundary colours, and Coloroid absolute white and black in the CIE XYZ system.

In the CIE colour diagram, Coloroid boundary colours lie along the line of spectrum colours between $\lambda = 450$ nm and $\lambda = 625$ nm, as well as along the straight line connecting points $\lambda = 450$ nm and $\lambda = 625$ nm. These have been defined so that tristimuli X_λ, Y_λ, Z_λ of Coloroid boundary colours equal hundred times the spectral tristimulus values $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ of dominant wavelength λ_d, that is (Fig. 3.53):

$$\begin{aligned} X_\lambda &= 100\bar{x}(\lambda_d) \, , \\ Y_\lambda &= 100\bar{y}(\lambda_d) \, , \\ Z_\lambda &= 100\bar{z}(\lambda_d) \, . \end{aligned} \tag{55}$$

Coloroid absolute white has been defined as the colour of a perfectly diffusely reflecting surface illuminated by a CIE illuminant. Depending on the kind of standard illumination under which the colour samples are observed, the coordinates are the same as those of the colour point in the corresponding standard illuminant, and tristimuli equal its tristimuli. Tristimulus Y_w of absolute white is invariably 100, that is:

$$Y_w = 100 \, . \tag{56}$$

Coloroid absolute black has been defined as the colour of a perfectly light absorbing surface of reflection $\varrho = 0$ illuminated by CIE illuminant. Its colour coordinates are the same as for absolute white, and all the tristimuli are zero:

$$X_s = Y_s = Z_s = 0 \, . \tag{57}$$

In the CIE 1931 colour diagram, colours of the same Coloroid hue are on radii starting from the colour point of the actual illuminant. Hue may also be indicated as the slope

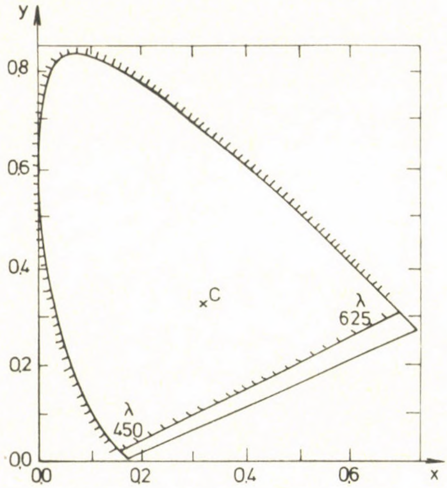


Fig. 3.53. Boundary colours of the Coloroid colour system are located along the spectrum line of the CIE 1931 diagram between the limiting points 450 nm and 625 nm, and along the line connecting these limiting points parallel to the purple line

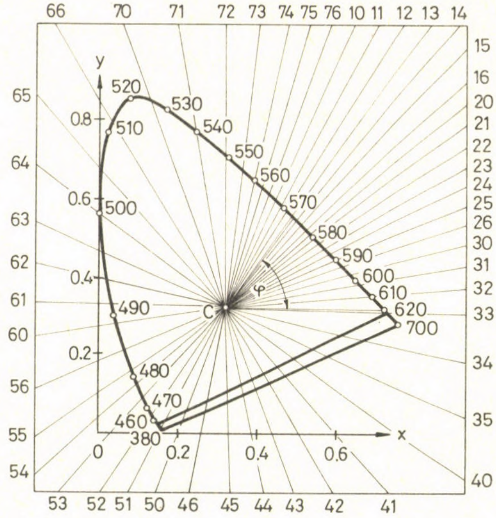


Fig. 3.54. Projections of colour planes containing Coloroid colours of equal hue if the Coloroid achromatic axis is drawn at point C and normal to the plane of the CIE 1931 diagram, Coloroid hues are characterized by angle φ formed with the x axis of the CIE 1931 diagram

of this radius (Fig. 3.54). For an angle φ included between this radius and the horizontal, the radius is inclined at $m = \text{tg}\varphi$, hence:

$$A = f(\varphi); \quad A = f(\text{tg}\,\varphi)\,. \tag{58}$$

Accordingly, all colours in a given Coloroid colour plane are of the same dominant wavelength. Colours of the Coloroid colour circle are selected from the colour planes of Coloroid colour circle. Their dominant wavelengths are also characteristic of Coloroid basic colours.

Coloroid basic colours and hues, basic colour tristimuli, as well as angles φ typical of basic hues at illuminations C and D65 were compiled in Table A.1. φ is the angle included between the radius starting from the colour point of ray distribution of the light source and axis x (Fig. 3.55). In Fig. 3.56, colours of the Coloroid colour circle are represented in the CIE 1931 colour diagram.

Tristimuli X, Y, Z in the CIE XYZ system of Coloroid colours produced by additive mixing may also be expressed according to their shares in the mix, as a sum of respective colour components of the boundary colour, absolute white, and absolute black:

$$\begin{aligned} X &= pX_\lambda + wX_w + sX_s \\ Y &= pY_\lambda + wY_w + sY_s \\ Z &= pZ_\lambda + wZ_w + sZ_s\,, \end{aligned} \tag{59}$$

where X, Y, Z; X_λ, Y_λ, Z_λ; and X_s, Y_s, Z_s are respective tristimuli of the given colour, its boundary colour, absolute black and white. Let ε be one hundredth of the sum

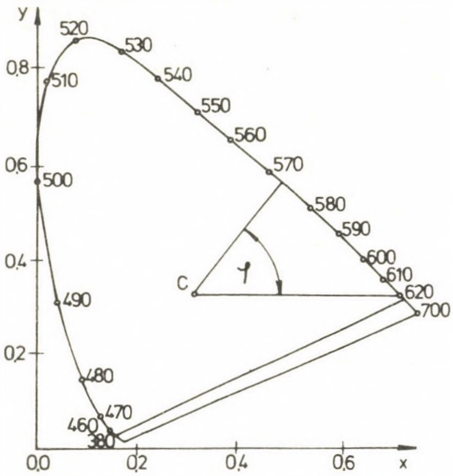


Fig. 3.55. Coloroid colours of equal hue are on the line starting from point C in the CIE 1931 diagram. Coloroid hues may also be described by angle φ with the radius x

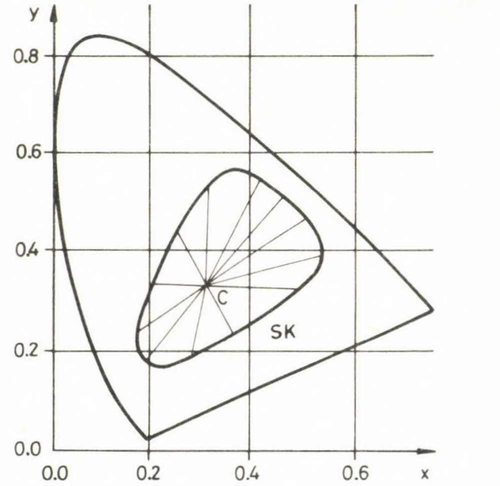


Fig. 3.56. Colours of the Coloroid colour circle in the CIE 1931 diagram

of tristimuli for a given colour point:

$$\varepsilon=\frac{X+Y+Z}{100} \tag{60}$$

then one hundredth of the sum of the equation above may be written as:

$$\varepsilon=p\varepsilon_{\lambda}+w\varepsilon_{\mathrm{w}}+s\varepsilon_{\mathrm{s}}\,. \tag{61}$$

This formulation is quite suitable to represent Coloroid colour points as sums of Coloroid colour components.

Tristimuli X, Y, Z and Coloroid colour components of any colour in the Coloroid colour space are also related by:

$$\begin{aligned} X&=p_{\mathrm{t}}X_{\mathrm{t}\lambda}+w_{\mathrm{t}}X_{\mathrm{tw}}+s_{\mathrm{t}}X_{\mathrm{ts}}\\ Y&=p_{\mathrm{t}}Y_{\mathrm{t}\lambda}+w_{\mathrm{t}}Y_{\mathrm{tw}}+s_{\mathrm{t}}Y_{\mathrm{ts}}\\ Z&=p_{\mathrm{t}}Z_{\mathrm{t}\lambda}+w_{\mathrm{t}}Z_{\mathrm{tw}}+s_{\mathrm{t}}Z_{\mathrm{ts}}\\ \varepsilon&=p_{\mathrm{t}}\varepsilon_{\mathrm{t}\lambda}+w_{\mathrm{t}}\varepsilon_{\mathrm{tw}}+s_{\mathrm{t}}\varepsilon_{\mathrm{ts}}\,, \end{aligned} \tag{62}$$

where $X_{\mathrm{t}\lambda}$, $Y_{\mathrm{t}\lambda}$, $Z_{\mathrm{t}\lambda}$ are tristimuli of a surface colour of the same dominant wavelength as the given colour, and $\varepsilon_{\mathrm{tw}}$ is one hundredth part of their sum; X_{tw}, Y_{tw}, Z_{tw} are tristimuli of the achromatic colour lighter than the given colour, and $\varepsilon_{\mathrm{tw}}$ is sum of their hundredth part; X_{ts}, Y_{ts}, Z_{ts}, and $\varepsilon_{\mathrm{ts}}$ are the same for an achromatic colour darker than the given colour.

Colours with identical numerical values for the CIE tristimulus Y are of the same Coloroid lightness. The numerical value of lightness is understood in the Coloroid system as ten times the square root of light density Y in the CIE XYZ system, that is:

$$V = 10\sqrt{Y}\,. \tag{63}$$

Numerical value of the Coloroid lightness of the colour is also obtained from:

$$\begin{aligned} V &= 10\sqrt{pY_\lambda + 100w}\,, \\ V &= 10\sqrt{p_t Y_{t\lambda} + w_t Y_{tw} + s_t Y_{ts}}\,, \end{aligned} \tag{64}$$

where Y_λ is tristimulus value of the Coloroid boundary colour with the dominant wavelength of the given colour; $Y_{t\lambda}$ is the tristimulus value of a colour of the same dominant wavelength but more saturated; Y_{tw} and Y_{ts} are tristimuli of achromatic colours lighter and darker, resp., than the given colour, while p, w, p_t, w_t, and s_t are Coloroid colour components.

It follows from what has been explained above, that there is an unambiguous correlation between the Coloroid and the CIE XYZ colour systems; that is, any point of the Coloroid colour space can be directly described in terms of CIE codes, by means of Coloroid codes of the given point of the colour space, and *vice versa*, CIE coordinates for any point of the colour space may be directly converted to Coloroid coordinates. Now this interconversion will be presented both ways.

Conversion from CIE XYZ to Coloroid system: given are x, y, Y, and we wish to calculate A, T, V. Using Eq. (58), Coloroid hue will be determined as:

$$\operatorname{tg}\varphi = \frac{y - y_0}{x - x_0}\,, \tag{65}$$

where x, y and x_0, y_0 are CIE coordinates of colour points of the given colour, and of the actual illuminant, respectively. φ corresponds to a definite A which has to be determined by linear interpolation from Table A.2 (Fig. 3.57).

Coloroid saturation is calculated by substituting into the first and second relationships of (59) the formulae (66) below, obtained by using the known relationship of the CIE

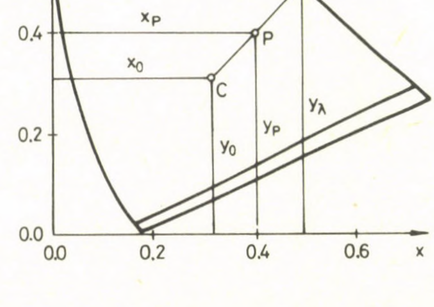


Fig. 3.57. To convert point P from CIE XYZ to the Coloroid system, coordinates of point P (x_p, y_p), of the neutral point C (x_o, y_o), and of the Coloroid boundary colour P_λ belonging to point P (x_λ, y_λ) are needed

XYZ system (see under 2.7.2) and Eq. (60), also taking into consideration Eq. (57):

$$X_\lambda = \frac{x_\lambda \varepsilon_\lambda}{100} \qquad X_w = \frac{x_0 \varepsilon_w}{100}$$
$$Y_\lambda = \frac{y_\lambda \varepsilon_\lambda}{100} \qquad Y_w = \frac{y_0 \varepsilon_w}{100}. \tag{66}$$

After substitution:

$$X = \frac{p x_\lambda \varepsilon_\lambda + w x_0 \varepsilon_w}{100}, \qquad Y = \frac{p y_\lambda \varepsilon_\lambda + w y_0 \varepsilon_w}{100}. \tag{67}$$

Substituting (66) and (61) into

$$x = 100 \frac{X}{\varepsilon} \qquad y = 100 \frac{Y}{\varepsilon} \tag{68}$$

obtained from the known CIE relationship results in the CIE coordinates of the given colour expressed by Coloroid colour mixing colour components, that is:

$$x = \frac{p x_\lambda \varepsilon_\lambda + w x_0 \varepsilon_w}{p \varepsilon_\lambda + w \varepsilon_w} \qquad y = \frac{p y_\lambda \varepsilon_\lambda + \varepsilon_w}{p \varepsilon_\lambda + w \varepsilon_w}. \tag{69}$$

Ordering the second equation in (59) for w, also considering (56) and (57):

$$w = \frac{Y - p Y_\lambda}{100} \tag{70}$$

then substituting w into (69) and ordering for p gives:

$$p = \frac{Y(x_0 \varepsilon_w - x \varepsilon_w)}{100(x \varepsilon_\lambda - x_\lambda \varepsilon_\lambda) + Y_\lambda (x_0 \varepsilon_w - x \varepsilon_w)}$$
$$p = \frac{Y(1 - y \varepsilon_w)}{100(y \varepsilon_\lambda - y_\lambda \varepsilon_\lambda) + Y_\lambda (1 - y \varepsilon_w)}. \tag{71}$$

Substituting (71) into (52) and considering (47) leads to Coloroid saturation:

$$T = 100 \frac{Y(x_0 \varepsilon_w - x \varepsilon_w)}{100(x \varepsilon_\lambda - x_\lambda \varepsilon_\lambda) + Y_\lambda (x_0 \varepsilon_w - x \varepsilon_w)}$$
$$T = 100 \frac{Y(1 - y \varepsilon_w)}{100(y \varepsilon_\lambda - y_\lambda \varepsilon_\lambda) + Y_\lambda (1 - y \varepsilon_w)}, \tag{72}$$

where x, y are colour coordinates of the given colour, Y is the tristimulus of the given colour; x_o is coordinate x of the colour point of the actual illuminant, x_λ, y_λ, are colour coordinates, and Y_λ is tristimulus of the Coloroid boundary colour with the dominant wavelength of the given colour, ε_w and ε_λ are hundredth parts of the sum of the actual illuminant, and of the sum of tristimuli of the Coloroid boundary colour, resp., to be determined by linear interpolation from Table A.2.

Coloroid lightness may be obtained from (63).

As an illustration of Coloroid to CIE conversion, let A, T, V be given, from which x, y, Y have to be calculated. Ordering (72) for x and for y yields:

$$x = \frac{100\,Y\varepsilon_w x_0 + 100\,T\varepsilon_\lambda x_\lambda - TY_\lambda \varepsilon_w x_0}{100\,T\varepsilon_\lambda - TY_\lambda \varepsilon_w + 100\,Y\varepsilon_w}$$
$$y = \frac{100\,Y + 100\,T\varepsilon_\lambda y_\lambda - TY_\lambda}{100\,T\varepsilon_\lambda + 100\,T\varepsilon_w\,Y_\lambda + 100\,\varepsilon_w\,Y}\,. \qquad (73)$$

Expressing Y from (63) and substituting into (73):

$$x = \frac{\varepsilon_w x_0 (V^2 - TY_\lambda) + 100\,T\varepsilon_\lambda x_\lambda}{\varepsilon_w (V^2 - TY_\lambda) + 100\,T\varepsilon_\lambda}$$
$$y = \frac{V^2 + 100\,T\varepsilon_\lambda y_\lambda - TY_\lambda}{\varepsilon_w (V^2 + TY_\lambda) + 100\,T\varepsilon_\lambda}\,, \qquad (74)$$

where T, V are Coloroid characteristics of the given colour, x_0 is coordinate x of the actual illuminant, x_λ, y_λ are coordinates, Y_λ is tristimulus of the Coloroid boundary colour with the dominant wavelength of the given colour, ε_w and ε_λ are hundredth parts of the sums of the actual illuminant, and of the tristimuli of the Coloroid boundary colour, respectively.

Tristimulus Y is obtained from (63):

$$Y = \left(\frac{V}{100}\right)^2. \qquad (75)$$

Relationships, similarities and differences between CIE XYZ and Coloroid colour systems may be illustrated by graphically representing lightnesses and saturations of basic colours of the Coloroid colour space and of the most saturated colours of the Coloroid colour solid, using symbols of both colour systems.

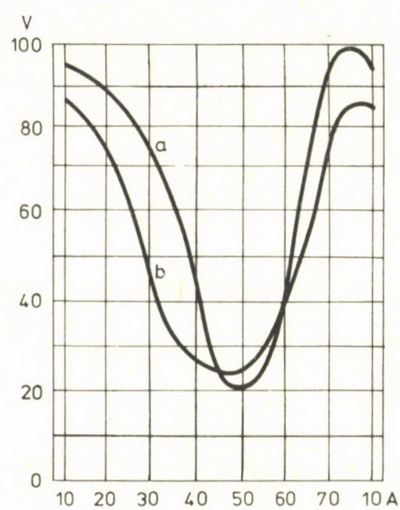


Fig. 3.58. Coloroid lightnesses of Coloroid basic colours (a), and of the most saturated colours (b) of the Coloroid colour solid

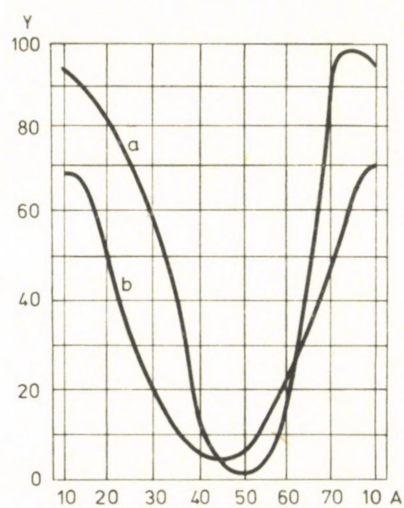


Fig. 3.59. CIE Y tristimuli of Coloroid basic colours (a) and of the most saturated colours (b) in the Coloroid colour solid

Numerical values of Coloroid lightnesses and of the CIE Y tristimuli of colour circle colours of the Coloroid colour space, furthermore, of the most saturated colours in the Coloroid colour solid were plotted in Figs 3.58 and 3.59, respectively. Figure 3.60 shows Coloroid saturations of colours of the Coloroid colour space, and of the Coloroid colour solid, while in Fig. 3.61, numerical values of the Helmholtz excitation purity p_c are seen. From the diagram it becomes apparent that deviations between V and Y values for the same colour are linear, while between T and p values they are not.

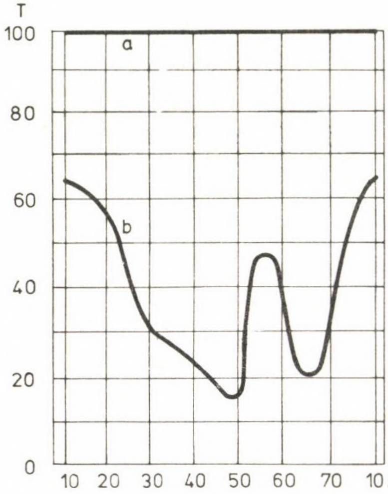


Fig. 3.60. Coloroid saturations of Coloroid basic colours (a) and of the most saturated colours (b) in the Coloroid colour solid

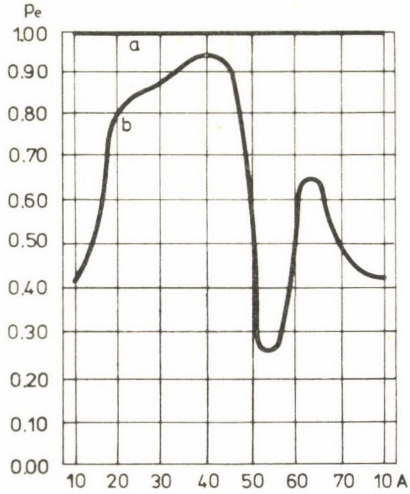


Fig. 3.61. Colour contents (P_e) of Coloroid basic colours (a) and of the most saturated colours (b) in the Coloroid colour solid

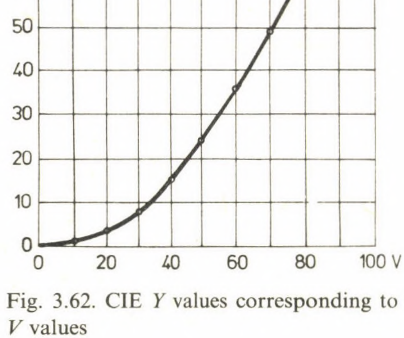


Fig. 3.62. CIE Y values corresponding to Coloroid V values

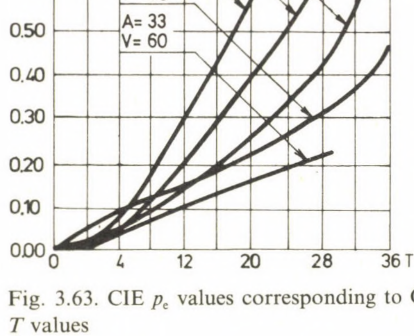


Fig. 3.63. CIE p_e values corresponding to Coloroid T values

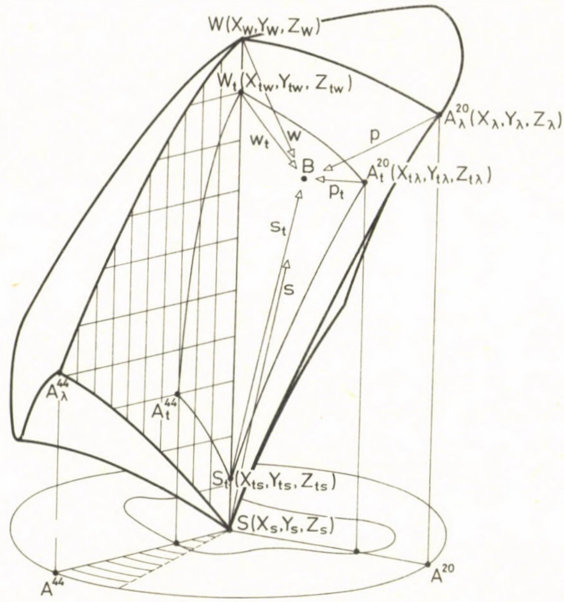


Fig. 3.64. From the 3D model of the Coloroid colour system, the part confined by axial sections for hues A20 and A44 has been removed. On both axial sections, sites of the most saturated surface colours $A20_t$ and $A44_t$ corresponding to the hues of the axial sections are indicated. Also boundary curves joining these points, confining surface colours in the axial sections are shown. Horizontal, and vertical lines of the mesh in the Coloroid half-plane for hue $A44$ accommodate colours of equal lightnesses, and saturations, respectively. Legend: B is an arbitrary colour in the Coloroid half-plane of basic hue $A20$; W and S are Coloroid absolute white and black, with CIE tristimuli X_w, Y_w, Z_w, and X_s, Y_s, Z_s, respectively; $A20_\lambda$ is Coloroid boundary colour defining the hue of Coloroid half-plane $A20$ including colour B; X_λ, Y_λ, Z_λ are CIE tristimuli of Coloroid boundary colour $A20_\lambda$; if we wish to describe colour B as an additive mix from $A20_\lambda$, W and S, p is the percentage of $A20_\lambda$ in the mix, w and s are percentages of Coloroid white and black, respectively, W_t and S_t are colours of practically available achromatic surfaces lighter and darker, respectively, than colour B, with CIE tristimuli X_{tw}, Y_{tw}, Z_{tw}, and X_{ts}, Y_{ts}, Z_{ts}, respectively; $A20_t$ is a surface colour of CIE tristimuli $X_{t\lambda}$, $Y_{t\lambda}$, $Z_{t\lambda}$ in the hue plane $A20$ more saturated than colour B, practically available for the display by additive mixing of colour B. Coloroid colour component p_t for practical colour mixing is percentage in the mix of a surface colour of the same dominant wavelength as that of the surface colour to be mixed, but more saturated than it is. Coloroid colour components w_t and s_t for practical colour mixing are percentages of achromatic surface colours lighter, and darker, respectively, than the surface colour to be mixed

Figures 3.62 and 3.63 show Y values corresponding to some V values, and p_c values pertinent to some T values, respectively. Clearly, for every saturation or every hue, a single Y value corresponds to any V value, while for every T value there are several p_c values, depending on hue and saturation.

Finally, in Fig. 3.64 derivation of colours of the Coloroid colour system from tristimuli of the CIE XYZ system is demonstrated.

3.3.5. Definitions of the Coloroid Colour System for Different Standard Illuminations

The colour of a given colour sample is perceived as different, when observed under different illuminations. Both Coloroid and CIE *XYZ* coordinates of a colour sample are illumination-dependent. Therefore, before specifying the coordinates of a sample, it has to be decided what illumination they should refer to. When displaying a colour given by its Coloroid or CIE *XYZ* codes it has to be known at what illumination these data are valid.

Relationships of the Coloroid colour system may be applied for any illumination. Practically, definition has to refer to an illumination available, and needed for the given task. For instance, working in, or developing a composition for, an environment illuminated by incandescent light, Coloroid is referred to standard light source "A". For colour composition, colour mixing or creation of colour harmony complexes at skylight, Coloroid definition for standard light source "C" is valid. Outdoors, data specified for standard light source "D65" prevail.

Subsequent data for absolute white and absolute black refer to standard illuminations "A", "C" and "D65". Other data for standard illuminations "C" and "D65" were compiled in Tables A.1 and A.2.

Standard illumination "A":

$$\begin{aligned} x_w &= x_s = x_0 = 0.447573 \\ y_w &= y_s = y_0 = 0.407439 \\ \varepsilon_w &= 2.454352\,. \end{aligned} \tag{76}$$

Standard illumination "C":

$$\begin{aligned} x_w &= x_s = x_0 = 0.310063 \\ y_w &= y_s = y_0 = 0.316158 \\ \varepsilon_w &= 3.162955\,. \end{aligned} \tag{77}$$

Standard illumination "D65":

$$\begin{aligned} x_w &= x_s = x_0 = 0.312726 \\ y_w &= y_s = y_0 = 0.329023 \\ \varepsilon_w &= 3.039296\,. \end{aligned} \tag{78}$$

3.4. Coloroid Colour Codes in Design Practice

In architectural design practice, Coloroid colour codes expressing relations between colour sensations may have various uses.

These codes represent unambiguous definition of every colour, and enable the user to imagine the colours and arrive at a fairly exact assessment of their environment. The code system permits recognition of colour relations—a decisive factor in colour design.

It is easy to assign numerical values to Coloroid codes describing colour-to-man and colour-to-man-to-environment relations, helping thereby the development of simple colour design methods.

In actual building work the use of Coloroid codes affect economic parameters, such as use of paints and other products colour-rated by codes to help to respect colour design specifications. Colour mixing relationships in terms of these codes may reduce paint expenditures, and since they reflect visually the colour rate, they simplify colour adjustment. They may be of use to define numerically deviations from planned colours.

Codes also assist in visually displaying the colour grade specified numerically in the plan, by means of a specially designed instrument Colour samples with codes enable to check fading and soiling in use by means of a device developed for this purpose.

3.4.1. Colour Rating

Uniform variation of codes leads to uniform variation of the colour grade. Since they refer to perceptional colour components they meet the requirement of the construction industry that perceptional colour rating should be expressible.

It is a feature of these codes that they present evenly perceptional variations along all three colour coordinates of sensation, adopting the principle of uniform quality steps in colour rating. This code system facilitates the categorization of a colour as a function of perceptional distance from another given colour.

A detail of the Coloroid 3D model is seen in Fig. 3.65, indicating the range of tolerance of nominal colour P in the plane for hue $A=12$. An area can be marked out, within the colour plane, in the surrounding of the specified point, within which the difference is small enough to be hardly perceptible, and also aesthetically negligible. As the area increases, the deviation also increases. A tolerance domain definable by a plane figure around point P can be assigned to a constant value of coordinate A. Of course,

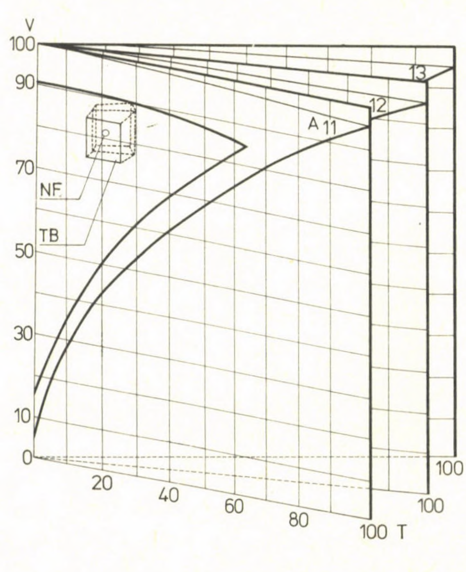


Fig. 3.65. Tolerance domain (TB) of a nominal colour (NF) in the Coloroid colour system

coordinate A can also be kept at its nominal value. Also the hues in the plane sections of the 3D model near $A=12$ vary proportionally with the distance from the given plane.

Thus, cylindrical coordinate surfaces separated by small hue differences can be determined. Consequently in the surrounding of the given nominal point, tolerance domains corresponding to colour grade categories may be defined.

A purposeful measurement program may decide on the domains to be marked from the area of colours applied for a given product in order to meet quality requirements.

3.4.2. Recording of Colour Design Data

In colour design, often different kinds of colour requirements have to be set for the whole design or concerning some of its colour bearing surfaces. E.g. in making colour designs for a row of houses in a street, colour demands suiting the styles and functions of individual buildings have to be described. Moreover, if one wishes to harmonize these two aspects of style and function and also demands arising from the orientation and dimensions of the buildings, it is advisable to operate with colour domains which can be easily realized and visually compared, rather than with actual colours. For instance, let us say that townscape aspects would suggest that a given house should be painted to some shade of moss, cactus or almond green, whereas from an historical point of view lavender green would be the colour of choice. Functionally any unsaturated colour

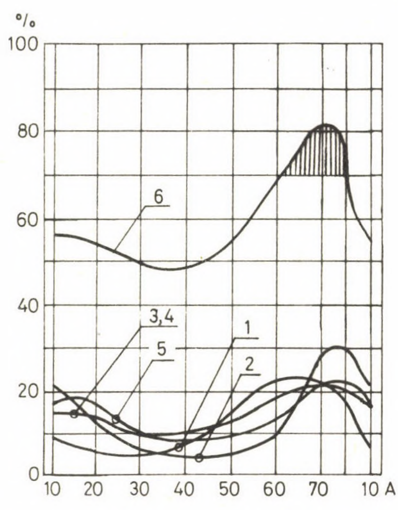


Fig. 3.66. Chart for hues to be applied as façade colours for the house Nr. 8, Táncsics Mihály street in the Buda Castle district, according to different aspects of design, here, for Coloroid hues of the colours. Colour suggestions are based on townscape aspects (curve 1), historical aspects (curve 2), function (curve 3), orientation and size of the building (curves 4 and 5 resp.) All these aspects were combined in curve 6. It is advised to select hues from the shaded area

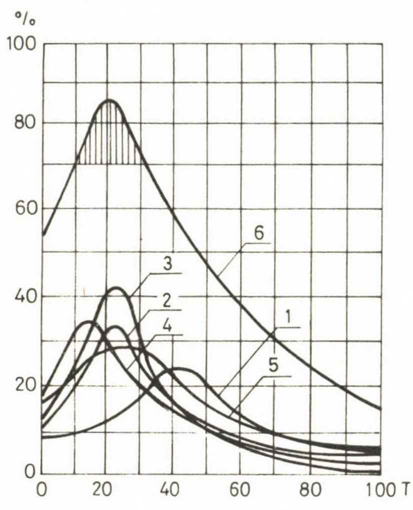


Fig. 3.67. Chart for the Coloroid saturations of façade colours for the house in Fig. 3.66, according to different aspects of design. (Notations as in Fig. 3.66.) It is advised to select saturations from the shaded area.

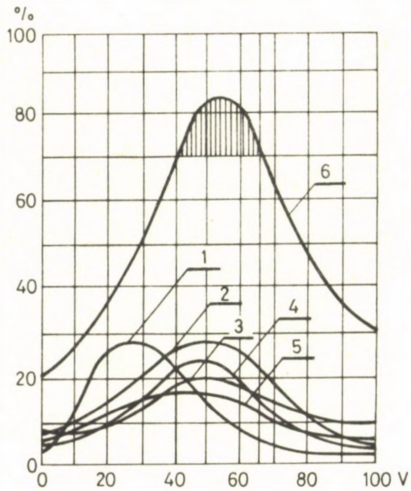


Fig. 3.68. Chart for Coloroid lightnesses of façade colours for the house in Fig. 3.66, according to different aspects of design. (Notations as in Fig. 3.66.) It is advised to select lightnesses from the shaded area

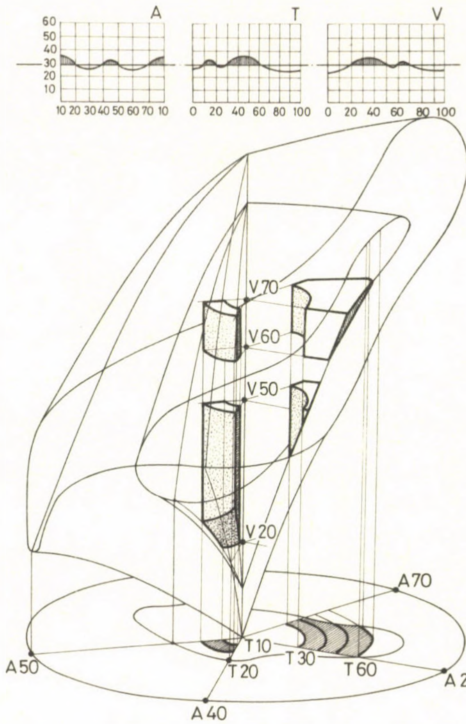


Fig. 3.69. Horizontal axes of diagrams in the top show Coloroid hue scale (A), saturation scale (T), and lightness (V) scale, in this order, while vertical axes show preference percentages in design, summarized according to different aspects. Shaded areas above the curves define domains for hue (A), saturation (T), and lightness (V) for the designed colours of the construction. These three diagrams permit to distinguish between regions of the Coloroid colour solid. The colour designer is expected to select from colours contained in these regions, clearly delimited in this figure

would suit—according to its orientation a rather cold and broken shade, and finally because of its dimensions, a moderate, not too dark colour. In terms of colour sensation parameter intervals, these requirements can be set out (all in Coloroid notation) as follows:

Townscape aspects impose colours of hue 65 to 72, lightness 15 to 25, saturation 40 to 50; historical aspects hue 70 to 76, saturation 5 to 25, lightness 45 to 50; functional aspects hue 10 to 76, saturation 5 to 30, lightness 10 to 80; and lastly dimensional aspects hues 10 to 25 and 55 to 76, saturation 10 to 30, and lightness 35 to 80, selected so as to cope with every aspect. The next step consists in summing up each of the colour sensation parameter intervals. This can easily be done graphically, as seen in Figs 3.66, 3.67 and 3.68 showing, as an example, colour ranges for a building in the Buda Castle district.

Envelope curves for graphs of different requirements suggest taking some medium light (V40 to 65), very broken (T10 to 30) green (A60 to 75) for the given house.

As a conclusion, colour ranges delimited for quantified colour design features and demands inside the Coloroid colour solid are shown in Fig. 3.69.

3.4.3. Principles and Tools for Colour Display

In the everyday practice of colour design, different colour sets, colour collections representing certain domains of the colour space, and exact data of these colour collections are needed. All of these requirements can be met by our system, in accordance with relationships outlined above.

First, a small electromotor driven by a 4.5 V battery, revolving at about 2500 rpm is needed. Discs are mounted on its axle for producing additive mixes of the desired colour when revolved. A tempera painted copy of the colour appearing on the revolving disc can then be added to our colour collection. Now, let us display first a colour given by its coordinates A, V, T, requiring two colour discs of hues well approximating to the hue of the colour to be displayed from either side of the hue scale, as well as white and black discs (Figs 3.70, 3.71, 3.72). Data of the discs provided with this book may be taken from the disc backs.

For display we need to know the data of colours entering the mix, and to determine

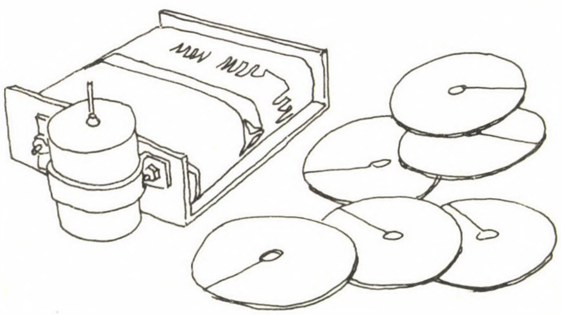


Fig. 3.70. Tools for colour display by a Maxwell disc

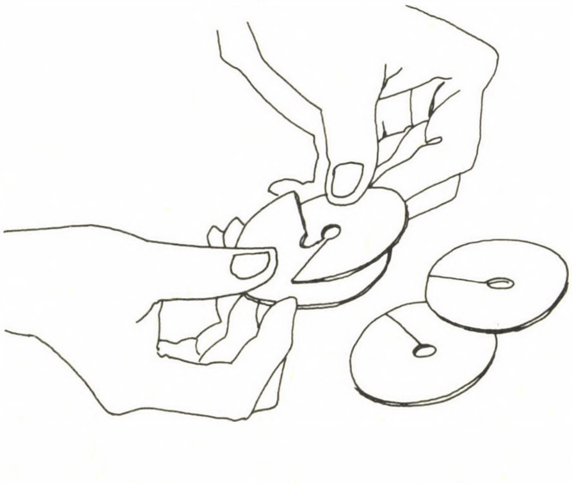


Fig. 3.71. First, the two coloured discs are applied to adjust the $\bar{p}_t$ value: $\bar{p}_t = \bar{p}_{t1} + \bar{p}_{t2}$

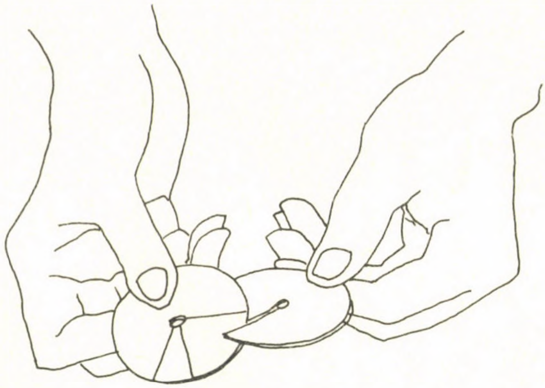


Fig. 3.72. Lastly, $\bar{s}_t$ is set by means of the black disc: $\bar{p}_t + \bar{w}_t + \bar{s}_t = 100$

Coloroid colour components, the p, w, s values and percentages of the colour to be displayed:

$$\begin{aligned} \bar{p} &= 100p, \qquad \bar{w} = 100w, \qquad \bar{s} = 100s \\ \bar{p}_t &= 100p_t, \qquad \bar{w}_t = 100w_t, \qquad \bar{s}_t = 100s_t. \end{aligned} \tag{79}$$

To become acquainted with all the relationships to follow, let us assume that the CIE XYZ tristimuli of the colours to enter the mix are known, and compute from them their Coloroid coordinates, as well as the CIE XYZ coordinates of the colour to be mixed. CIE tristimuli on the four discs applied for mixing are:

— for the colour of a hue deviating in one direction from the hue of the colour to be mixed: X_1, Y_1, Z_1;

— for the colour of a hue deviating in the other direction from the hue of the colour to be mixed: X_2, Y_2, Z_2;

— for white: X_w, Y_w, Z_w;

— for black: X_s, Y_s, Z_s.

Hence CIE XYZ coordinates for these colours are:

$$\begin{aligned} x_1 &= \frac{X_1}{X_1+Y_1+Z_1} \qquad x_2 = \frac{X_2}{X_2+Y_2+Z_2} \\ y_1 &= \frac{Y_1}{X_1+Y_1+Z_1} \qquad y_2 = \frac{Y_2}{X_2+Y_2+Z_2} \end{aligned} \tag{80}$$

Colour coordinates of white and black discs depending on the illumination are given by (76), (77) and (78).

CIE XYZ coordinates of the fictitious colour with the dominant wavelength of the colour to be mixed from colours with CIE coordinates x_1, y_1, and x_2, y_2, sufficient in itself, together with white and black, for mixing the colour indicated with coordinates A, T, V will be:

$$\begin{aligned} x_t &= \frac{y_\lambda - m_2 x_\lambda + m_1 x_1 + y_1}{m_2 - m_1} \\ y_t &= \frac{y_1 \dfrac{m_2}{m_1} + m_2(x_\lambda - x_1) - y_\lambda}{\dfrac{m_2}{m_1} - 1}, \end{aligned} \tag{81}$$

where m_1 and m_2 result from

$$m_1 = \frac{x_1 - x_2}{y_1 - y_2} \qquad m_2 = \frac{x_0 - x_\lambda}{y_0 - y_\lambda}, \tag{82}$$

where x_λ and y_λ are coordinates of the Coloroid boundary colour of the dominant wavelength of the wanted colour.

Coloroid hues of the two coloured discs entering the mix are obtained as:

$$\begin{aligned} \operatorname{tg} \varphi_1 &= \frac{y_1 - y_0}{x_1 - x_0} \qquad & \operatorname{tg} \varphi_2 &= \frac{y_2 - y_0}{x_2 - x_0} \\ \operatorname{ctg} \varphi_1 &= \frac{x_1 - x_0}{y_1 - y_0} \qquad & \operatorname{ctg} \varphi_2 &= \frac{x_2 - x_0}{y_2 - y_0} \end{aligned} \tag{83}$$

and

$$A_1 = f(\operatorname{tg} \varphi_1) \qquad A_2 = f(\operatorname{tg} \varphi_2)\,. \tag{84}$$

Let us now determine Coloroid saturations of the two colour discs entering the mix, as well as that of a fictitious disc sufficient in itself to display—with white and black—the wanted colour:

$$T_1 = 100 p_1, \qquad T_2 = 100 p_2, \qquad T_t = 100 p_t \tag{85}$$

p_1, p_2 (for colours really entering the mix) and p_t (fictitious) are obtained from:

$$\begin{aligned} p_{1x} &= \frac{Y_1(x_0 \varepsilon_w - x_2 \varepsilon_w)}{100(x_1 \varepsilon_\lambda - x_\lambda \varepsilon_\lambda) + Y_\lambda (x_0 \varepsilon_w - x_1 \varepsilon_w)} \\ p_{2x} &= \frac{Y_2(x_0 \varepsilon_w - x_2 \varepsilon_w)}{100(x_2 \varepsilon_\lambda - x_\lambda \varepsilon_\lambda) + Y_\lambda (x_0 \varepsilon_w - x_2 \varepsilon_w)} \\ p_{tx} &= \frac{Y_t(x_0 \varepsilon_w - x_t \varepsilon_w)}{100(x_t \varepsilon_\lambda - x_\lambda \varepsilon_\lambda) + Y_\lambda (x_0 \varepsilon_w - x_t \varepsilon_w)} \\ p_{1y} &= \frac{Y_1(1 - y_1 \varepsilon_w)}{100(y_1 \varepsilon_\lambda - y_\lambda \varepsilon_\lambda) + Y_\lambda (1 - y_1 \varepsilon_w)} \\ p_{2y} &= \frac{Y_2(1 - y_2 \varepsilon_w)}{100(y_2 \varepsilon_\lambda - y_2 \varepsilon_\lambda) + Y_\lambda (1 - y_2 \varepsilon_w)} \\ p_{ty} &= \frac{Y_t(1 - y_t \varepsilon_w)}{100(y_t \varepsilon_\lambda - y_\lambda \varepsilon_\lambda) + Y_\lambda (1 - y_t \varepsilon_w)}\,. \end{aligned} \tag{86}$$

For $-1 < \operatorname{tg} \varphi < +1$, formulae for p_x, and for $-1 < \operatorname{ctg} \varphi < +1$, those for p_y are applied. ε_w is any of (77), (78), or (79), depending on the light source and ε_λ the hundredth part of the sum of components of the Coloroid boundary colour with the dominant wavelength of the colour to be mixed.

The next step is the determination of Coloroid lightnesses of the two colour discs needed for colour display, as well as that of a fictitious disc colour, made by additively mixing them and having the same hue as the wanted colour:

$$V_1 = 10\sqrt{Y_1}\,, \qquad V_2 = 10\sqrt{Y_2}\,, \qquad V_t = 10\sqrt{Y_t}\,, \tag{87}$$

where Y_t results from:

$$Y_t = \vartheta Y_1 + (1-\vartheta) Y_2 , \tag{88}$$

where ϑ is the percentage of the surface of light density Y_1 needed to obtain a surface of light density Y_t by additively mixing surfaces with light densities Y_1 and Y_2.

ϑ is obtained as:

$$\vartheta = \frac{\varepsilon_2(x_2 - x_t)}{\varepsilon_1(x_t - x_1) + \varepsilon_2(x_2 - x_t)}, \tag{89}$$

where ε_1 and ε_2 are hundredth parts of sums of tristimuli X_1, Y_1, Z_1 and X_2, Y_2, Z_2, respectively.

Now, it only remains to determine the value of one hundred times the Coloroid colour components of the colour to be displayed, that is, disc area percentages and CIE XYZ coordinates of colours entering the mix:

$$\begin{aligned}
\bar{p}_t &= 100\frac{T}{T_t}, \quad \bar{p}_1 = \bar{p}_t\vartheta, \quad \bar{p}_2 = \bar{p}_t(1-\vartheta) \\
\bar{w}_t &= \frac{\bar{p}_t(Y_s - Y_t) + 100\left(\dfrac{V}{10}\right)^2 - 100\,Y_s}{Y_w - Y_s} \\
\bar{s}_t &= 100 - (\bar{p}_t + \bar{w}_t) \\
x &= \frac{\varepsilon_w x_0 (V^2 - TY_\lambda) + 100\,T\varepsilon_\lambda x_\lambda}{\varepsilon_w(V^2 - TY_\lambda) + 100\,T\varepsilon_\lambda} \\
y &= \frac{V^2 + 100\,T\varepsilon_\lambda y_\lambda - TY_\lambda}{\varepsilon_w(V^2 - TY_\lambda) + 100\,T\varepsilon_\lambda}.
\end{aligned} \tag{90}$$

In common practice, a hundred times the Coloroid colour components may be determined by means of nomographs such as those in Appendices A4 and A5 to this

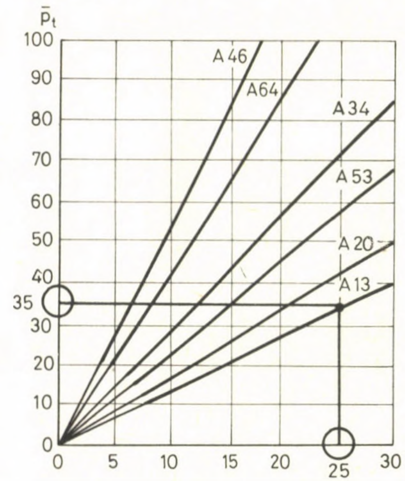


Fig. 3.73. Determination of Coloroid colour components of the colour with Coloroid codes 13–25–80. As a first step, p_t for $T=25$ is determined on the proper nomograph. This percentage (35) is adjusted on the colour disc

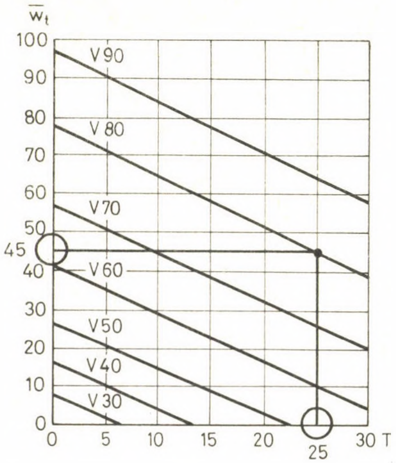


Fig. 3.74. Determination of Coloroid colour components of the colour with Coloroid codes 13–25–80. As the second step, $\bar{w}_t$ for the given $T=25$ will be determined on the proper nomograph. This percentage (45) is set on the white disc, while the percentage to be adjusted on the black disc will be $100-(35+45)=20$

book. These nomographs can be used in colour mixing by means of fifty colour discs also given with this book. The nomographs are to be used as follows: First, according to the Coloroid saturation of the colour to be displayed, from the set of nomographs in Figs A4.1–4.4 the value of $\bar{p}_t$ is taken from the one agreeing by hue. $\bar{p}_t$ shows the percentage of the disc with the hue of the wanted colour to cover the Maxwell disc area so as to produce the given colour (Fig. 3.73). White percentage $\bar{w}_t$ for the mix is read off the given nomograph in the set according to saturation and lightness (Fig. 3.74). Black percentage in the mix is given by $\bar{s}_t=100-\bar{p}_t-\bar{w}_t$.

The disc accordingly composed is spun, the resulting colour is copied, taking care to respect specifications on observation and illumination geometries, as well as on illumination intensity and colour temperature given in the Chapter on Colorimetry. Also when they are compared the revolving disc and the copy should be about flush and directly contacting each other, and comparison should be made after drying.

3.4.4. Principles and Tools for Colour Determination

Coloroid colour components may be applied for the simple colorimetry of a colour without expensive instruments, i.e. for the determination of its Coloroid and CIE XYZ coordinates. In this case, Coloroid colour components are known and colour coordinates are calculated therefrom.

Let us select a disc (from the fifty in this book) with chromatic data such that its hue should be the same as that to be measured. Thereafter, using a white and a black disc, attemps are made to adjust percentages on the discs until the spinning disc displays the colour to be measured. Now, reading the adjusted percentages ($\bar{p}_t$, $\bar{w}_t$, $\bar{s}_t$), their hundredth parts yield Coloroid colour components p_t, w_t, s_t of the measured colour, from which the wanted colour coordinates are obtained by means of the formulae below.

First, Coloroid coordinates are determined. Coloroid hue, i.e. the A value of the colour to be measured will equal that of the colour disc applied in mixing. Coloroid saturation is given by:

$$T = p_t T_t \,, \tag{91}$$

where T_t is the Coloroid saturation of the colour disc.

Coloroid lightness is obtained as:

$$V = 10\sqrt{p_t Y_t + w_t Y_w + s_t Y_s} \,, \tag{92}$$

where Y_t, Y_w and Y_s are radiance factors of the colour disc, white, and black discs, respectively.

CIE XYZ coordinates of the colour results from:

$$\begin{aligned} x &= \frac{p_t x_\lambda \varepsilon_\lambda + \varepsilon_w x_0 w_t}{p_t \varepsilon_\lambda + \varepsilon_w w_t} \\ y &= \frac{p_t y_\lambda \varepsilon_\lambda + w_t}{p_t \varepsilon_\lambda + \varepsilon_w w_t} \\ Y &= p_t Y_t + w_t Y_w + s_t Y_s \,, \end{aligned} \tag{93}$$

where ε_w, x_0 result, depending on illumination, from either of (76), (77) or (78), x_λ, y_λ are CIE coordinates of the Coloroid boundary colour referring to the measured colour, while ε_λ is the hundredth part of the sum of CIE tristimuli of the Coloroid boundary colour of the measured colour.

These data, depending on the Coloroid A value of the colour, are obtained by linear interpolation from Table A.2.

If a disc of the same hue as that of the measured colour is not available, mixing is done as described above, but using two discs instead of one. Hues of the two discs should if possible approximate to that of the measured colour from two opposite directions on the hue scale. Relative proportions of the two disc surfaces have to be corrected by trial and error until their additive mix results in the hue of the colour to be specified.

Additive mixing of the colour to be measured by adjustment of colour, white and black percentages may be facilitated by a simple device. Any proportion of areas of two adjacent colours, as well as of white and black serving as components of additive colour mixing may be adjusted by manipulating discs or rings on the measuring surface of the device which acts as a secondary light source. In this instrument, a common light source illuminates the surface to be measured and a surface of the same area, but assembled from surfaces of the two colours and white and black in variable proportions. The resultant colour produced by diffuse spectral mixing of the light reflected from the measuring surface may then be varied.

Colour matching is carried out under illumination by a single light source built into in the device, ensuring that all light paths are perfectly identical. During the experiment both measured and reference surfaces reflect under identical conditions. Light paths are devised so as to permit the measurement of both dull and bright surfaces (Fig. 3.75).

The colour to be measured is placed under the aperture of the instrument, light is switched on and looking into the instrument, the measured colour appears in one half of the visual field. The colour appearing in the other half field is adjusted by moving the instrument scales until it equals its counterpart. First the colour scale is moved to adjust the hue. Thereafter white and black surfaces are slid before the aperture so as to

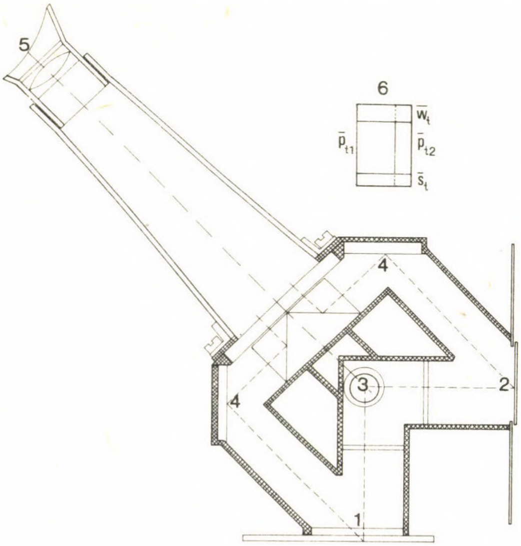


Fig. 3.75. Scheme of optical colour mixing. (1. surface to be measured, 2. measuring surface, 3. light source, 4. diffuse mirrors, 5. eyepiece, 6. orthogonal view of the measuring surface, with surface percentages $\bar{w}_t$, $\bar{p}_{t1}$, $\bar{p}_{t2}$ and $\bar{s}_t$ entering the mix)

approximate saturation and lightness of the measured colour. First, the hue of the mixed colour is improved by modifying colour surfaces; secondly, saturation and lightness are adjusted by modifying white and black, until the two colours perfectly match. Finally percentages, i.e., Coloroid colour components, are read off the scales, and used to calculate the colour coordinates using the formulae above.

3.4.5. Making Colour Scales

In colour design practice, the designer is often faced with problems requiring colour scales of special intervals not found in colour collections, if only to be able visually to check his ideas. Or, colour scales are to be constructed so as to cope with colour features of a given building or surfacing materials to be used in colour composition. Making such scales will be illustrated below, relying on relationships in the previous sections. In every example determination of Coloroid colour components needed for producing scale members by additive mixing will be presented. Scale members may be displayed on Maxwell discs or otherwise, e.g. by optical mixing using the equipment in Fig. 3.75. Tempera paint copying of the displayed colour will be made as described above.

Example 1. A uniform gray scale with small intervals is needed, so as to have 12 steps between a floor of Coloroid lightness 13, and a ceiling of Coloroid lightness 56 for some surfaces to be kept achromatic. First, Coloroid colour components of the wanted gray scale's first member, of the floor lightness, are determined as:

$$w_t = \frac{Y_{g1} - Y_s}{Y_w - Y_s} \qquad s_t = 1 - w_t\,, \tag{94}$$

where Y_{g1} is CIE tristimulus of the first member in the gray scale, Y_s and Y_w are CIE tristimuli of black and white surfaces, respectively, entering the mix.

CIE tristimulus Y is obtained from Coloroid lightnesses V according to (75).

Coloroid colour components of member n of the gray scale consisting of 12 members is obtained by transforming the formula for w_t above as:

$$w_t = \frac{Y_{gn} - Y_s}{Y_w - Y_s} \tag{95}$$

where

$$Y_{gn} = Y_{gl} + (n+1)\,Y_i \tag{96}$$

Y_i results from:

$$Y_i = 10\sqrt{\frac{\sqrt{Y_1} - \sqrt{Y_{12}}}{12}}\,. \tag{97}$$

Discs are adjusted according to (79).

Example 2. Scales are to be constructed for different hues, or members with equal Coloroid lightnesses and with Coloroid saturations uniformly increasing, by e.g. steps of four Coloroid saturation grades within every hue. Members of every hue scale are equidistant colours at the intersection of a Coloroid colour plane by a horizontal plane normal to the axis. In the optimum case, colours of each scale may be mixed from three colour discs for every hue: a colour disc, a white disc, and a black disc. Scales according to example 2 are seen in Fig. C28. Every colour in a scale of a row in this figure has equal hue and lightness. Saturations of scale members uniformly increase within different limits. Scale members may be displayed with the aid of nomographs in this book and the discs annexed. To display colour in the top row, let us select the disc for Coloroid hue 10, as well as a white and a black disc. Colour disc percentages to be adjusted on the Maxwell disc for additive mixing can be read off nomograph A.4. Readings are those Coloroid colour component percentages p_t with which colours of different saturations in the scale can be produced. Thereafter percentages w_t of the Coloroid component white will be read off nomograph A.5. s_t values are calculated according to (90).

Example 3. Next, scales of different hues, equal Coloroid saturations and uniformly varying Coloroid lightnesses are needed. Members of these scales will lie at intersection lines of Coloroid colour planes and a cylindrical surface representing colours of equal saturations. Such scales are seen in Fig. C29. Similarly as for the example above, its construction applied the nomographs, and colour discs of this book. Coloroid colour components of any member in the scales result from:

$$p_t = \frac{T_a}{T_t}$$

$$w_t = \frac{p_t(Y_s - Y_t) + \left(\frac{V_a}{10}\right)^2 - Y_s}{Y_w - Y_s} \tag{98}$$

$$s_t = 1 - (p_t + w_t)\,,$$

where T_a and T_t are Coloroid saturations of the colour to be displayed, and of the colour disc, respectively, V_a is Coloroid lightness of the colour to be displayed; Y_t, Y_w and Y_s are CIE tristimuli of the colour, white and black surfaces, respectively, used for display. Discs are adjusted according to (79).

Example 4. Scales of colours on the boundary of the Coloroid colour solid are needed.

Peripheral scales of equal hues are easy to obtain. They may be either of two kinds. One is a scale of decreasing saturation and increasing ligtness, which can be obtained by mixing white to the saturated colour. Scale members are uniformly distributed along the intersection line between a Coloroid colour plane and the Coloroid colour solid, at the boundary curve of surface colours. A peripheral scale of decreasing saturation and increasing lightness is shown in Fig. C30. Scale colours are simply obtained by mixing a coloured surface of the hue pertinent to the colour plane of the scale with a white surface.

As the first step of the display, either lightnesses of the scale colours for uniformly varying saturations or saturations for uniformly varying lightnesses have to be determined using:

$$\frac{T_R}{T_t} + \frac{-T_R Y_t + T_t\left(\frac{V_R}{10}\right)^2}{T_t Y_w} = 1\,, \tag{99}$$

where T_R, V_R are Coloroid coordinates of the colour to be displayed; T_t, Y_t are Coloroid saturation and CIE tristimulus of the colour surface applied for display; Y_w the CIE tristimulus of the white surface for display.

In knowledge of Coloroid coordinates of the equidistant boundary points, Coloroid colour components of each scale colour are obtained from relationships already known.

Example 5. An unknown complementary of a given colour can be determined as shown in Fig. C31. Columns 1 to 7 show consecutive steps of the procedure. In column 1 it is assumed that the complementary of the given blue is lemon. Mixing of these two colours in any proportion on the Maxwell disc does not produce, however, medium gray. Yellow is to be modified toward orange until in a certain proportion it leads to gray as shown by the fifth column. Thus, the complementary of the given colour is orange of the shade shown in our figure. Balanced complementaries are obtained by reducing the saturation of one of the colours—observing columns 6 and 7—until the two colours mixed in equal proportions result in gray.

Example 6. Two surfaces in an interior have given colours. The colours are of the same hue, but of significantly different saturations and lightnesses. The designer makes use of these features by applying colours of the same hue in the entire room to create a special colour mood based on a single hue.

Let the given colour be expressed as:

$$F_a(A,\ T_a,\ V_a); \qquad F_b(A,\ T_b,\ V_b)\,. \tag{100}$$

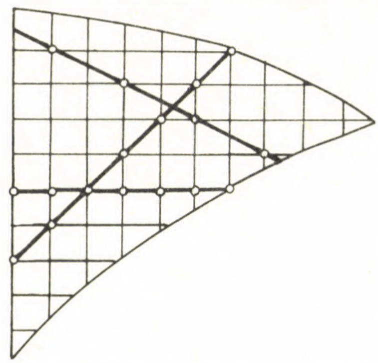
The designer intends to apply further n colours in the interior. According to his artistic intention, these n colours are to be assembled so as to have saturations and lightnesses ranging between those of the given two colours, thus, to constitute—with the two given colours—a harmonic scale.

It will be seen later that, in general, colours along straight lines in the Coloroid colour plane are felt to be harmonic (Fig. 3.76).

Saturation and lightness differences between the $(n+2)$ members of the scale to be created are, for $T_b > T_a$ and $V_b > V_a$:

$$q_T = \frac{T_b - T_a}{n}\,, \qquad q_V = \frac{V_b - V_a}{n}\,. \tag{101}$$

Fig. 3.76. In any Coloroid colour plane, colours along the straight lines are felt to harmonize



Coloroid codes of the scale members are:

$$
\begin{aligned}
&F_a(A,\ T_a,\ V_a)\\
&F_{a+1}\ (A,\ T_a+q_T,\ V_a+q_V)\\
&F_{a+2}\ (A,\ T_a+2q_T,\ V_a+2q_V)\\
&\vdots\\
&F_{a+n}\ (A,\ T_a+nq_T,\ V_a+nq_V)\\
&F_b(A,\ T_b,\ V_b)\,.
\end{aligned}
\tag{102}
$$

Display of the scale members requires a colour surface with CIE or Coloroid codes, of the same hue, but more saturated, as well as a white, and a black surface.

Data

$$P_t(x_{tp},\ y_{tp},\ Y_{tp}) \quad \text{or} \quad (A_{tp},\ T_{tp},\ V_{tp}) \tag{103}$$

$$W_t(Y_{tw}) \quad \text{or} \quad (V_{tw}) \tag{104}$$

$$S_t(Y_{ts}) \quad \text{or} \quad (V_{ts}) \tag{105}$$

refer to the coloured, white, and black surfaces, respectively, entering the mix.

Coloroid colour components of colour point F_{a+n} are:

$$
\begin{aligned}
p_t &= \frac{T_a+nq_T}{T_{tp}}\\
w_t &= \frac{p_t(Y_{ts}-Y_{tp})+\left(\dfrac{V_a+nq_V}{10}\right)^2-Y_{ts}}{Y_{tw}-Y_{ts}}\\
s_t &= 1-(p_t+w_t)\,.
\end{aligned}
\tag{106}
$$

Percentages of coloured, white and black discs are adjusted on the Maxwell disc area according to (79).

Example 7. For two complementary colours, a third one, of saturation and lightness between those of the two given colours, and of a hue either the same as that of the one or the other, or an achromatic colour, is required.

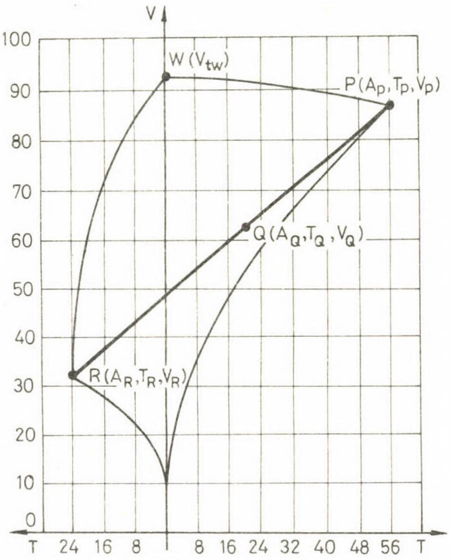


Fig. 3.77. Vertical axial section of Coloroid. The straight lines connecting colour points P and R accommodates their mix Q

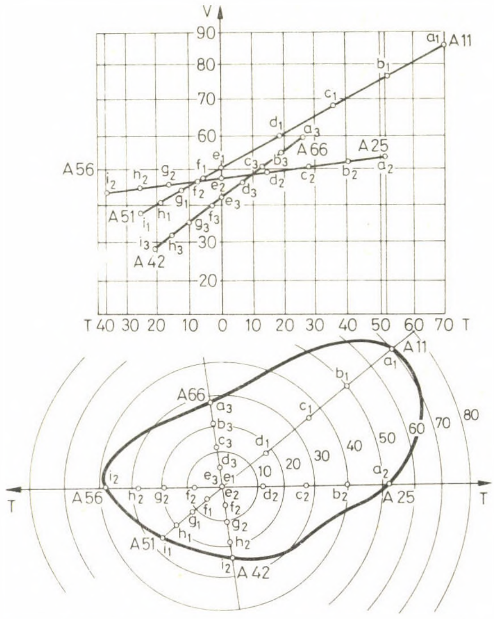


Fig. 3.78. Diametral scales resulting from mixing colours of complementary hues. The heavy solid curve indicates Coloroid saturation of the most saturated pigment colours in the mix

First, Coloroid coordinates of colour point Q of the diametral row between given colour points P and its complementary R are to be determined (Fig. 3.77). Thus, $P(A_p, T_p, V_p)$ and $R(A_R, T_R, V_R)$ are given, and $Q(A_Q, T_Q, V_Q)$ is sought.

Let us take a quantity β of colour P, and $(1-\beta)$ of colour R. Assume $0 \leqq \beta \leqq 1$. Coloroid coordinates of the mixed colour Q are:

$$T_Q = \beta T_P - (1-\beta) T_R \tag{107}$$

and

$$V_Q = 10 \sqrt{\beta \left(\frac{V_R}{10}\right)^2 + (1-\beta)\left(\frac{V_R}{10}\right)^2} . \tag{108}$$

For $T_q > 0$ then $A_q = A_p$, for $T_Q < 0$, then $A_Q = A_R$ and for $T_Q = 0$ it is an achromatic colour.

Now, Coloroid colour components of colour Q can be computed according to those in previous sections, and colour Q can be mixed on a disc or optically. In Fig. 3.78, diametral scales obtained by mixing colours of complementary hues are shown in Coloroid sections. Coloroid coordinates of scale members may also be approximated graphically. The heavy solid curve in the horizontal section refers to Coloroid saturations of the most saturated pigment colours. Similar scales are also shown in Fig. C32.

Example 8. The designer has to work with two, quite different colours, i.e., having very different hue, saturation and lightness. His artistic idea is to apply further colours intermediate to the two given colours regarding all three colour parameters, so that the new and given colours should form a harmonic scale. In the following, a single member of this imaginary colour series will be determined.

The first step will be to determine Coloroid coordinates of the wanted colour as follows.

According to the conditions set, F_1 with Coloroid coordinates F_1 (A_1, T_1, V_1), where $A_1 = f(\varphi_1)$ and F_2 with Coloroid coordinates $F_2(A_2, T_2, V_2)$, where $A_2 = f(\varphi_2)$ are given.

Colour F with Coloroid coordinates $F(A, T, V)$ is to be found.

Colours F_1 and F_2 are assumed to be mixed in quantities β and $(1-\beta)$ respectively for obtaining colour F. β is assumed to range from $0 \leqq \beta \leqq 1$.

The required formulae are deduced by first changing from Coloroid polar coordinates to Cartesian coordinates (Fig. 3.79). Here points F_1 and F_2 will be given by u_1, v_1, n_1, and u_2, v_2, n_2, respectively. Since every T falls into the plane uv, in conformity with Fig. 3.79 it can be written:

$$
\begin{aligned}
u &= \beta T_1 \cos\varphi_1 + (1-\beta) T_2 \cos\varphi_2 \\
v &= \beta T_1 \sin\varphi_1 + (1-\beta) T_2 \sin\varphi_2 \,.
\end{aligned}
\tag{109}
$$

Returning to polar coordinates, from the figure it can be written:

$$
T = \sqrt{u^2 + v^2}\,, \qquad \operatorname{tg}\varphi = \frac{v}{u}\,. \tag{110}
$$

To determine Coloroid hue code A, first φ will be computed as:

$$
\varphi = \operatorname{arc\,tg} \frac{\beta T_1 \sin\varphi_1 + (1-\beta) T_2 \sin\varphi_2}{\beta T_1 \cos\varphi_1 + (1-\beta) T_2 \cos\varphi_2}\,. \tag{111}
$$

A values for the computed φ may be determined by interpolation from Table A.2.

Coloroid saturation code T for the wanted point F—also in conformity with those

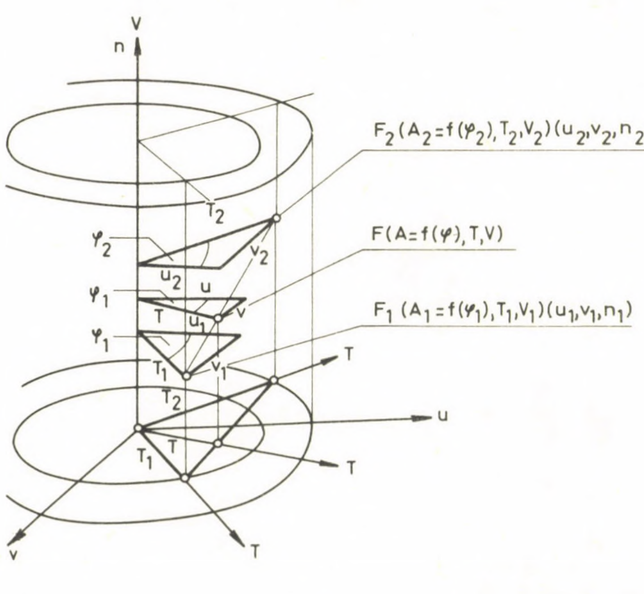


Fig. 3.79. Determination of coordinates in the Coloroid system of a new colour (F) arising from the additive mixing of two different colours (F_1 and F_2) of the Coloroid colour space

above—is determined as:

$$T=\sqrt{[\beta T_1\cos\varphi_1+(1-\beta)T_2\cos\varphi_2]^2+[\beta T_1\sin\varphi_1+(1-\beta)T_2\sin\varphi_2]^2} \tag{112}$$

and Coloroid lightness V of point F as:

$$V=10\sqrt{\beta\left(\frac{V_1}{10}\right)^2+(1-\beta)\left(\frac{V_2}{10}\right)^2}\,. \tag{113}$$

Now, Coloroid colour components p_t, w_t and s_t of the colour can be determined as before and used to adjust percentages on the Maxwell disc according to (79), and finally to display the colour by spinning the disc.

3.4.6. Colour Codes and Colour Names

The colour designer is expected—in particular, by the customer—to name the colours used in his/her colour design by informative names.

Most of our current colour names look back to oldest times. Initially, colours were indicated by names of coloured objects in our environment, flowers, plants, minerals, metals, animals, natural phenomena. Names of several colours refer to places where the corresponding pigments were extracted, or produced in the best quality. Some products made always in the same colour have lent their names to given colours. Over the ages, a given colour name might have denoted several, sometimes rather different shades; conversely a given shade had several names. A large number of colour names have become almost international, indicating the same shade in most countries. Other colour names are current only in certain geographical regions or language territories.

To help in ensuring that informative colour names can be used in colour design, the tables below give colour names to be applied to colours indicated by the given Coloroid colour codes. Table A.3 contains names of Coloroid colour domains and basic colours, while in the set of Tables A.6, names of colours in sections of the colour solid corresponding to Coloroid basic hues are listed.

4. Colour to Man Relations

This chapter discusses relations concerning the effects of colour on man as a thinking, feeling, remembering being, as much as possible abstracting man in his relation to colour from his built environment.

4.1. Composition Relations Resulting from Colour Vision Processes

Considering man as a visual sensory system we first of all have to look at the psychophysical and psychophysiological aspects of our colour vision. The disclosed scientific results enable colour dynamics to find new laws of composition.

4.1.1. Psychophysical Appreciation

In addition to psychically definable perceptions elicited in man by physical stimuli, man classifies and ranks these perceptions in conformity with the eliciting physical stimuli. This activity of man is performed as a psychophysical system, and physical stimuli result in psychically defined judgements.

Relations between perceptions can be examined only by statistical methods. Hence, psychophysics as a field of research involves statistical surveys.

The 1860 book on psychophysics by Fechner, mathematician and physicist, was the first scientific work to publish statistically processed test results on the relation between physical stimuli and perceptions. Much of this book has been devoted to methods for the statistical processing of different psychophysical test methods and results.

Determination of stimulus thresholds and of difference thresholds has been considered over a long period as the fundamental objective of psychophysical experiments. Determination of difference thresholds, that is, of just perceptible differences, is essential in colour dynamics for construction of a perceptionally uniform colour space.

For difference thresholds Weber's well-known law from 1834 holds, stating that the given stimulus has to be increased by a constant fraction of its value (*Weber's constant*) to be perceptibly changed. Or, in mathematical terms: $K = \Delta I/I$, where I is the intensity of stimulus and ΔI the increase just enough for test person to notice that the stimulus has become more intensive. The smaller the Weber's constant, the finer the distinction. With a continuous increase of stimulus intensity, the perceptible stimulus increment grows.

Psychophysical methods of determining difference thresholds are similar in that all confront a constant standard stimulus and a variable comparative stimulus. Fundamental psychophysical methods are:

1. Methods of limits where test subjects approximate to the standard stimulus by small steps of the comparative stimulus.

2. Methods of mean error where test subjects repeatedly adjust the comparative stimulus to the standard stimulus, then errors are averaged.
3. Frequency methods, where test subjects confront the comparative stimulus to the standard stimulus, and the frequency of responses in different categories is counted.

Just as scales have been elaborated in physics and colorimetry for measuring light and colour stimuli, in psychophysics it has been attempted to develop psychological scales for measuring light and colour perceptions. This resulted in so-called colour order scales, equidistant scales, and proportion scales. Order scales arrange data according to some parameter, for equidistant scales, data have equal intervals; finally proportion scales have also a real zero point.

Scales without a physical continuum in which to arrange the objects of stimuli are called psychometric scales.

4.1.2. Colour Adaptation

Adaptation is the adjustment of eyes to adapt to environments illuminated by light sources of different luminances and light temperatures. The adaptational condition of the eye is controlled by illumination intensity and light temperature, as well as by surface colours prevailing over the given space complex.

Artificial light sources have become necessary and indispensable accessories of our environment. Conscious design of their application has to reckon with the laws of colour adaptation, especially when designing environments affected by sharply different luminous intensities or hues. The time factor in adaptation is of importance in the colour design of consecutive spaces. A typical example of the role of the time factor is that after having admired the sunlit façade of a historical monument, minutes have to pass before one is able to appreciate the shady gateway.

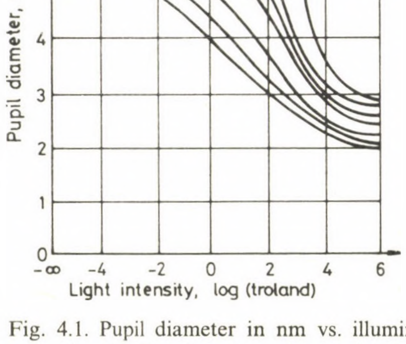


Fig. 4.1. Pupil diameter in nm vs. illumination in troland units, based on experiments by SPRING and STILES. Curves refer to individual test persons

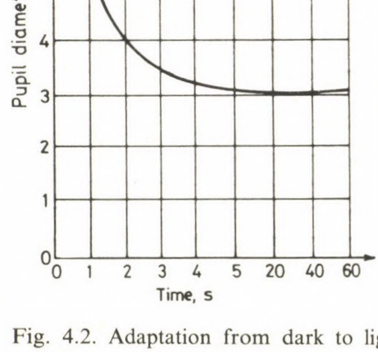


Fig. 4.2. Adaptation from dark to light vs. time, based on experiments by REEVES

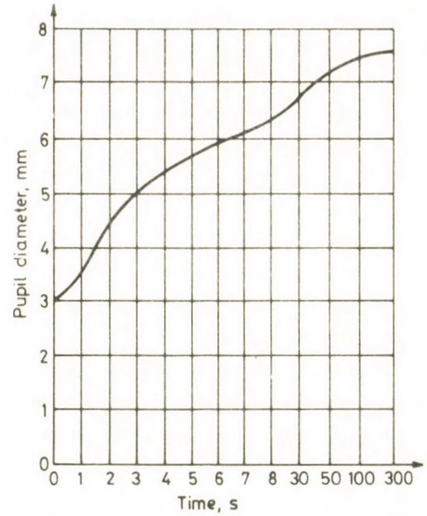


Fig. 4.3. Adaptation from light to dark vs. time, based on experiments by REEVES

Among eye adaptation processes, that to various light densities, the so-called *light–dark adaptation*, is the easiest to measure and has therefore been the most thoroughly studied. It is tested by measuring first the pupil diameter at different luminances and then the time until the pupil diameter follows the change of luminance.

Fundamental results by SPRING and STILES (1948) are seen in Fig. 4.1. Diagrams show pupil diameters of test persons at different illuminations, but also that luminous intensity variation is differently followed by pupils of different individuals. Adaptation times from gloom to light, and from light to gloom are seen is Figs 4.2 and 4.3, respectively, after tests by REEVES (1918).

Adaptation takes place predominantly on the retina, as demonstrated by tests by HECHT (1931), KOHLRAUSCH (1931), COOK (1933), MILES (1943), and WRIGHT (1934). They have found that visual purple fades in light, and reappears in lasting gloom. This assumption is supported by the ability of the two eyes simultaneously to make opposite adaptations: one may adapt to light, while the other to darkness.

Adaptation to light and to darkness has been evaluated by determining from time to time stimulus thresholds, that is, the minimum of luminous intensity just perceivable. Test results showed that the sensitivity of the eye adapts to extreme darkness about one million times better than to extreme lightness.

In addition to dark–light adaptation, space colour design has to take the adaptability of the eye to various colour effects into consideration. In an environment illuminated by coloured light or built up from large coloured surfaces, eyes undergo colour retuning. After having looked at an orange surface for some minutes, it seems yellower than before, while violet looks more bluish, i.e., exposure for some time somewhat alters the colour sensation transmitted by the visual organ although the colour remains the same. This finding may often be decisive in interior design. Note that not every colour effect elicits such a retuning. In retuning, the visual sensation exhibits a certain regularity: in conformity with the Bezold–Brücke effect, colours ranging from red through yellow to green are shifted toward yellow, while those in the range from violet through blue to green tend to blue. If the retuning colour is complementary to the reacting colour, then the reacting colour seems to be more saturated.

Trends and intensity of adaptation retuning for colours of various saturations and lightnesses in the Coloroid colour circle are seen in Fig. 4.4. Curves F_0 to F_5 refer to colours of the Coloroid colour solid shown in Fig. 4.5.

Retuning strains the eye, so that after a time, colour fatigue arises, temporarily reducing colour vision.

Experimental results by HELSON (1948) and the present author (NEMCSICS, 1969) are compared in Fig. 4.6. Observers have found a perceptional decrease of red light intensity as a function of time. It was also HELSON who pointed out that test persons perceived patterns darker than the walls of the room as bluish green i.e. the complementary after-image of the red illumination—and this bluish green seemed the more saturated, with decreasing reflectivity of the patterns. The same was found in the author's tests.

The mechanism of colour adaptation is not yet fully understood but it may be assumed that—at least in part—it is due to increased decomposition of some of the receptors participating in colour vision. This phenomenon is related to the mechanism of chromatic and achromatic vision. Signals in one channel may affect those in the other. This interaction, and one of the up-to-date models of counter-colour theory have been described by GUTH (1964). This model relies on antagonistic mechanisms attributed to the variability of spectral sensitivity: radiation of one wavelength range incident on the eye alters sensitivity to the other.

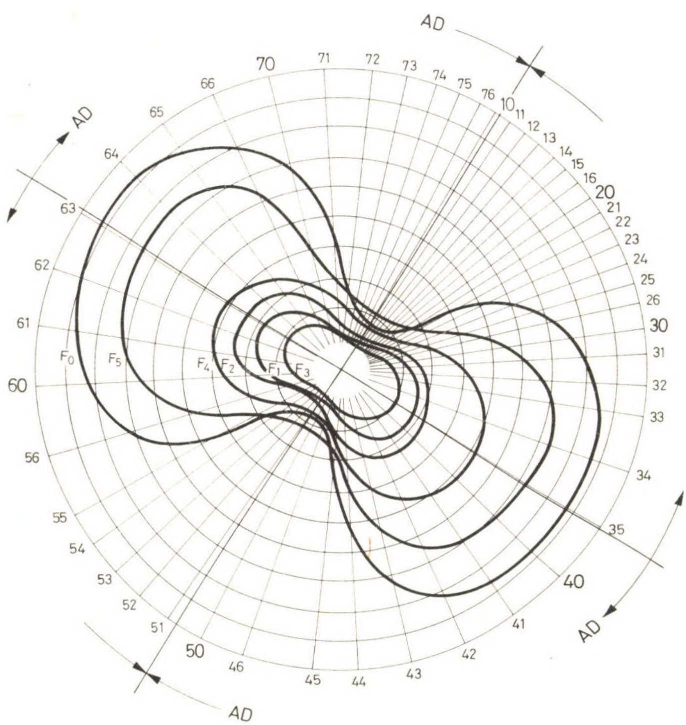


Fig. 4.4. Directions (AD) and values of adaptational retuning for colours of different saturations and lightnesses of the Coloroid colour circle. Numbers along the perimeter of the circular diagram refer to different Coloroid basic hues. Adaptation intensity increases from centre to perimeter. Curves F_0 to F_5 show adaptational retuning values for colours marked in the Coloroid colour solid (see Fig. 4.5)

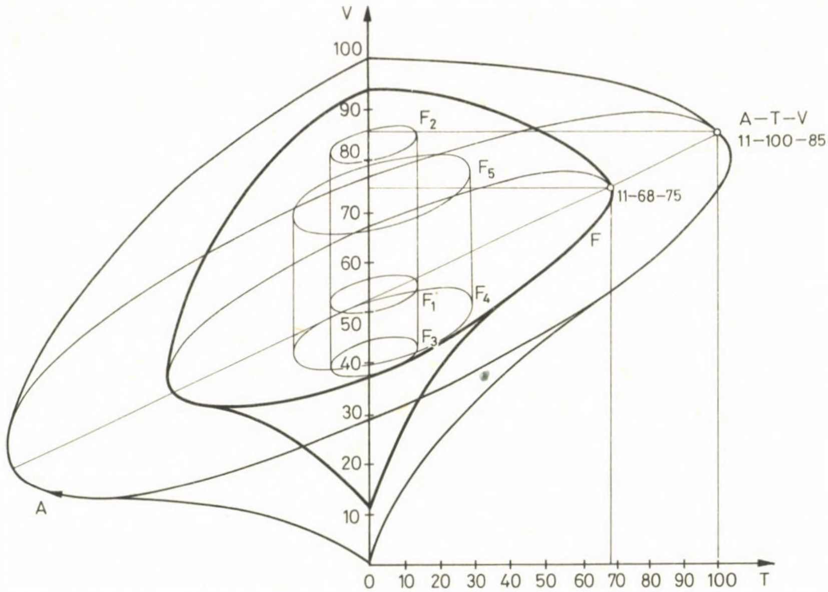


Fig. 4.5. Discrete colours of the Coloroid colour solid. Curves are geometric loci of the most saturated surface colours (F_0), unsaturated, medium light colours (F_1), unsaturated, very light colours (F_2), unsaturated, dark colours (F_3), medium saturated, dark colours (F_4) and medium saturated, light colours (F_5)

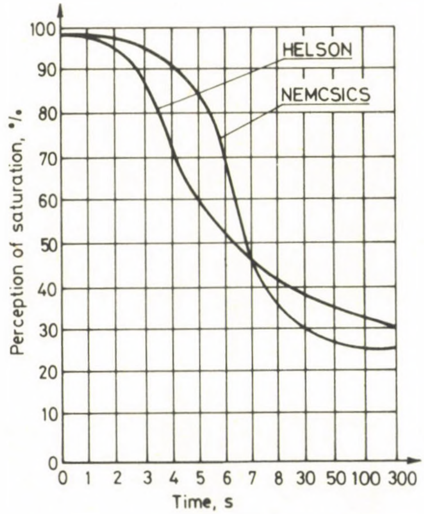


Fig. 4.6. Adaptation to red light of 625 nm dominant wavelength vs. time after experiments by HELSON, and the Author

Another important problem in environment colour design is to find out when the process of adaptation to various hues favourably or unfavourably affects the spatial resolution. Also we have to settle the magnitude of the area to be considered as an adaptation field sufficient to elicit the adaptation process. Surfaces in our environment are textured rather than smooth, therefore it would be useful to study adaptation processes also from this angle.

4.1.3. Colour Constancy

Variations of stimuli affecting our eyes are often accompanied by a certain constancy of the colour sensations, called colour constancy. This phenomenon is of importance in recognizing objects in our environment, because it helps to identify them by permanent, essential properties, in spite of lesser or greater variation of the stimuli elicited by them. Under illuminations of different spectral distributions, radiations from surrounding objects affecting the eye are different, whereby different colour shades are exhibited, but this is not such an important feature of the objects as to be decisive in our relation to them and the economy of our perception is manifested by the fact that relatively minor differences are not reflected in our colour sensations. The basis of colour constancy is the sensitivity of the eye to relations between stimuli.

Primarily by affecting the spatial articulation of the visual fields as a result of higher level functions of the nervous system, so-called central correction processes contribute to the phenomenon of colour constancy.

Memory has also a role in colour constancy. The colour most frequently seen on surrounding objects is indelible from our memory, and its after-image becomes a permanent characteristic. The so-called real colour of a given object is, in fact, the colour associated to this object in our memory.

Any object known from previous experience or believed to be of known colour is seen through the "spectacles" of colour memory. The painter representing an object endeavours to grasp colour stimuli, but the everyday observer is often confused by this because he wants to see the object in the picture as dictated by his own memory colours.

According to tests by Brunswik (1934), Ansbacher (1937) and Katz (1935), an object is sensed as having different colours under different illuminations if it is unknown for the observer. Colour impacts from a given object elicit definite excitations of a plexus in the cortical visual centre, but the process of excitation spreads to areas of the visual centre storing traces of earlier, similar impressions which are thereby revived. As stated by Evans and Klute (1943) the conscious colour impression itself comes into being by an interaction between the actual excitation centre and the revived traces, hence it is a synthesis of direct perception and memory functions.

In perceiving an object as having the same colour in spite of its actual colour deviations—, apart from previous impressions—, our colour sensation is also affected by verbal–mental knowledge on the object. Empirical knowledge is more than learning the name of an object; when seeing the object not only does its name appear in our consciousness, but owing to the above mentioned higher nervous processes, also some of its constant attributes are verbally recorded. At the sight of the object these words are recalled and fundamentally affect later impressions of the given object.

Hurvich and Jameson (1967), and recently, Tánczos (1971) commented on the role in colour constancy of the ratio of all the available excitable receptor elements to those actually stimulated.

4.1.4. Colour Contrast

Relationship between colour perception of different colours is largely determined by *contrast phenomena.* When looking simultaneously at two colours, our sensation is influenced by the contrast relationship between the two. Therefore the achievements of colour contrast studies are indispensable for the practice of colour dynamics. These tests approached colour contrast mainly as a *retinal physiological* process, in part in connection with the phenomenon of colour constancy.

In colour dynamics, contrast phenomena have to be considered mainly as a psychophysiological motivation of *compositional regularities*. In this respect observations by ITTEN (1961) and KLEE (1961) as well as by ALBERS (1963) are of interest.

Contrast is understood as difference between two adjacent colour effects. A maximum of difference is called *opposite* or *polar contrast*. For instance, extreme degrees of the oppositions: big–small, black–white, cold–warm, are polar contrasts. Our sensory organs perform sensing by comparison. Thus, a line appears to be longer if it is next to a shorter one. Similarly, the impact of a given colour value can be enhanced or diminished by contrasting.

Contrast phenomena may be attributed to the so-called *mutual induction phenomena* and counter-colour generation, respectively, participating in the process of vision. Exposing e.g. a white dot on black background, retinal excitation intensity increases on the retinal area corresponding to the white point, raising an inhibition in its surroundings. Due to this inhibition the white dot is seen more sharply on a black background. If, however, a black dot is placed on white background, then this interaction of stimulus and inhibition, the above mentioned mutual induction, acts in a way that excitation by the intensive stimuli of the white background so to say confine—and thereby inhibit—the less excited area of the retina corresponding to the black dot.

The contrast phenomenon observed when looking at Fig. 4.7: the so-called *marginal contrast* or *irradiation* may be interpreted along similar lines. Intersection points are exposed to two environmental effects. Accordingly, at the contact points the double effect of black and white prevails, so that these areas seem darker than white and lighter than black, that is, they seem to be gray. Contrast phenomena underlie various delusions, as exemplified in Fig. 4.8.

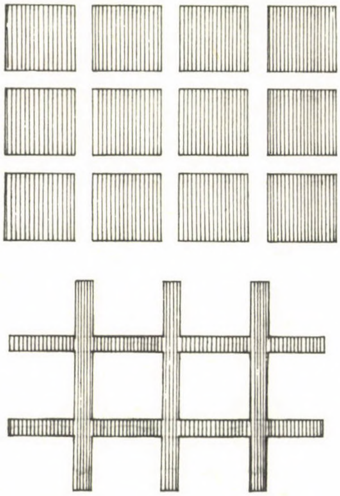


Fig. 4.7. An example for the development of marginal contrast

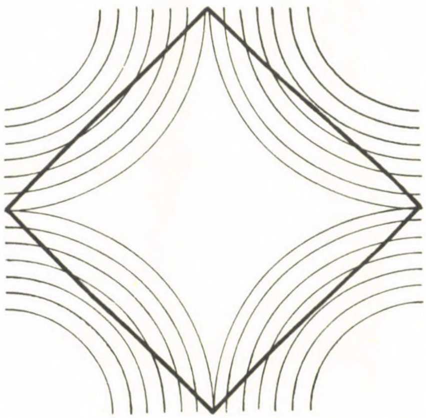


Fig. 4.8. Contrast phenomenon as basis of delusions

Contrast phenomena have already been studied by GOETHE (1810), BEZOLD (1876), CHEVREUL (1871) and HOELZEL (1910). The first scientific developments were the theories of peripheral and central contrast. The former were due to HERING (1931), the latter to HELMHOLTZ (1925), GELB (1929), and KOFFKA (1931). Later, this problem has been dealt with by THOULESS (1931), RIEDEL (1937), WALLACH and GALLOWAY (1946).

Among the wide range of contrast phenomena, the following will be outlined below: hue contrast, saturation contrast, lightness contrast, cold–warm contrast, quantitative contrast, qualitative contrast, simultaneous contrast, and successive contrast.

Hue contrast

As seen above, our colour perception is susceptible to hue variations. If two colour perceptions differing only by hue coincide, their interaction is called hue contrast. This interaction may be manifest both by similarity and contrast. Two colour perceptions are the most contrasting for complementary colours. *Complementary contrast* is an extreme case of hue contrast.

A complementary pair of colours having the same saturation and lightness may induce a tense but balanced sensation. Complementary pairs have been the preferred means of expression in fine arts since ancient times. If the composition involves only one member of the complementary pair, the absence of the other causes an unbalanced tension feeling. Thereby hue contrast may be a compositional tool of expression in space shaping by colour dynamics (Fig. C33).

Several interesting observations on hue contrast were made by BLACKWELL (1961) and BRINDLEY (1965). For instance, it has been demonstrated that the more the local stimulus is shifted from the green towards blue, the less the colour contrast between stimulus and background.

This phenomenon may be explained by the fact that the image of the background on the retina is shifted from the fovea centralis towards the sensitivity of the bacillary layer, i.e. towards blue and green. According to studies by KINNEY (1965) contrast effectiveness of blue and green differs from that of red and yellow.

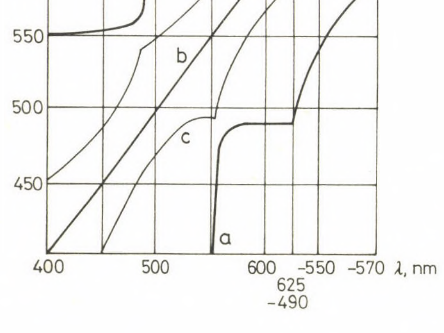
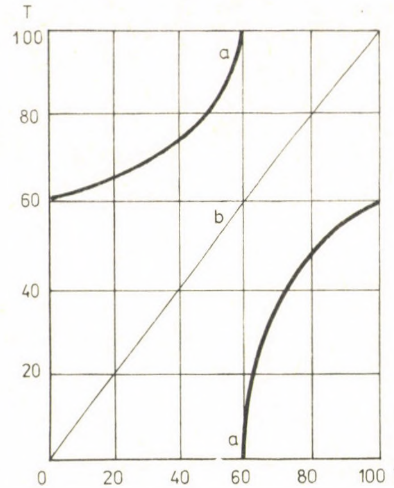


Fig. 4.9. Development of hue contrast between colours of different hues. On the axes dominant wavelengths of the hues of the contrasting pair are marked. Points on curve a) refer to the most contrasting hues and points on line b) to hues without contrast. Contrasts between hues on curve c) are slight enough to be negligible in design

Fig. 4.10. Development of saturation contrast between reds of different saturations. Saturation contrast of useful magnitude for environment design is in areas outside curve a). Along line b) contrast is zero



On the horizontal and vertical axes in Fig. 4.9 colours of identical lightness and saturation each of a Coloroid colour circle are given in wavelengths. Any colour of any colour circle may get into contrast relation with any colour of another circle. If identical colours are correlated no contrast effect arises. Curves in the figure are based on experimental results and show how the contrast effect increases with increasing dissimilarity and discrepancy. The sharpest contrast effect arises with the complementary effect (thick line).

In practice, a sterile hue contrast is exceptional. It is either enhanced or diminished by variations of saturation and lightness. Collection and systematization of relevant data and observations are future tasks of colour dynamics.

Saturation contrast

This is the least known contrast phenomenon and has been rather neglected by psychophysiology. It has not much been considered either by architects or by painters, although it is of importance not only in painting, but also in the colour design of environment.

Recently, some problems of colour ordering by perception are attempted to be answered by HÅRD (1976). To define colour saturation grades, he applied saturation contrast tests—rather than colour discrimination—for examining the sharpness of boundaries between surfaces of different saturations. Similar tests have been carried out by BOYNTON (1960), KAISER (1968), and WAGNER (1954).

Changes in the saturation of a colour perception are sensed by the eyes differently in various domains of hues. In general, saturation changes are better recognized for hues of longer wavelengths, such as yellows, oranges, reds, than for cold greens and blues. As a rule, among various colour perception parameters it is saturation to which our eye is the least sensitive. Nevertheless, it is of great importance, since no harmonic composition can be created without—exactly definable—relationships between saturations of harmonizing colours (Fig. C34).

Saturation contrast between values of different saturations of red of a Coloroid hue $A = 25$, of 625 nm wavelength, is shown in Fig. 4.10. Axes in this diagram refer to members of different saturation of a chromatic series of identical hues and lightnesses. Saturation contrast can arise only in areas outside the thick lines.

Lightness contrast

This is the best known contrast phenomenon, also a favoured subject of experimental psychology. Theories on its induction have already been developed by HERING (1964) and HELMHOLTZ (1925), then by KIRSCHMANN (1927). Later experiments by EVANS and KLUTE (1943) and by KATZ (1935) deserve interest. Recently, its fundamental laws have been formulated by KINNEY (1965) and HEINEMANN (1972). Unfortunately their conclusions are of purely physiological character and have no direct relevance for colour dynamics, unless as a starting point. This subject also attracted the interest of prominent artists, such as MOHOLY-NAGY (1961), KEPES (1965), ITTEN (1961) and KLEE (1925). Their statements were deduced from their creative activities and not from exact experiments and therefore lack general validity.

The human eye is most sensitive to light intensity variations, perceiving quite small differences of lightness between two colours. For colours of the same saturation and hue its sensitivity to changes in lightness surpasses that of the most advanced instruments.

Stress effects can be elicited only by two colours having a lightness difference exceeding a certain limit, or at lightness values corresponding to complementarity (Fig. C35).

Figure 4.11 demonstrates contrasts at different lightnesses for a constant Coloroid saturation $T=30$ and hue $A=25$, while Fig. 4.12 shows hue and lightness contrast variations for colours of various saturations and lightnesses in the Coloroid colour circle.

Lightness contrast has a strong *space effect modulation*, lending it importance for environment design. The significance of tone contrast is enhanced by the difference between the colours of the colour circle due to their specific lightness values.

Contrast between cold and warm colours

Coldness or warmness of colours primarily reflect effects on the *vegetative nervous system*. As known from tests by KRAWKOW (1950), red and yellow, blue and green have

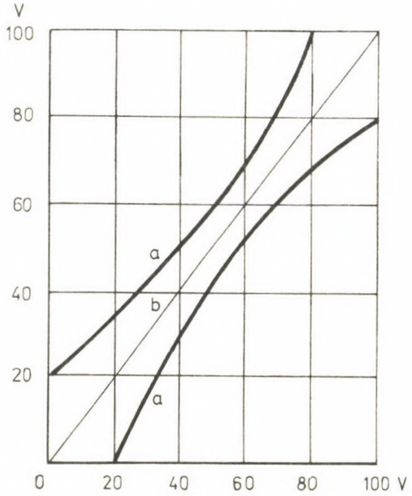


Fig. 4.11. Development of lightness contrast between red colours of different lightnesses. Lightness contrast of useful magnitude for environment design is in areas outside curve a). Along line b) contrast is zero

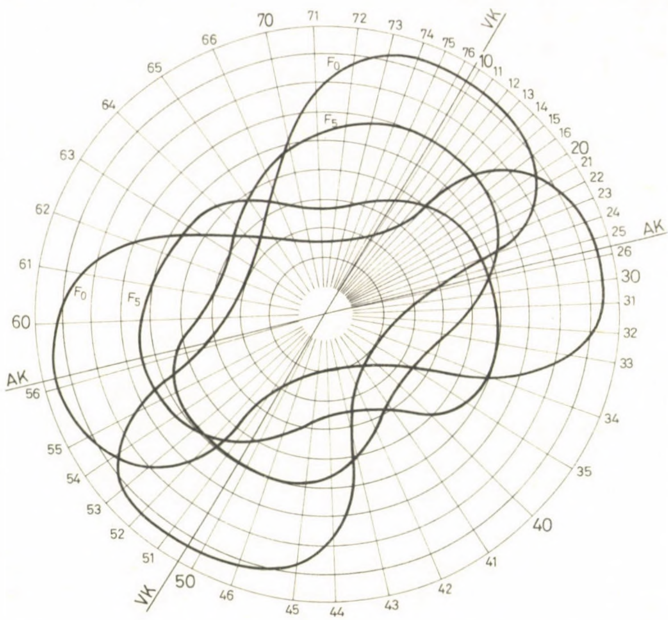


Fig. 4.12. Variation of hue and lightness contrast intensities for differently saturated and differently light colours of the Coloroid colour circle. Numbers along the perimeter of the circular diagram refer to different Coloroid hues. Contrast intensity increases from centre to perimeter. Curves F_0 and F_5 refer to the most saturated surface colours, and to medium saturated light colours, respectively. Hue contrast is most intensive along line AK, light contrast along line VK

opposite effects on the sympathic and the parasymphathic nervous system. KRAWKOW also stated that sympathic excitement affects oppositely the photopic and the scotopic systems. According to experiments by KOFFKA and HARROWER (1931), the ranking of colours for their formative power is the same as their order from warm toward cold, i.e. red, yellow, green, and blue.

Limits of the formation of contrasts between cold and warm colours are seen in Fig. 4.13. Contrast between cold and warm involves colours closely related to the following opposites: shady–sunny, transparent–opaque, comforting–exciting, thin–thick, airy–earthy, close–far, light–heavy, wet–dry (Fig. 4.14). These pairings show the potentials of expression by contrast. Beyond a picturesque effect, it also carries emotional expressive force.

The warm effect of a surface or space composition may be upgraded by applying, among the colours, a properly selected cold hue, and vice versa. In colour composition, it is of crucial importance to consider the cold–warm effect. A colour complex is much better responded to if its cold–warm psychological character is immediately felt (Figs C36, C37).

Quantitative contrast

This is of importance both in fine arts and in the colour design of the environment. Its relevance for space formation has first been recognized by the "Bauhaus" school. If in a composition or a coloured space no colour overwhelms the other, then we regard them as balanced or in equilibrium. For this *equilibrium*, two factors are of primary importance: lightness and the area occupied by each of the colours.

Quantitative contrast is the relationship of colours balancing each other by their different surface areas.

According to ITTEN (1961), pairwise balancing of each two of the three complementary colours requires the following surface ratios: yellow : violet = 1/4 : 3/4; orange : : blue = 1/3 : 2/3; red : green = 1/2 : 1/2. Quantitative proportions between surface areas of saturated main and accessory colours are: yellow : orange = 3 : 4; yellow : red = 3 : 6; yellow : violet = 3 : 9; yellow : blue = 3 : 8; yellow : red : blue = 3 : 6 : 8; orange : violet : green = 4 : 9 : 6 (Fig. C38).

Qualitative contrast

Qualitative contrast is closely related to the texture of the material carrying the colour. It always has a favourable effect when in the same composition or, in the case of environmental colour design, in the rooms, different colour values are associated with different surface qualities. Conversely, it is rather awkward to have the same colour on surfaces of different qualities.

Simultaneous contrast

"Colour values change character when adjacent. This is called simultaneous contrast. Simultaneous contrast makes colour suitable for aesthetic use"—stated GOETHE (1810).

Any of the contrast effects described above may arise by looking at the contrasting colours either simultaneously, or shifted in time. The former is known as simultaneous contrast, the latter as successive contrast.

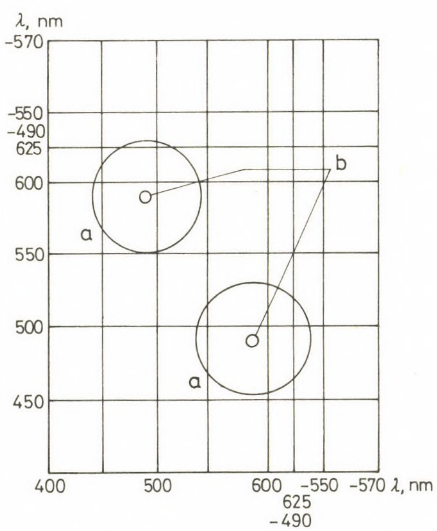


Fig. 4.13. Limits to the development of cold to warm contrast. On horizontal and vertical axes of the diagram hues of contrast pair members are shown, in terms of dominant wavelengths. Cold to warm contrast useful in environment design is inside curves a). Contrast is maximum at b)

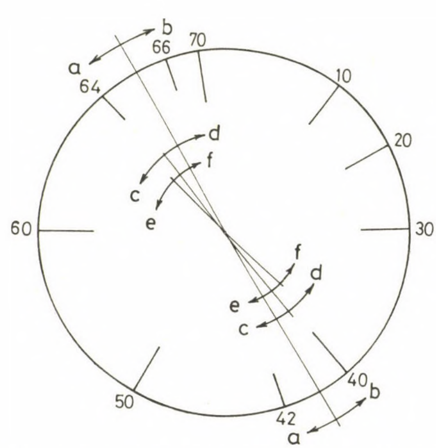


Fig. 4.14. Contrast pairs assigned to cold to warm contrasts in the Coloroid colour circle (a) cold, b) warm, c) shady, d) sunny, e) moist, f) dry)

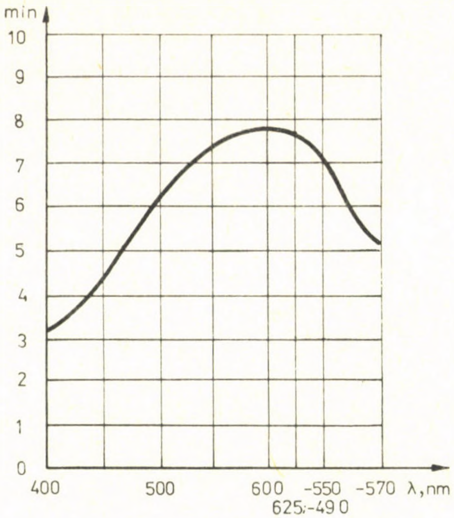


Fig. 4.15. Time limits of development vs. dominant wavelengths of different hues of successive contrast effect. The horizontal axis shows the wavelength values characteristic of the various hues, the vertical axis shows the time limit of the development of the successive effect, in minutes

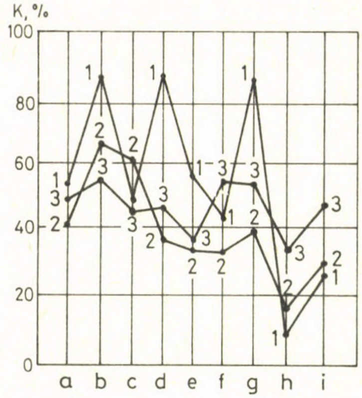


Fig. 4.16. Significances of different contrast effects in rooms having different functions (a) bedroom, b) nursery, c) study, d) public nursery, e) classroom, f) ward, g) waiting room, h) surgery, i) textile workshop). Vertical axis shows frequency of the contrast. Points 1), 2) and 3) refer to hue, saturation, and lightness contrasts, respectively

Experimental psychology examining the formative and contour shaping potential of various hues is concerned with the facts of simultaneous contrast. Its statements on the specific formative value of hues, and on the order of colours according to their contour shaping value, are essentially derived from the evaluated hue in the context of simultaneous contrast. Phenomena connected with looking at maximum saturated colours, such as the so-called *Liebmann effect*—primarily examined by KOFFKA and HARROWER (1931), and by RATLIFF (1965)—contribute to our knowledge on simultaneous contrast (Fig. C39).

Successive contrast

The effects of colours interact not only when viewed simultaneously, but also when looked at successively. A strong impression of a colour effect in a room persists for minutes after having left the room, dimming or enhancing the impression made by the colour in the next room.

These statements are of decisive importance mainly for the colour design of adjacent rooms. But successive contrast is also of importance for the relationship between outdoors and indoors. Figure 4.15 based on our own tests shows how long a successive effect may persist for different hues.

In practice, the significance of various contrast effects also depends on the *function* of the room (Fig. 4.16).

4.2. Colour Preferences

One is at ease in an environment surrounding one with one's preferred colours. In such an ambience we feel well, our accomplishments are higher. This experience made colour preference of those working in a given surrounding a fundamental aspect in conscious environment design since its very beginning. Initially, environment design relied on results of preference tests undertaken for various psychological or commercial purposes. It has soon become clear that these results were not suitable for environment colour design, since they referred to a few discrete colours, of which only the preference order was defined, raising debates whether colour preference was meaningful for environment design. Most of the researchers, however, ranked colour preference among problems of colour dynamics to be solved in the future.

In this chapter, the colour preference index number system will be presented as a possible solution to the problem.

Colour preference means simply that one colour is liked more than another. Colours can be arranged according to taste into scales—called psychometric scales, because they result from judgement. A reasonable choice between two colours can be taken only when based on the judgement of a group of people. The position of the colour expresses apart from its order, its position on a proportional psychometric scale having both a starting and an end point. The use of a scale of proportions in the field of colour preference is a novel idea; its introduction permits, in principle, settlement of preferences for all the members of the colour space, and this is decisive for environment colour design.

In the following, requirements for a colour preference system, from the point of view of colour dynamics, is presented. As to colour dynamic requirements for colour preference, the results of colour preference tests can be used as practical tools for environment colour design to satisfy requirements only if they formulate typical man to colour relations involving all the colours of the colour space. Now, let us examine the results, and their potential for the possibility of practical application of our series of colour preference tests. These were performed with the aspects of colour dynamics in mind and meeting the above requirements.

4.2.1. The Beginnings of Colour Preference Investigations

The first colour preference tests date back to the 1890s. In his book published in 1894, TRAGY referred to colour preference tests by ALLEN, GENZMER, RACHLMAN, PREYER, and BINET. Tests, intitially without definite goals, were performed at random mainly in the USA and in Great Britain on small groups of schoolchildren. MAYOR applied BRATLEY's colour set but colours applied by other researchers cannot now be identified in terms of colour codes which would assist in their reproduction.

Colour preference being markedly affected by age, researchers made tests on definite age groups, as did HOLDEN and BOSSE (1900), SHINN (1904), ENGELSBERGER and ZEIGLER (1905), as well as BALDWIN (1906). Other researchers, TITCHENER (1905), MARDSON (1903), WELSON and WASHBURN (1913), and GORDON (1923) have included several age groups. Others evaluated boys' and girls' preferences separately, such as BULLOUGH (1906), WRIGHT (1906), SMERS (1908) and WASHBURN (1911), or were concerned, as HAVELOCK (1900), NORRIS and WASHBURN (1911), with relations to single colours.

Colour preference experiments followed essentially two methods. In one, the whole set of test colours was shown simultaneously, and the test subjects had to arrange them in the order of preference. MAYOR's experiments (1895) were the first among this ranking-type method, which became later almost universally applied. In the other method, tests were made by pair-wise comparisons, as introduced by COHN in 1894. For test persons this is the simplest method, as they are presented with only two colours at a time from which to choose, then another pair follows until all the alternatives have been judged. Comparison of n colours with each other results in $k = n(n-1)/2$ pairs.

The first tests using unambiguously defined colours were performed by PAUL and OSTWALD and published in 1922 under the title: "Favorite Colours of Children". Separate tests were made with boys and girls in wide age groups. Those in the lower age group were shown only the four primitive colours, while those in the higher age group the eight principal colours in the colour circle of Ostwald's colour solid.

Ever since the potential of colours to affect work accomplishments was demonstrated quantitatively colour preference tests have gained in popularity. Workers of entire industries were subjected world-wide to tests, in order to improve working conditions and productivity. Colour research groups were formed, applying different methods, quite different colours, on a varying population of test persons. Requirements set for coloured space design and applied initially mainly in industry, especially in textile manufacturing were gradually extended to other establishments. Similar tests have been made for offices, hospitals, schools, nurseries, day-time homes, and many other institutions. The results of these tests are, however, only of limited relevance for environment colour design, mainly since those who devised them did not take into consideration the requirements of colour dynamics. Let us now consider these requirements severally.

4.2.2. Colour Preferences in Typical, Numerous Populations

The first requirement of colour preference tests and their results both by colour dynamics as a science, and by practical environment colour design is to express the attitude to colours of a numerous, typical population.

From practical experience it is known that small children prefer fiery red to brick red, while adults prefer to be surrounded by dull shades. Women prefer yellow and violet, whereas men like blue and green. Patients with fever hate orange surroundings, which is, in turn, the very colour preferred by elderly, chilly or anaemic persons. Those of a sanguine character like vermilion and crimson surroundings, while melancholics badly tolerate these colours, and prefer dull greens and pale violets. Relevant test results by FRIELING (1963) were plotted in Fig. 4.17.

Mentally handicapped people are known to opt for dark brown and dark greyish green, while criminals like deep caput mortuum, grayish crimson, and blackish ultramarine blue. Saturated and dull colour preferences of normal people and of convicts are compared in Fig. 4.18, based on studies by NEMCSICS (1968), and by SZENTE and SZAMOSFALVI (1976), respectively. Mountaineers and flatlanders have different colour preferences. Different environment colours make an African, a German or a Frenchman feel at ease. Colours act differently in winter cold and in the summer, in sunshine or in incandescent light. Preferences of the same test subjects for the same colours in daylight

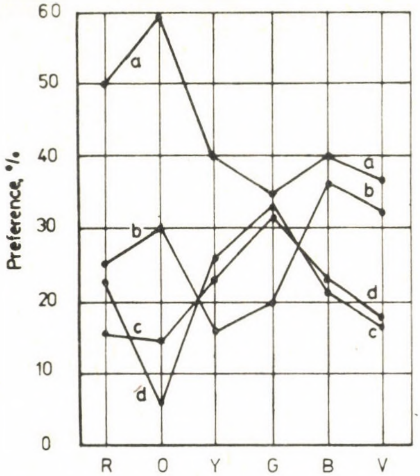


Fig. 4.17. Colour preferences of sanguine (a), melancholic (b), phlegmatic (c), and choleric (d) persons in dependence of hue after tests by FRIELING. R red, O orange, Y yellow, G green, B blue, V violet. Vertical axis shows preference in per cents.

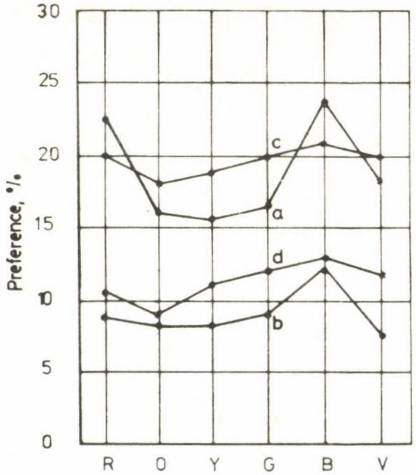


Fig. 4.18. Colour preferences of men aged 25, (a, b) and of convicts aged 25 (c, d) after tests by NEMCSICS and SZENTE, respectively. Curves a) and d) refer to saturated, b) and c) to dull colours. Colour notation as in Fig. 4.17

and in incandescent light based on experiments by LUCKIESH (1916) were plotted in Fig. 4.19.

The above statements indicate that colour preference is a highly complex phenomenon. No human preference in general can be spoken of, but only of that of some defined population living in a given environment. In environment colour design, preferences can be unambiguously applied only if data on typical populations are available which can be associated with certain life functions. For example, in the colour design for primary schools colour, the preferences of normal, healthy children of 6 to 14 years of age have to be considered, but for individual classrooms, preferences of an even narrower age group should be honoured.

Ages of women working in a textile factory fall into a relatively narrow range; thus preferences can be rather well defined and this group can be considered as a typical population. Another typical group is that of sufferers from gastro-enterology or cardiology in a hospital. Colour preferences of healthy people and of cardiac and intestinal patients were compared in Fig. 4.20, based on tests by FEHÉR and NEMCSICS (1977).

In most of the colour preference experiments made up to now, no typical populations living in a well defined environment have been involved, leading to incomparable results. The insufficient numbers of participants also contributed to deviations between results. Comparing, however, results referring to similar populations, from among the wealth of publications, diagrams plotted from processed results are rather similar, on the basis of a hundred test persons. This is manifested from Fig. 4.21 showing colour preferences of boys seven years old, based on experiments by LUCKIESH (1927), GARTH (1924), DORCUS (1926), and KATZ (1935), as well as of boys ten years old after tests by DEN TANDT (1971), FRIELING (1949), DÉRIBÉRÉ (1968), and NEMCSICS (1967) (Fig. 4.22). Curves are strikingly similar, in spite of the decades that passed between experiments made in different countries.

For a very large number (at least thousands) of test persons, colour preference of large population groups shows a definite pattern, for example, results obtained on white and coloured people by Eysenck (1941) in Fig. 4.23, or by Nemcsics (1977d) on Hungarian, German and French persons in Fig. 4.24. Accordingly, in colour dynamics, such colour preference test results are most useful when they refer to typical and numerous populations. Further essential aspects in grouping test populations seem to be sex and age.

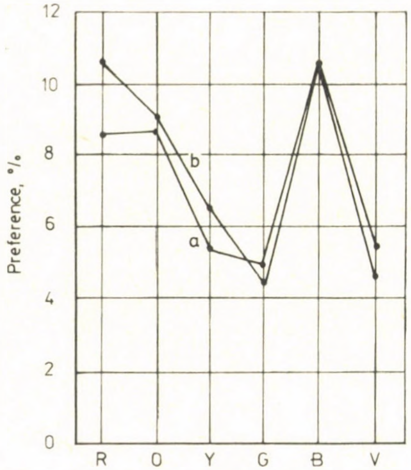


Fig. 4.19. Colour preferences of adults in daylight (a), and in incandescent light (b), after tests by Luckiesh. Notations as in Fig. 4.17

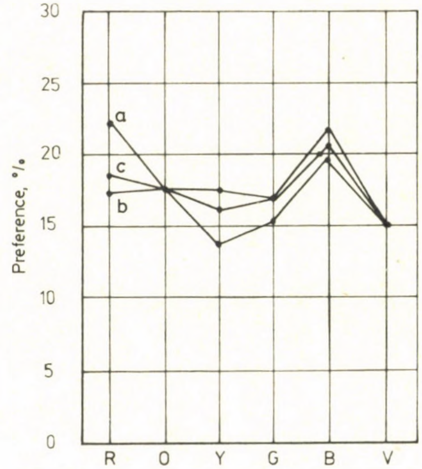


Fig. 4.20. Colour preferences of healthy (a), cardiac (b) and dyspeptic (c) adult men, based on tests by Nemcsics, and Fehér. Notations as in Fig. 4.17

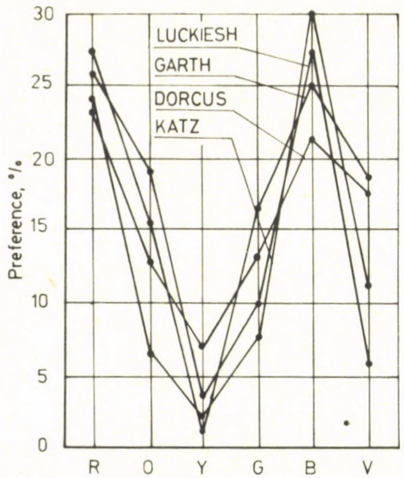


Fig. 4.21. Colour preferences of boys aged 7, after tests by Luckiesh, Garth, Dorcus, and Katz. Notations as in Fig. 4.17

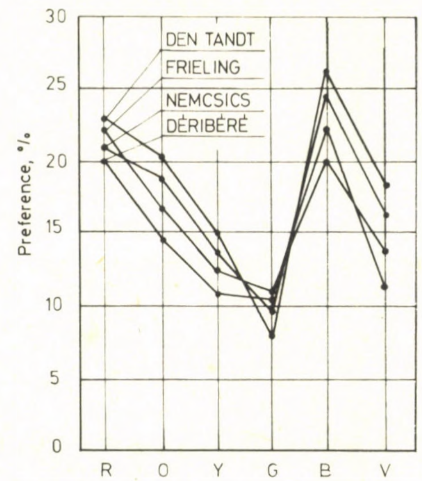


Fig. 4.22. Colour preferences of boys aged 10, after tests by Den Tandt, Frieling, Dériberé and the Author. Symbols on diagram axes are the same as in Fig. 4.17

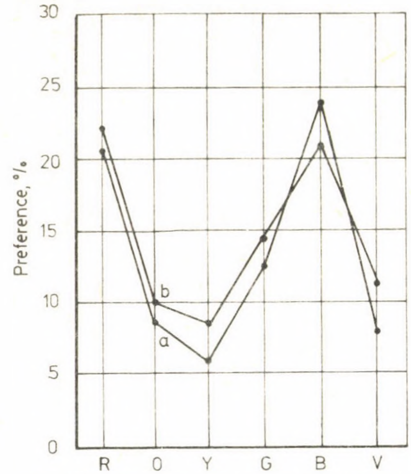


Fig. 4.23. Colour preferences of white (a) and coloured (b) people, after tests by Eysenk. Notations as in Fig. 4.17

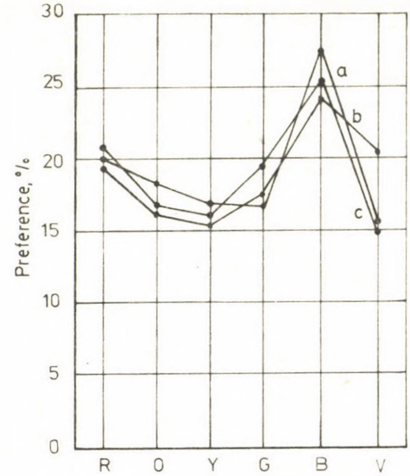


Fig. 4.24. Colour preferences of German (a), French (b), and Hungarian (c) adults based on tests by Nemcsics. Notations as in Fig. 4.17

4.2.3. Preferences for Defined Colours

The second requirement for colour preference tests acceptable for colour dynamics as a science and for the practice of environment colour design is that data should be based on defined colours, and involve every surface colour.

Colour preference experiments indicate that saturation and lightness variation of a colour, irrespective of its hue, or of the test person's identity, may in itself more or less influence colour preference. This recognition explains doubts on the applicability of colour preference results in environment colour design, based on the fact that certain authors reported divergent preference data for saturated green, ultramarine, and some other colour shades, while for other colours, their results were in agreement.

Such differences and coincidences occurred between test results by Frieling (1955b) and Nemcsics (1967b) concerning saturated green and olive green. Figures 4.25 through 4.28 are comparisons between preferences for saturated and dull varieties of a colour each, after tests by Frieling and Nemcsics. Curves marked by a and b refer to men and women, respectively, on the abscissas age groups of test subjects are indicated. Characteristics of the tested saturated greens were:

In tests by	Coloroid	CIE		
	A T V	*x*	*y*	*Y*
Frieling	64.30–21.40–52.30	0.2546	0.3749	27.35
Nemcsics	64.35–23.10–54.20	0.2538	0.3769	29.38

The two colours differred only by saturation and lightness. Saturation and lightness values were similar for the olive green.

In tests by	Coloroid	CIE		
	A *T* *V*	*x*	*y*	*Y*
Frieling	64.10–15.20–55.25	0.2777	0.3478	30.53
Nemcsics	64.20–13.30–57.70	0.2844	0.3423	33.29

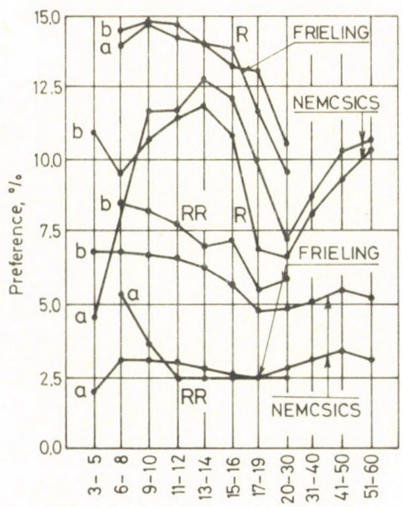


Fig. 4.25. Preferences of men (a) and women (b) for red (R) and pink (RR), vs. age, based on tests by Frieling, and Nemcsics. Horizontal axis bears age groups

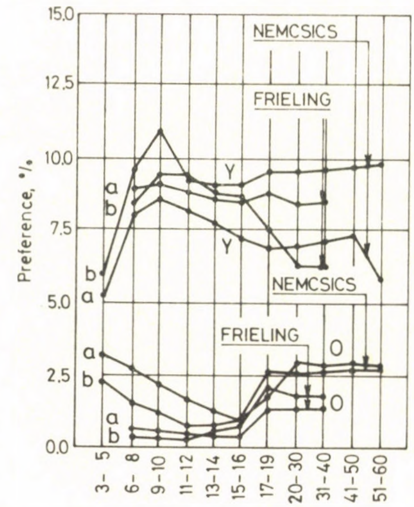


Fig. 4.26. Preferences of men (a) and women (b) for yellow (G) and ochre (O) vs. age, based on tests by Frieling and Nemcsics. Notations as in Fig. 4.25

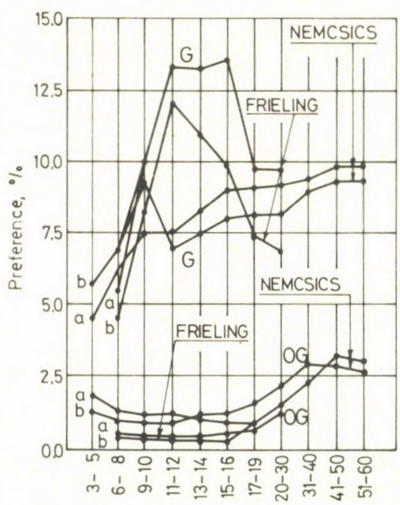


Fig. 4.27. Preferences of men (a) and women (b) for green (G) and olive green (OG) vs. age, based on tests by Frieling and Nemcsics. Notations as in Fig. 4.25

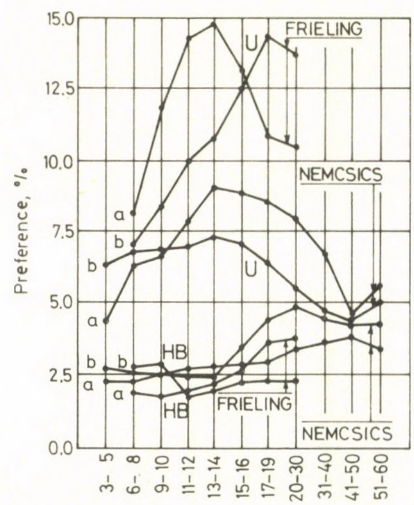


Fig. 4.28. Preferences of men (a) and women (b) for ultramarine (U) and light blue (HB) vs. age, after tests by Frieling and Nemcsics. Notations as in Fig. 4.25

Preference diagrams deviated more for saturated green than for olive green. In the former case a slight change of saturation abruptly altered preference, while in the latter, the variation of saturation was hardly followed by that of preference. Moreover, curves in Figs 4.29 and 4.30 of the colour preference index number system based on votes by over 75 thousand test subjects showed that there are certain critical saturations, for which preference depends more on saturation than for others.

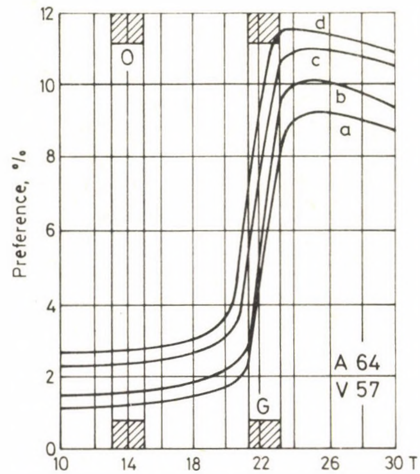


Fig. 4.29. Preferences vs. saturations of boys (a) and girls (b) aged 15 to 16, and of men (c) and women (d) aged 31 to 40 for greens of the same hue ($A=46$) and lightness ($V=57$), but different saturations (O olive green, G saturated green) after tests by Nemcsics

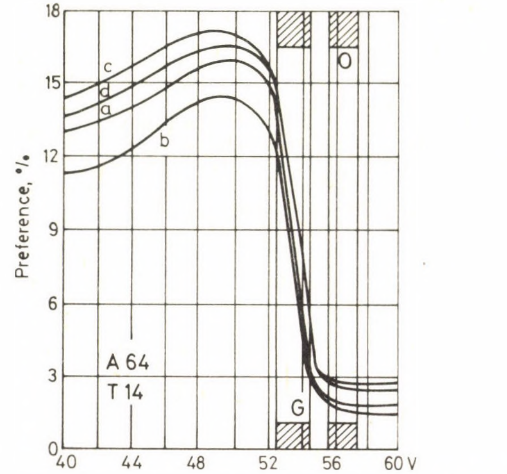


Fig. 4.30. Preferences vs. lightness of boys (a) and girls (b) aged 15 to 16, and of men (c) and women (d) aged 31 to 40 for greens of the same hue ($A=64$) and saturation ($T=14$) but different lightnesses (O = olive green, G = saturated green), after tests by Nemcsics

It follows, that for colour dynamics, data are useful only if they refer to exactly defined colours. Unfortunately, most of the published colour preference experiments ignored this condition.

Application of colour preference test results to colour dynamics is also hampered because data are not available for all the surface colours. Until now tests seldom determined preferences for more than a few hundred surface colours, moreover in tests involving a large number of persons, at most 25 to 30 colour shades were tested. If against the millions of colours distinguishable to the human eye, we take the number of the colours of available building materials and paints as about ten thousands there is a large gap between the number of colours tested and those utilized. One way to resolve this contradiction is to settle for very few shades for building uses, but this results in a bleak, "stereotyped" environment. Or else, preferences for every utilized colour have to be determined, and this was the approach followed in developing the colour preference index number system outlined below (Nemcsics, 1980c).

4.2.4. Recording Colour Preference Data

The third requirement posed by colour dynamics as a science and the practice of environment colour design for colour preference experiments and their results is that it should be possible to express preference data on a scale with limits. In the current practice of processing colour preference experiments numbers represent only the preference order of colours. For instance, in FRIELING's experiments (1968), red was the first, purple the second, greenish blue the eleventh among the tested 25 colours as valued by girls 5 to 8 years old. This scale of orders simply means that under certain environmental conditions, girls aged 5 to 8 prefer red to purple, and purple overtakes greenish blue by ten colours. It is not known, however, by how much red is preferred to purple and purple to greenish blue.

This scale of orders is unable to demonstrate the degree of liking, albeit preference should be considered in the selection of colours for a space to be designed, it is just the degree of liking that decides whether a certain colour is suitable in a given surrounding for a given population. That is, for the purposes of colour dynamics colour preference values are ordered according to a proportional psychometric scale with beginning and end points. The colour preference index number system was built up from such scales.

4.2.5. Colour Selection in Practice

The fourth requirement of the science of colour dynamics and of practical environment colour design for colour preference experiments and results is that they should express the active relation of man to colour.

In addition to passively perceiving colours, man's attitude to colour has also active components. Man is active when deciding about the colour of a hat he buys, the colour of his walls to be painted. A schoolchild is active when selecting colours for a drawing. An essential problem of practical colour dynamics is the relation between this active colour selection and colour preference diagrams obtained in tests. If colour preference results obtained in tests do not perfectly fit practical colour selection they are useless for design. Therefore experiments have to be made in stages, so that the test person should be induced to exhibit an active attitude toward colours.

Such a multistage test series performed with the needs of colour dynamics in mind served to create the colour preference index number system for use in practical environment colour design. Test results have been compared to colour preferences manifested, on one hand, in colour drawings of a child spontaneously depicting his sensations, and on the other, in creations of painters. In Fig. 4.31, colour averages found in drawings and experimental colour preferences of six year old children have been compared to average colour preferences proper to their ages given by the index number system. According to all three, concordant results, children of six years prefer and utilize most frequently red and orange. It is even more striking to compare colours in "Still Life with Sunflowers" painted by VAN GOGH at 35 years, "Senecio" painted by KLEE at 43 years, and "Ox Skull" painted by PICASSO at 74 years, and the given age-dependent colour preference average curves (Figs 4.32 to 4.34). Test results from pair-wise comparisons and from ranking methods are represented by separate curves. Ranking test results have been separated between those for saturated and for dull colours. Special curves represent

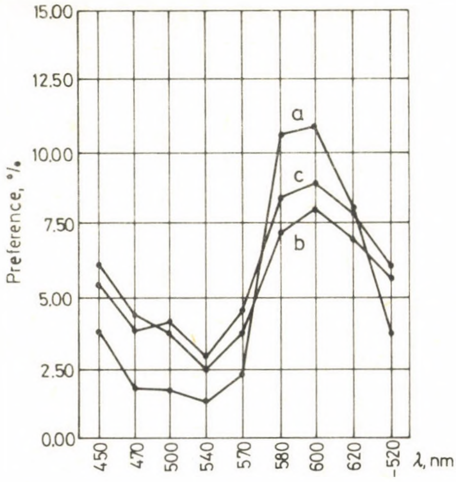


Fig. 4.31. Comparison of colour preferences in % vs. dominant wavelengths of the hues (after NEMCSICS). Curve a) preference shown in drawings of a boy aged 6, curve b) preferences of the same boy in test, c) average preference for the age group

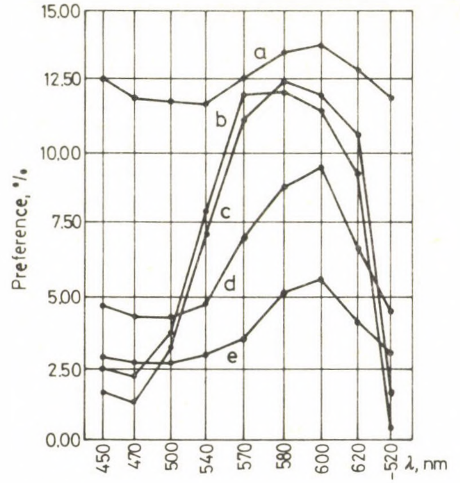


Fig. 4.32. Colour preference expressed in VAN GOGH's "Sunflowers", typical of men aged 35. Notations as in Fig. 4.31. a) Preferences by men aged 35 obtained by pair-wise comparisons, b) preferences in VAN GOGH's picture, c) colour selection for the concept of summer, d) preferences for saturated colours obtained by ranking, for men aged 35, e) preferences for dull colours obtained by ranking, for men aged 35

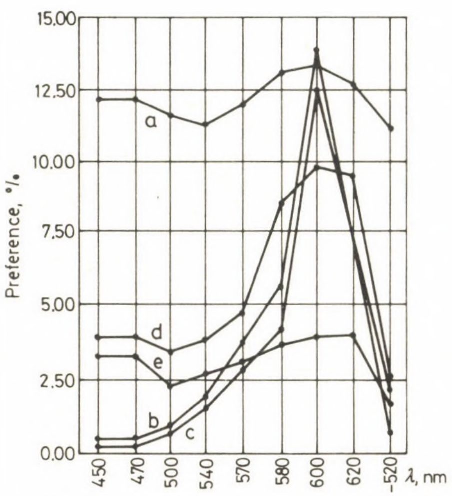


Fig. 4.33. Colour preference manifest in KLEE's "Senecio" typical of men aged 43. Curve a) as in Fig. 4.32. Curve b) refers to preference manifest in colours of KLEE's picture, while curve c) to colour selection for the concept of love

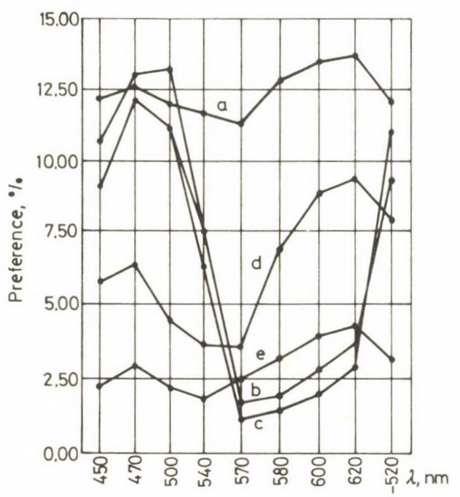


Fig. 4.34. Colour preference manifest in PICASSO's "Ox Scull" typical of men aged 74. Notations as in Fig. 4.32. except curves b) and c). Curve b) refers to preference manifest in colours of PICASSO's picture, while curve c) to colour selection for the concept of fear

colour percentages in the pictures, as well as relative proportions of colours related to the conceptual message of the pictures, i.e. their colour association content. Diagrams demonstrate that in the pictures by Van Gogh and Klee, preferences of the artists were in conformity with preference test results. This is not true for Picasso's picture where the message overwhelms colour preference in his age group.

4.2.6. Multistage Colour Dynamic Experiment

In conformity with the aspects above, we undertook at the Technical University of Budapest a multistage colour preference test series in order to create a colour preference index number system (Nemcsics 1967b, 1977d, 1980c). The experiments comprised six stages, such as: determination of 24 representative points of the colour space, of the continuous colour circle, of the achromatic and lightness scale, of the saturation scale, of colour preferences for discrete colour planes of the colour space, and lastly, recording colour preference surfaces and the inherent colour preference index numbers.

Experiments involved over seventy-thousand test persons, and were carried out under the following personal and material conditions: Ages covered a very wide range, from babies to very old people, classified in 12 age groups. Results were processed group-wise according to sex, age, education, profession, and environmental conditions, using punched cards, sorting devices, and computers.

Colour samples of 15 to 100 sq.cm area were displayed on horizontal surfaces in light incident through the window at about 45°, samples were observed at 90° from a distance of 100 cm. Care was taken not to have reflective coloured surfaces in the room and to have an achromatic ambience. Before the test, persons spent at least five minutes in the room to let their eyes adapt to the illumination level and the achromatic surrounding.

In order simultaneously and uniformly to perform this experiment involving a high number of test subjects, a large team was required. Identity of conditions was carefully checked. Test samples were selected from among a very high number of painted colour samples, on the basis of tristimulus colorimetry data. Correctness of colorimetry data was checked at random by means of a spectrophotometer. Coloroid and CIE *XYZ* coordinates of every test colour have been recorded. Test results refer to Coloroid coordinates.

4.2.7. Preferences for Representative Points of the Colour Space

The first step in our tests was to determine preferences for colour points representing the entire colour space, to serve as references in subsequent tests. Test colours were of different hues and lightnesses. Test persons were selected so as to embrace in correct proportions all age groups of both sexes. The twelve age groups were: 0 to 3, 4 to 5; 6 to 8; 9 to 10; 11 to 12; 13 to 14; 15 to 16; 17 to 20; 21 to 30; 31 to 40; 41 to 50, and over 50 years (Nemcsics, 1967). Testing teams worked simultaneously. Identity of test materials between all the groups was safeguarded; also test conditions were kept uniform in each group. Test samples were illuminated by reflected daylight incident from the

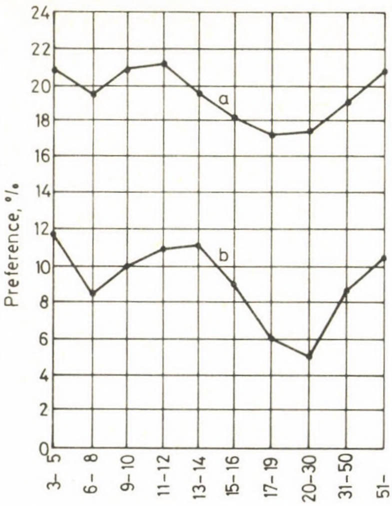


Fig. 4.35. Comparison of women's preferences vs. age groups for red obtained by (a) pairwise comparison and (b) ranking based on tests by NEMCSICS

north sky. Illumination was about 1500 lx. Circumstances, environment, weather, and illumination were recorded on special sheets.

Tests were made both by ranking and pair-wise comparison. For both methods, colours were presented to test persons in a definite arrangement. In the ranking experiments, all the test colours were simultaneously presented and the persons were invited to arrange them in the order of their liking. In pair-wise comparison, test persons had to choose from each two colours until all the possible pairs were judged. Test sheets were such as to be compatible with computer processing. Millions of data from test sheets were punched on cards, then classified by computer and colour preferences by age groups of both sexes were expressed in percentages, such as:

$$x_p = \frac{100 n_P}{m}, \tag{114}$$

where x_P is the preference percentage for colour P; n_P is the number of votes for colour P; and m the total number of test persons. Processing involved principal colours, colour pairs, colour groups, colour series, and perceptional colour characteristics.

Some of the results which are already useful for environment colour design, will now be presented. Figure 4.35 showing preferences for red by women of different ages serves only to illustrate differences between results obtained by pair-wise comparison and by ranking. The two curves are strikingly similar, which means that for a sufficiently large number of test persons, both methods yield similar results.

Environment colour design may directly exploit results for colour pair preferences (Figs 4.36 through 4.40). These figures demonstrate how much the preference for a colour is affected by the colour adjacent to it. It also shows that at different ages of life not only the relation to a given colour varies but also the other colour to which the given colour is preferred. Let us see some examples.

Co-preference for red and orange is about uniform throughout one's life, except for women aged 20 to 30 significantly preferring orange emitting warmth to red (Fig. 4.36). For pairs of red and green, preference is given to red at any age, albeit in different percentage (Fig. 4.37). In general, red is preferred to almost any accompanying colour and even if displaced by blue for a significant period of life, it loses ground gradually.

The situation is different in ranking yellow and violet. Boys aged 18 definitely prefer yellow, while men aged 31 to 50, violet (Fig. 4.38). Interestingly, women react to this pair of colours less extremely than do men; in spite of that they are more sensitive to any of these colours when seen isolated than are men. In contrast, women's preference for a

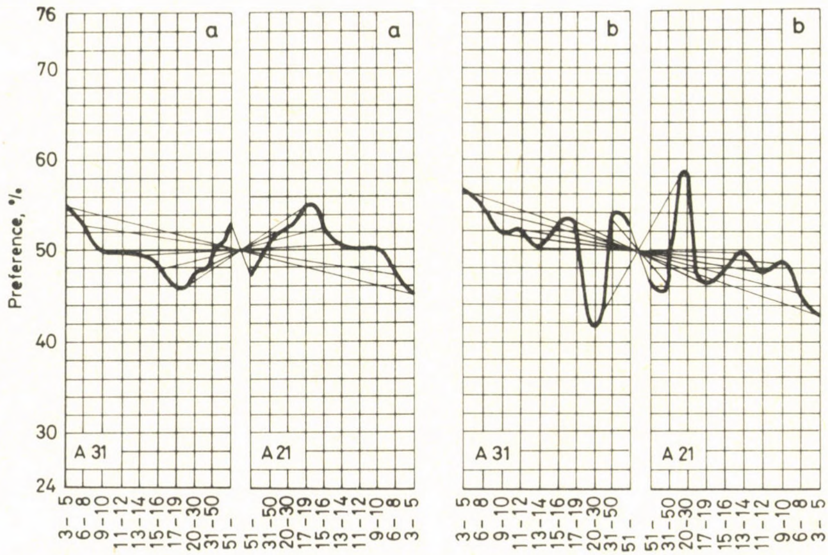


Fig. 4.36. Preferences vs. age groups for the pair of colours red (*A*31) and orange (*A*21) by men (a) and women (b)

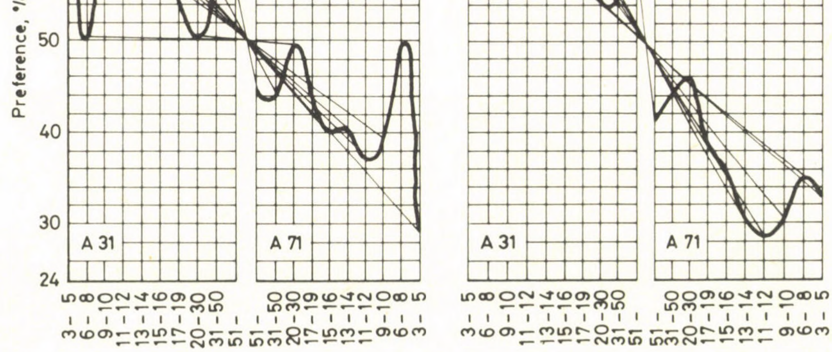


Fig. 4.37. Preferences vs. age groups for the pair of colours red (*A*31) and green (*A*71) by men (a) and women (b)

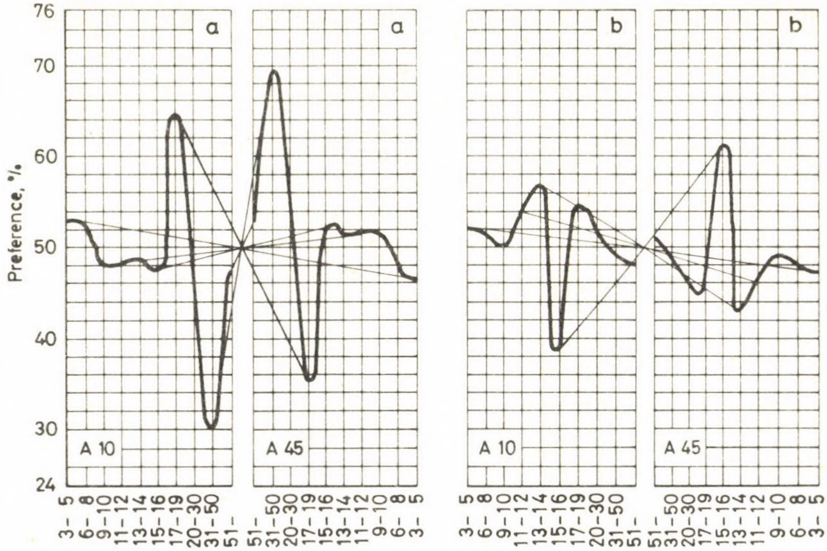


Fig. 4.38. Preferences vs. age groups for the pair of colours yellow (*A*10) and violet (*A*45) by men (a) and women (b)

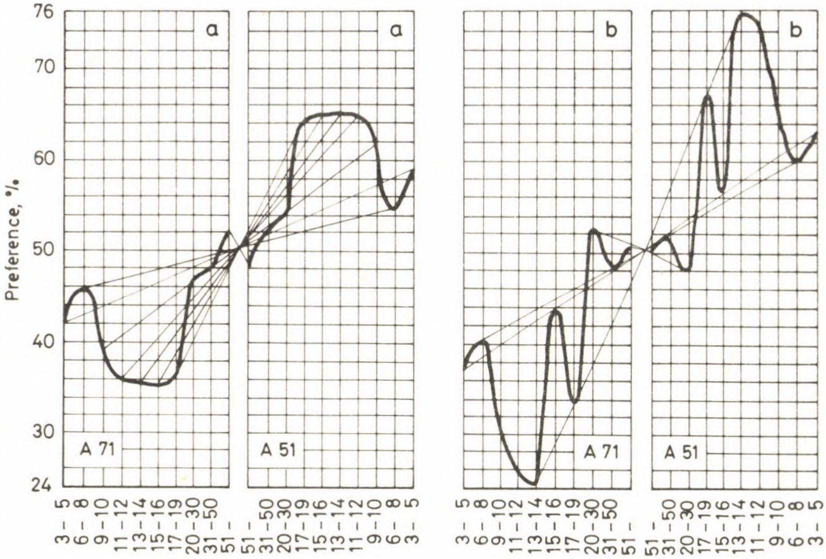


Fig. 4.39. Preferences vs. age groups for the pair of colours green (*A*71) and blue (*A*51) by men (a) and women (b)

combination of green and blue varies dynamically with age (Fig. 4.39). Young boys are especially sensitive to the combination of orange and yellow (Fig. 4.40). Such findings are useful in colour design because they inform us about which colour combinations are to be applied for an environment intended for a given age group.

Comparison of preferences in given age groups for colours in a given domain of different saturations and lightnesses in various colour domains yields, depending on the hue, rather different conclusions. In the red domain the most saturated red is preferred by any age group, save men aged 20 to 30 who prefer red-brown to scarlet. Preference curves for colours throughout the red domain are rather similar (Fig. 4.41). On the other hand, preferences for colours in the green and blue domains are more differentiated. Notably for any hue, the most saturated colours are not those which are preferred. In both colour domains women react more sensitively to colours than men (Figs 4.42, 4.43).

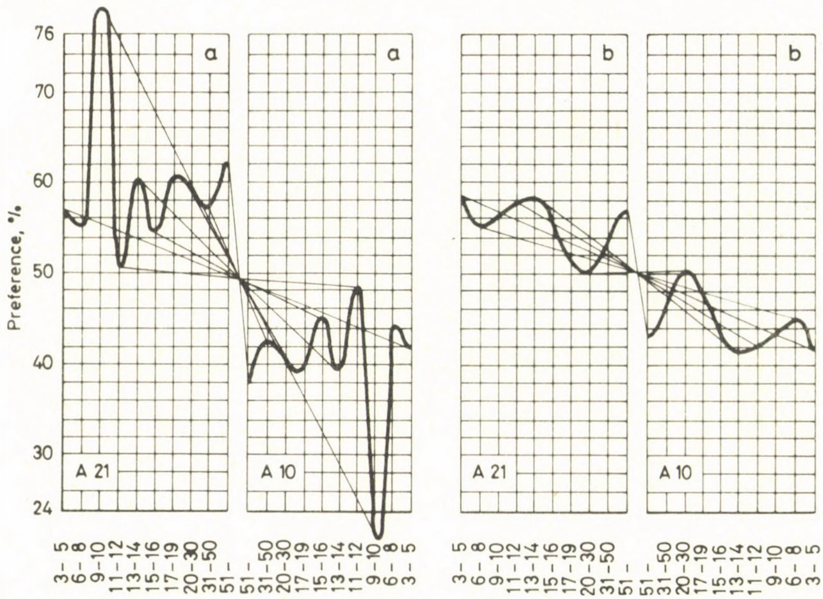


Fig. 4.40. Preferences vs. age groups for the pair of colours orange (*A*21) and yellow (*A*10) by men (a) and women (b)

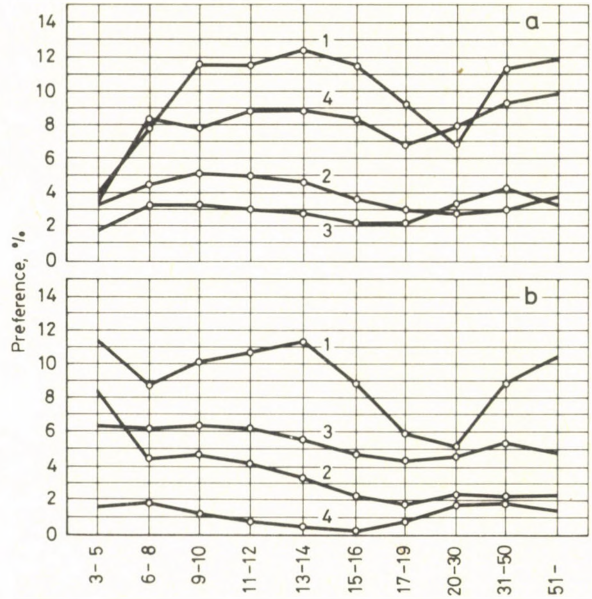


Fig. 4.41. Preferences vs. age groups for different shades of red by men (a) and women (b). 1. vermilion, 2. carmine, 3. pink, 4. English red

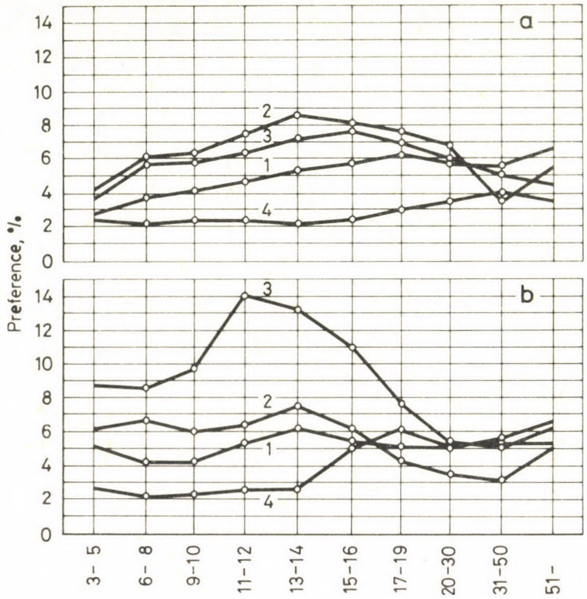


Fig. 4.42. Preferences for age groups for different shades of blue by men (a) and women (b). 1. cobalt blue, 2. ultramarine, 3. manganese blue, 4. light blue

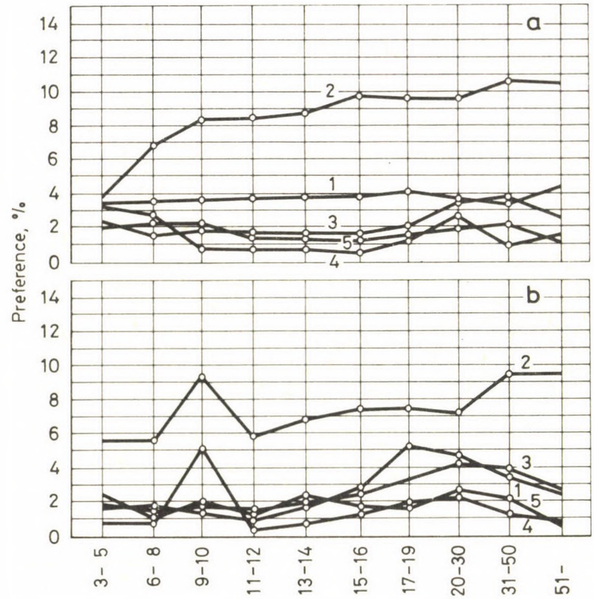


Fig. 4.43. Preferences vs. age groups for different shades of green by men (a) and women (b) in different age groups. 1. viridian dull, 2. yellowish green, 3. viridian hydrate, 4. olive green, 5. light green

It is striking to compare preferences for saturated and dull colours. It is obvious from Fig. 4.44 that saturated colours are preferred by women up to 19 years, and by men up to 20 years, but while thereafter the relation of men to colours hardly varies, women of 20 to 50 years—against the common belief—definitely prefer dull colours, only to return to saturated colours over 50. Sexes agree much more in their attitude towards light and dark colours. Both prefer light colours throughout their whole lives. Preferences for light and for dark colours differ the least at about 18 years for both sexes (Fig. 4.45). Sorting colours according to their associative messages as cold and warm ones, it is found that men prefer warm colours up to 15 years, then, from 15 to 30 years, cold ones, only to return later to warm colours. On the other hand, women prefer emotional, warm colours nearly throughout their lives, except for 17 to 19 years, the age of mental maturation (Fig. 4.46).

The above and similar result were both tabulated and plotted. In order to apply results as references for proportional scales to be set up in subsequent experiments, preference

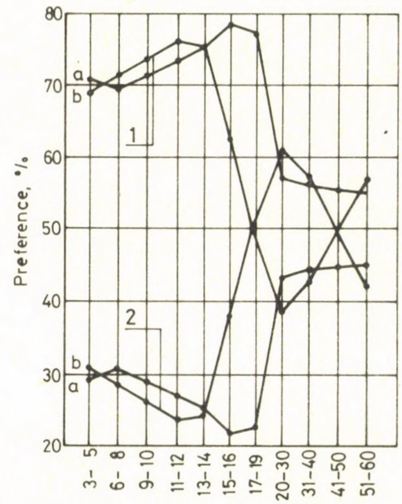


Fig. 4.44. Preferences vs. age groups for saturated (1) and dull (2) colours by men (a) and women (b)

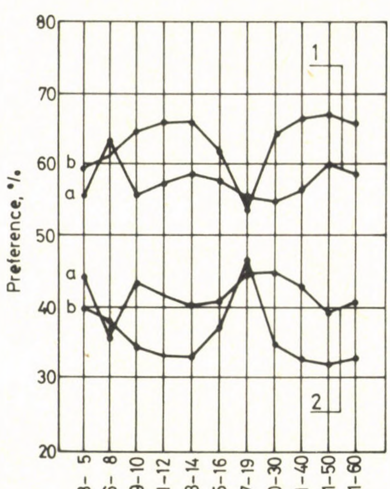


Fig. 4.45. Preferences vs. age groups for light (1) and dark (2) colours by men (a) and women (b)

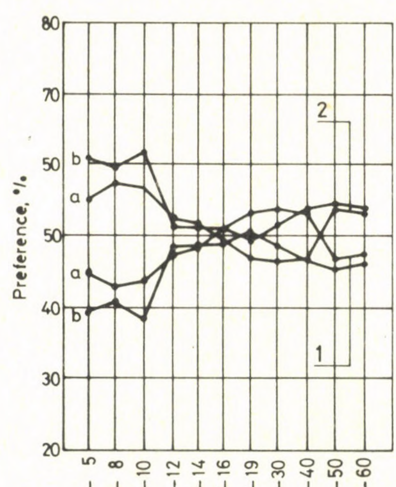


Fig. 4.46. Preferences vs. age groups for cold (1) and warm (2) colours by men (a) and women (b)

percentages were converted to *relative preferences* rated from 0 to 100:

$$x_{P_{rel}} = \frac{100 x_P}{x_{P_{max}}}, \tag{115}$$

where $x_{P_{rel}}$ is the relative preference for colour P; x_P is preference for the colour defined by (114), and $x_{P_{max}}$ is the highest preference percentage among the tested colours.

4.2.8. Preferences in the Continuous Colour Circle

The second stage of our test series was to determine preferences for members of the colour circle comprising surface colours of the highest saturations possible. For the experiment the most saturated colours which could be mixed out of paints, representing the 48 Coloroid hues, were assorted. Care was taken that the lightness of the selected colours should vary continuously. Colours were presented to test persons together, i.e. six samples were fixed on a board each. Test conditions, observation and illumination geometries, light intensity, and spectral energy distribution of the light source were as before and the ranking approach was used.

Results have led to the conclusion that among saturated colours, children prefer two colours: red and blue, adding up later to three: red, green and blue, i.e. the basic colours of colour vision.

In order to enable comparison between "preference for saturated colours" of the colour circle with "preference for dull colour" in former tests, the "preferences for the continuous colour circle" curves were transformed so as to be comparable to curves for "preferences for representative points of the colour space". Transformation was made normally to axis t defined by test preferences for two colours (Fig. 4.47). Coloroid and CIE XYZ coordinates of these two colours were:

	Coloroid	CIE		
	A T V	x	y	Y
Colour P_1	22.00–57.00–71.00	0.5220	0.4289	50.41
Colour P_2	51.00–28.00–33.00	0.1945	0.1492	10.89

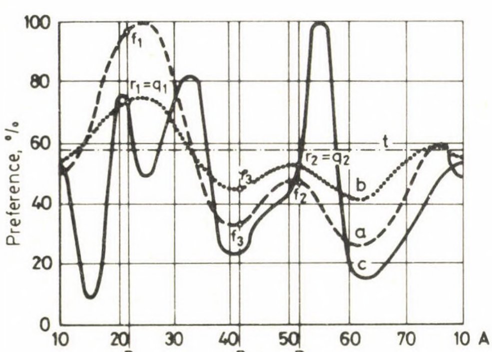


Fig. 4.47. Transform (b) of the preference curve of the continuous colour circle (a) in the reference system defined by curve (c) for the relative preferences for representative points of the colour circle. Horizontal axis shows hues in the Coloroid colour circle

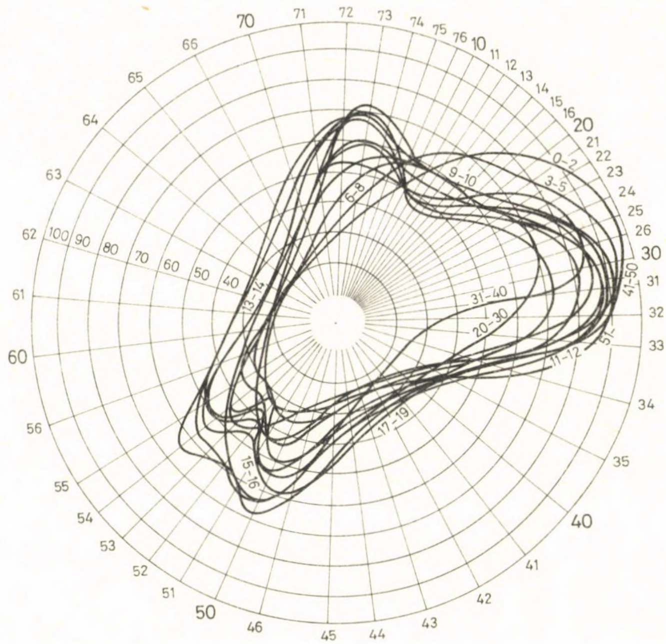


Fig. 4.48. Preferences by men of different ages for colours of the saturated colour circle. Perimeter of the circular diagram shows various Coloroid hues. Preference increases from the centre toward the perimeter. Curves refer to different age groups

Preference percentages for colours P_1 and P_2 among "representative points", that is, in our reference system, and in the "continuous colour system" are marked r_1, and f_1, respectively. According to Fig. 4.47:

$$(r_1-t):(f_1-t)=(r_2-t):(f_2-t) \tag{116}$$

whence the axis of normal affinity applied for transformation is defined as:

$$t=\frac{r_2 f_1-f_2 r_1}{f_1-f_2+r_2-r_1}. \tag{117}$$

In Fig. 4.47 relative preferences by boys aged 17 to 19 for representative points of various hues is shown by a solid line, preference for the continuous colour circle by a dashed line, and transformed of this latter by a dotted line.

If f_3 be the preference for an arbitrary colour P_3 out of the test on preference for the continuous colour circle and q_3 its transformed in the reference system, then, according to Fig. 4.47:

$$(q_3-t):(f_3-t)=(r_2-t):(f_2-t), \tag{118}$$

yielding the degree of affinity as:

$$q_3=\frac{r_2 f_3-t(r_2+f_3-f_2)}{f_2-t}. \tag{119}$$

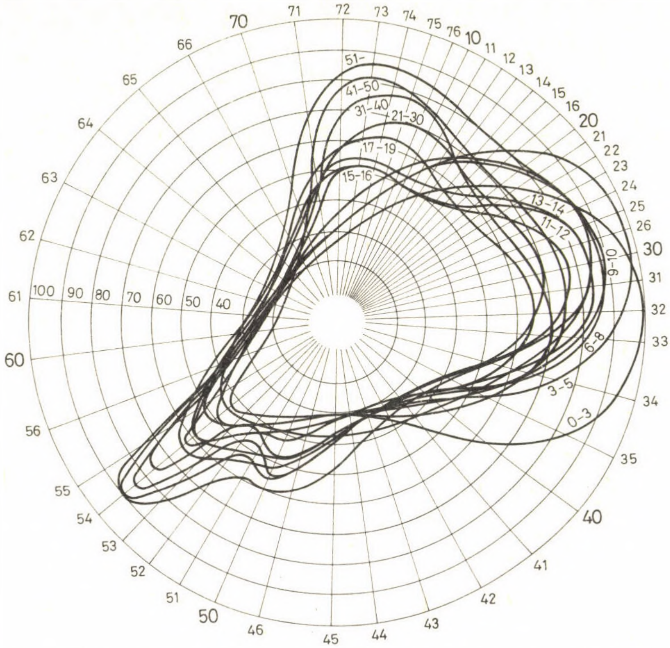


Fig. 4.49. Preferences by women of different age groups for colours of the saturated colour circle. Notations as in Fig. 4.48

Owing to this transformation comparison of colour preferences of different age groups can be conveniently illustrated on a circular diagram. Colour preferences of men and women in different age groups were represented in Figs 4.48 and 4.49, respectively. Diagram circumferences show preference values for various Coloroid hues, while radii show those for saturated colours of the given hue on the colour circle. Figures point out important variations with age in preferences primarily for yellowish green, red and blue, while those for bluish green and violet hardly vary throughout one's life. Attitudes of women to colours vary much more than those of men. For women, variation is most conspicuous in the domain of cold blues, and for men in that of warm blues.

4.2.9. Preferences on the Achromatic and Lightness Scales

Tests on representative points of the colour space involved also white, medium gray and black. Among the achromatic colours in most age groups medium gray was the least preferred. No data were, however, available, such as to indicate whether the preference varies continuously with decreasing lightness. This prompted us to perform an additional preference test on nine achromatic colours. Achromatic colours presented to test persons had Coloroid lightnesses of 95, 85, 75, 65, 55, 45, 35, 25, 20. Tests were also made with colours of different Coloroid lightnesses, hues and saturations. Colours were fixed on boards but not in the order of their lightness. Colour sample sizes, test circumstances, observation and illumination geometries, light intensity and spectral energy distribution of the light source were as above. The tests were conducted by the ranking method.

Results are shown in Figs 4.50 and 4.51, referring to achromatic scale preferences of men in different age groups. The same for women is shown in Figs 4.52 and 4.53. From the diagrams it is obvious that preference variation can be described by a continuous curve parallel to colour lightness variation, as well as, that it is the preference for middle gray which varies the most with age. Grays somewhat lighter or darker than medium are always more popular than medium gray.

As before results were transformed to preference system serving as reference. Coloroid and CIE *XYZ* coordinates of colours P_1 and P_2 defining the axis of transformation

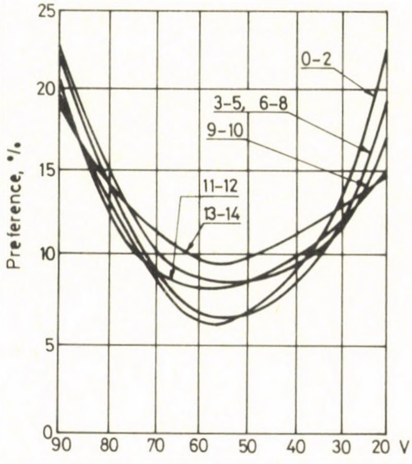


Fig. 4.50. Preferences vs. lightness by boys of different ages for colours in the achromatic scale. Horizontal axis shows lightnesses, vertical axis shows preferences in per cents. Curves refer to different age groups

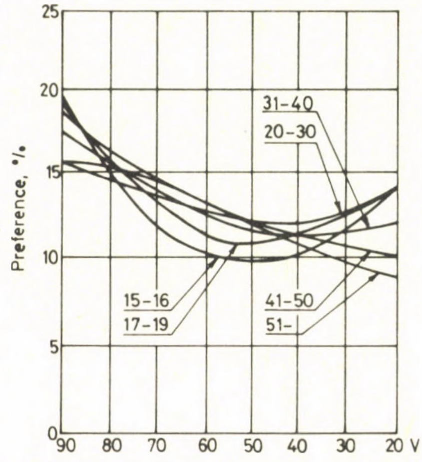


Fig. 4.51. Preferences vs. lightness by men of different ages for colours in the achromatic scale. Notations as in Fig. 4.50

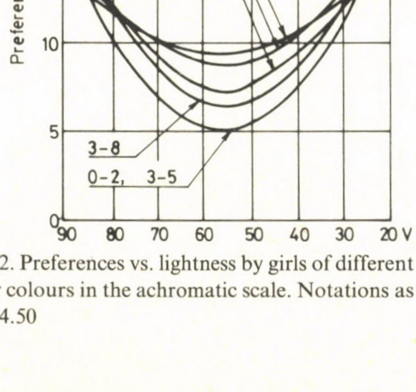


Fig. 4.52. Preferences vs. lightness by girls of different ages for colours in the achromatic scale. Notations as in Fig. 4.50

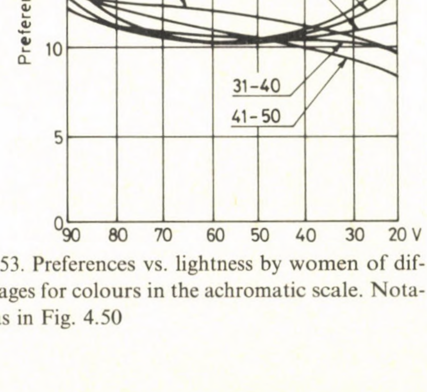


Fig. 4.53. Preferences vs. lightness by women of different ages for colours in the achromatic scale. Notations as in Fig. 4.50

are:

	Coloroid	CIE		
	$A \quad T \quad V$	x	y	Y
Colour P_1	00.00–00.00–55.00	0.31006	0.31616	30.25
Colour P_2	00.00–00.00–20.00	0.31006	0.31616	4.00

Transformation applied Eqs (119) and (121).

4.2.10. Preferences in the Saturation Scale

Again we wished to collect data concerning the effect of saturation on preference for different hues. Four hues were selected and saturation scales comprising colours of equal lightnesses were prepared.

Test persons were presented colour samples fixed on boards and grouped by hues but not ordered according to saturations. Otherwise, conditions were as before.

Results showed preferences to vary along a continuous curve parallel to the variation of saturation. Preference was found to vary unevenly between the most saturated surface colour and gray of the same lightness. Preferences for points at one third of scale can be used to characterize preferences for other scale points. This finding was utilized later, in selecting colours for preference tests on discrete colour planes of the colour space. The statements above are illustrated by Figs 4.54 through 4.59, referring to preferences for given hues and lightnesses by men and women in different age groups.

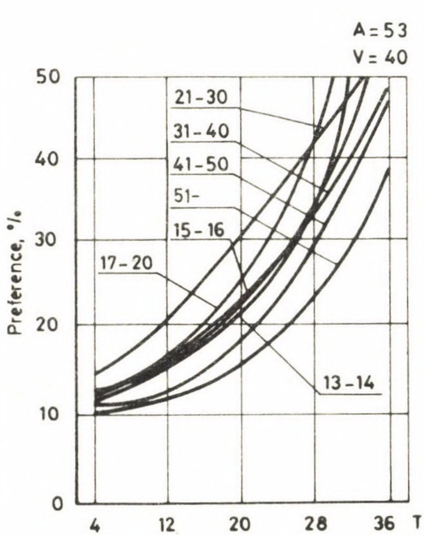


Fig. 4.54. Preferences vs. saturation by men of different ages for blues ($A53$) of different saturations, darker than medium gray ($V40$). Horizontal axis shows saturations, vertical axis shows preference in per cents. Curves refer to different age groups

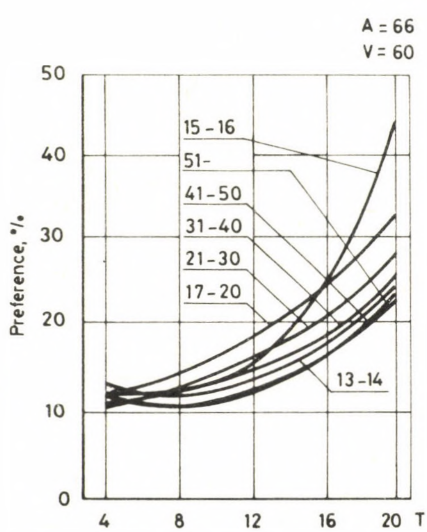


Fig. 4.55. Preferences vs. saturation by men of different ages for greens ($A66$) of different saturations, lighter than medium gray ($V60$). Notations as in Fig. 4.54

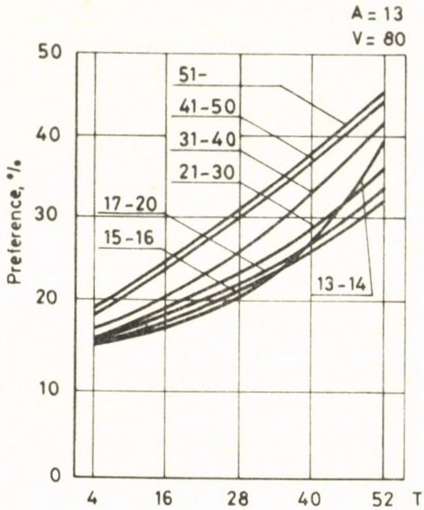


Fig. 4.56. Preferences vs. saturation by men of different ages for very light (*V*80) yellows (*A*13). Notations as in Fig. 4.54

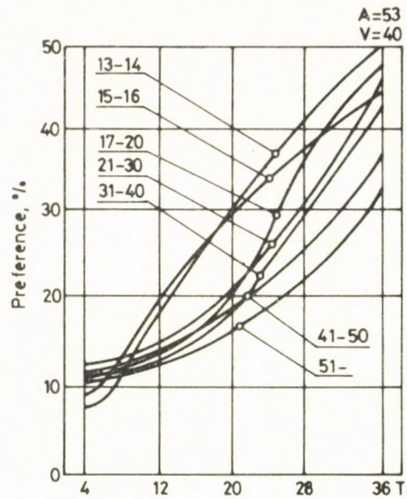


Fig. 4.57. Preferences vs. saturation by women of different ages for blues (*A*53), darker than medium gray (*V*40). Notations as in Fig. 4.54

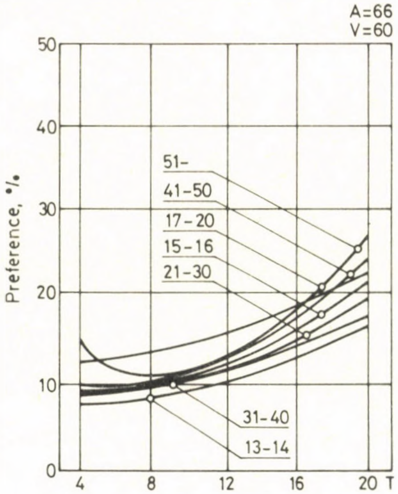


Fig. 4.58. Preferences vs. saturation by women of different ages for greens (*A*66), lighter than medium gray (*V*60). Notations as in Fig. 4.54

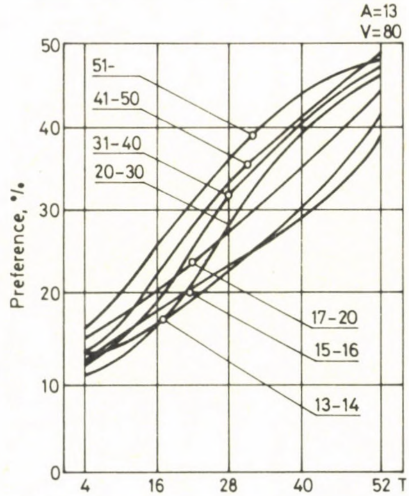


Fig. 4.59. Preferences vs. saturation of women of different ages for very light (*V*80) yellows (*A*13). Notations as in Fig. 4.54

4.2.11. Preferences in Discrete Colour Planes of the Colour Space

The last test series dealt with discrete colour planes of the colour space. Since within the planned system, we wished to assign preference value to each surface colour of the colour space, data for those points of the colour space were needed between which preferences for the intermediate colours could be determined by relationships resulting from correlations described before. In view of previous tests we thought that the knowledge of preferences for nine colour points each, properly selected in 48 discrete colour planes for Coloroid basic hues would suffice to approximate preferences for all the surface colours.

Examination of preference curves obtained from tests on lightness and saturation scales has led to the conclusion that by preference values for colour points pertinent to a colour plane a continuous preference surface situated above the given colour plane can be defined (Fig. 4.60). The distance of the surface points from the colour plane is proportional to the preference value of the colour represented by that point. These

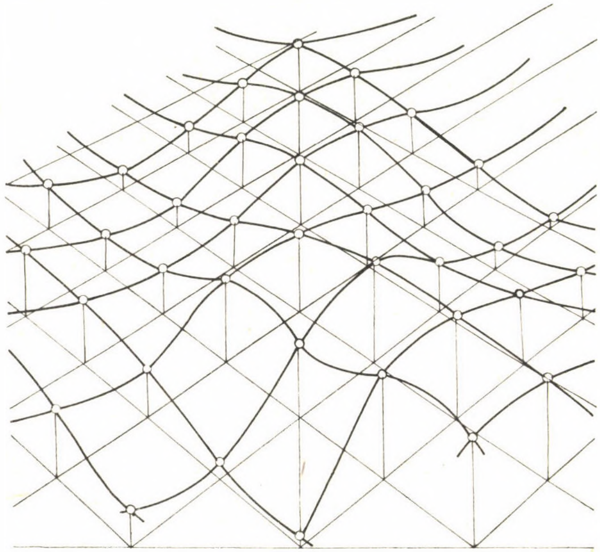


Fig. 4.60. Colour preference surface overlying a Coloroid colour plane. Distances of the intersections of normals at colour points and the preference surface are characteristic of the preference for that colour point

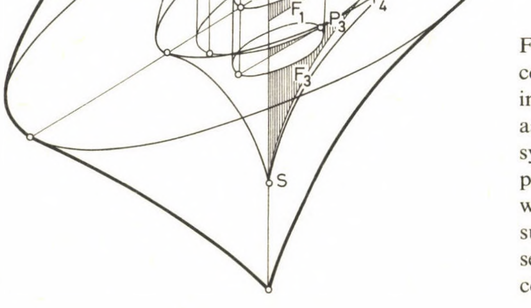


Fig. 4.61. Geometric loci (F_0, F_1, F_2, F_3, F_4, F_5) of colours of discrete colour planes of the colour space in the Coloroid colour solid with preferences serving as the basis of the colour preference index number system. Basic data for preference surfaces are preferences for 9 points in every colour plane, such as white (W), gray (G), black (S), the most saturated surface colour (P_0) in the colour plane, and intersection points P_1, P_2, P_3, P_4, P_5 of curves in the colour plane

preference surfaces are closely approximated to by a quadratic two-variable function written for nine, adequately selected points. Out of the nine colours, three are achromatic, one saturated, and the other five properly selected dull colours.

Preferences for achromatic and saturated colours being available from previous tests, the actual test was expected to furnish preferences for five differently dull colours for each hue, totalling 240, to make up the still missing basic data of the colour preference index number system. These 240 surface colours were located within the colour space under the following conditions: colours represented two saturations for each hue, dividing into three parts the saturation scale. Less saturated colours occurred in three, more saturated ones in two varieties for each hue.

Locations within the Coloroid colour space of the selected colours are shown by curves in Fig. 4.61. Colours applied to determine preferences for discrete colour planes of the colour space lie on curves F_0, F_1, F_2, F_3, F_4, F_5. For the construction of preference surfaces, initial data were obtained from preferences for the nine points i.e. white (W), gray (G), black (S), the most saturated surface colour in the colour plane (P_0), and intersection points of the curves and the colour plane (P_1, P_2, P_3, P_4, P_5).

Colour samples were fixed on boards and presented to test persons one Coloroid hue after the other. Test conditions were as before, evaluation was by ranking. Test results were transformed to the reference preference system. Transformation axis was defined by the preference for the most saturated colour of each hue, and for gray of Coloroid lightness V55.

4.2.12. The Colour Preference Index Number System

Preference values for 291 colours uniformly distributed over the colour space are the basic data of the colour preference index number system. Using these data, to every colour of the colour space a number from 0 to 100, proportional to its preference can be assigned, making up the colour preference index number system.

Colour preference conditions in various domains of the colour space can be best visualized by plotting the basic data in circular diagrams. Preferences for colours in the colour space based on a total of 6912 basic data obtained in twelve age groups each of both sexes were plotted in Figs 4.62 through 4.85. Curves show preference rates of colours of different saturations and different lightnesses of the 48 Coloroid basic hues. Preference values range from 0 to 100, increasing from the centre of the diagram to its periphery. Curves P_0, P_1, P_2, P_3, P_4, P_5 refer to the most saturated surface colours, to unsaturated medium light, unsaturated very light, unsaturated very dark, medium saturated dark, and medium saturated light colours, respectively.

Some typical conclusions to be drawn from these diagrams are as follows: Both girls and boys up to 8 years prefer mainly red and at this young age, saturated colours are preferred. But there are also differences. For instance, orange is preferred by girls two years old, and by boys eight years old. The opposite is true for vermilion. Up to eight years of age, boys and girls prefer colours of different saturations and lightnesses in the same order. Over this age, colour preferences of boys and girls gradually diverge. At ten years of age, boys increasingly prefer yellowish green and warm blue, while girls prefer orange and cold blue. Girls aged 14 definitely prefer cold blue to red, while boys of the same age still prefer red. Boys place medium saturated light colours before medium

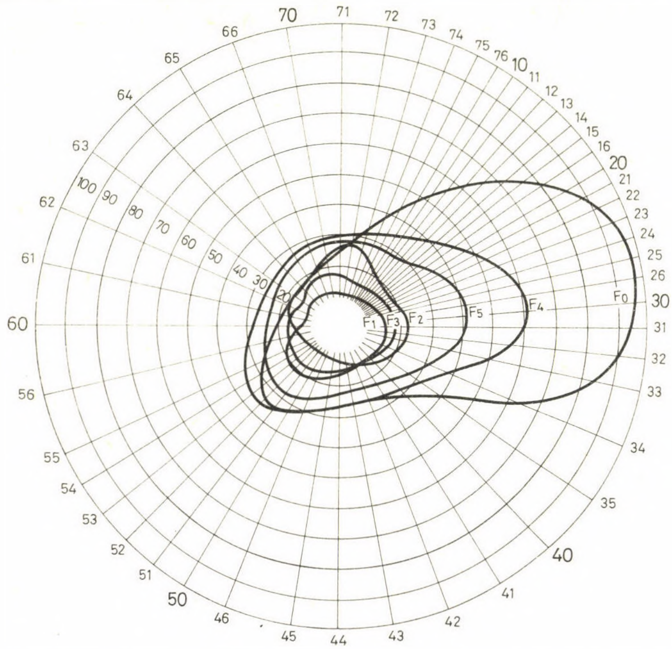


Fig. 4.62. Preferences by boys aged 0 to 2 for 291 colours uniformly distributed in the colour space

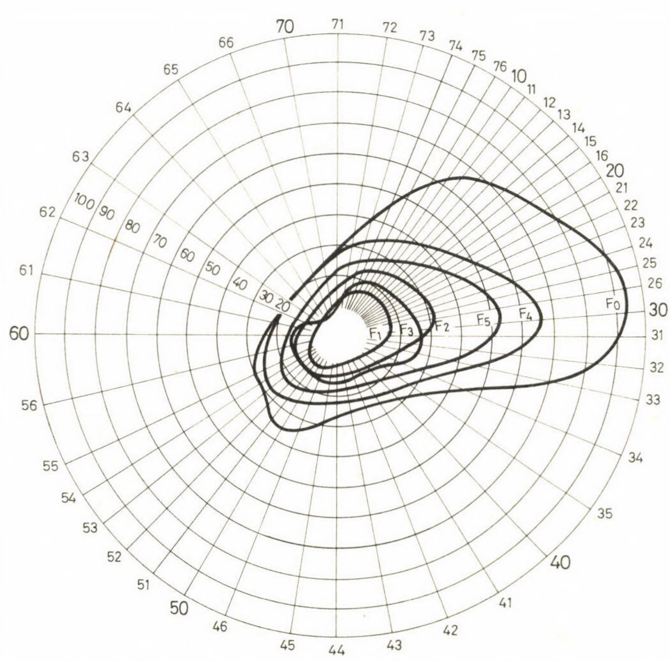


Fig. 4.63. Preferences by boys aged 3 to 5 for 291 colours uniformly distributed in the colour space

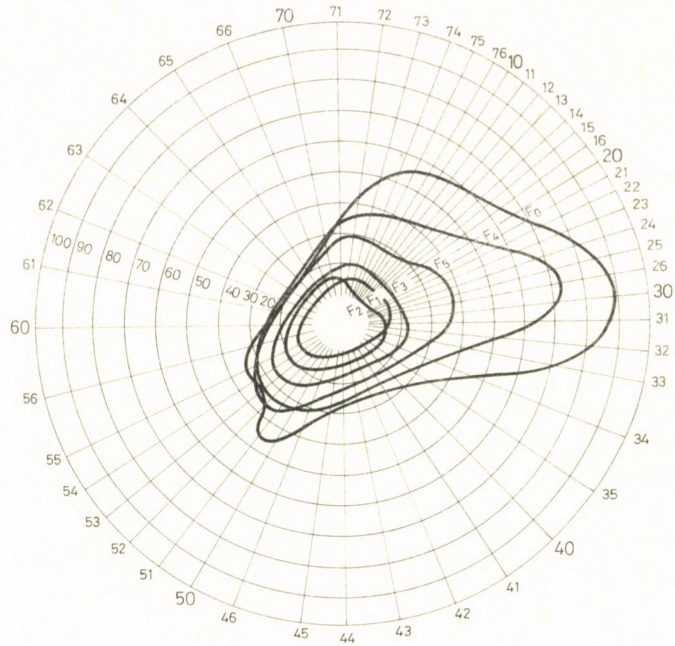


Fig. 4.64. Preferences by boys aged 6 to 8 for 291 colours uniformly distributed in the colour space

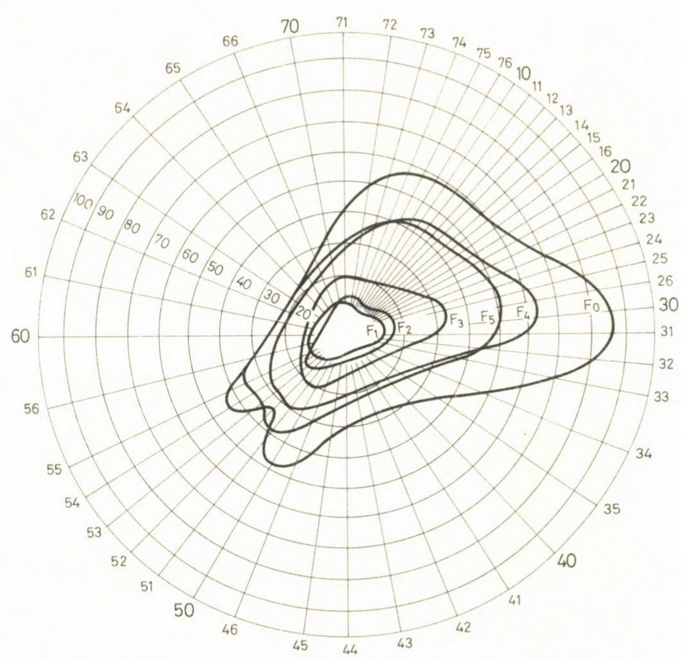


Fig. 4.65. Preferences by boys aged 9 to 10 for 291 colours uniformly distributed in the colour space

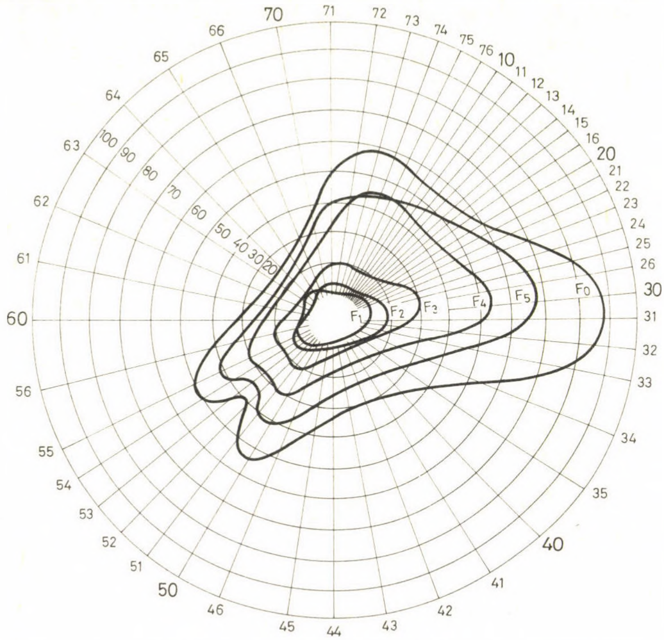


Fig. 4.66. Preferences by boys aged 11 to 12 for 291 colours uniformly distributed in the colour space

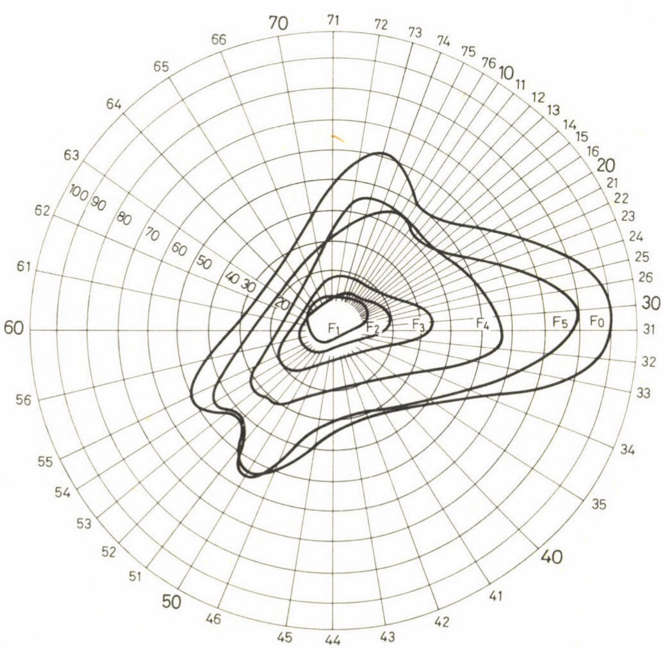


Fig. 4.67. Preferences by boys aged 13 to 14 for 291 colours uniformly distributed in the colour space

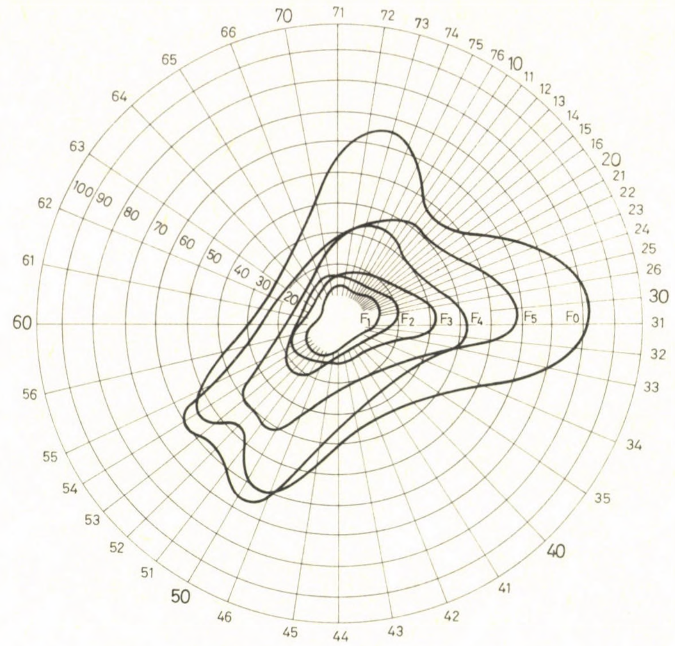


Fig. 4.68. Preferences by boys aged 15 to 16 for 291 colours uniformly distributed in the colour space

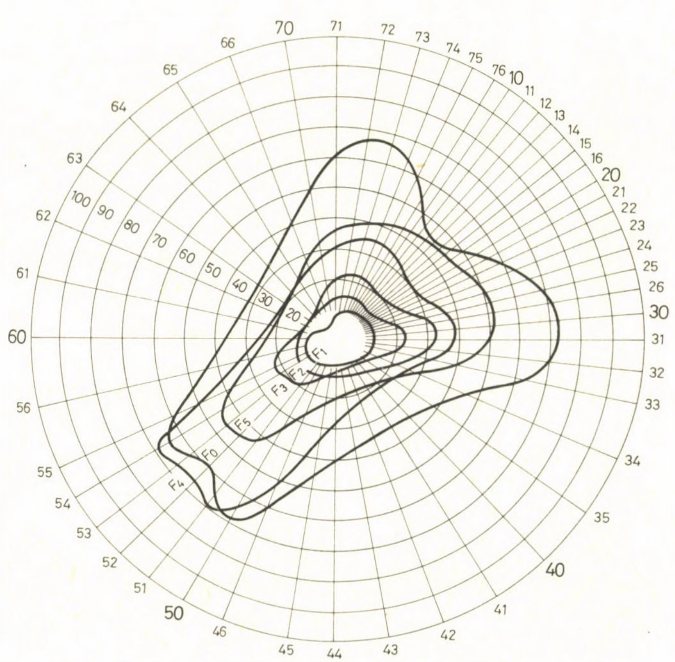


Fig. 4.69. Preferences by boys aged 17 to 19 for 291 colours uniformly distributed in the colour space

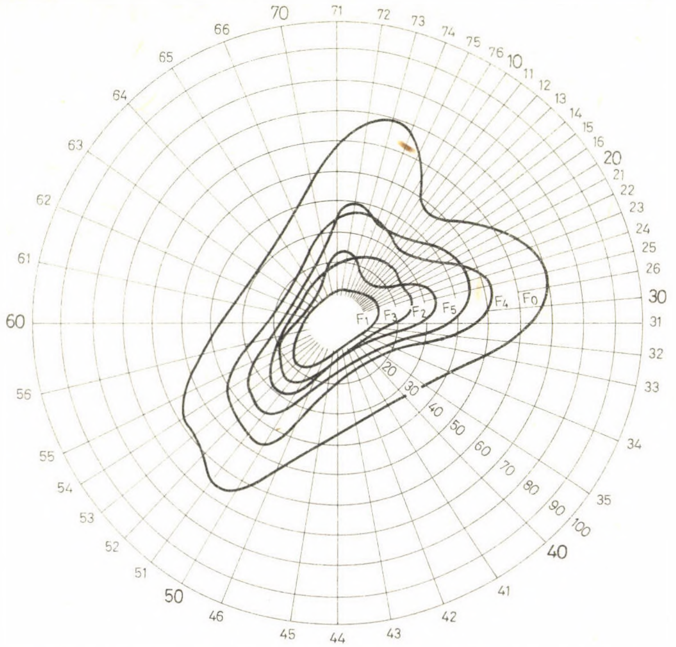


Fig. 4.70. Preferences by men aged 20 to 30 for 291 colours uniformly distributed in the colour space

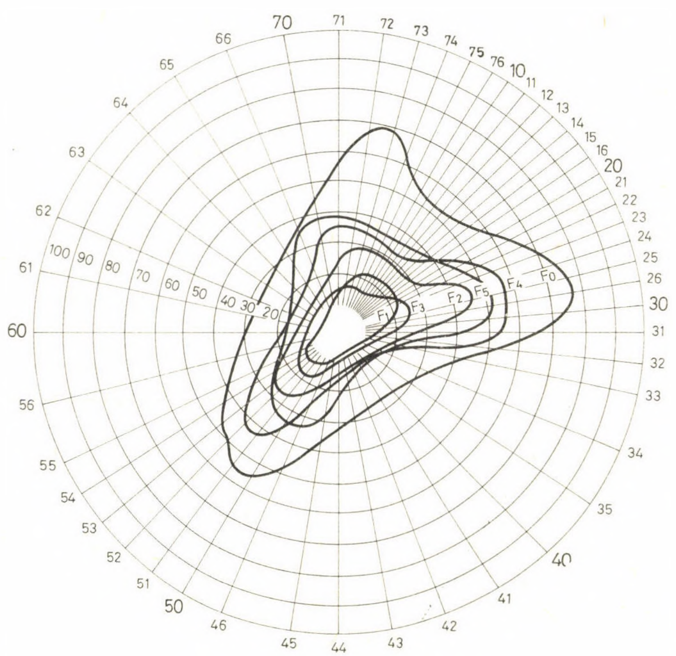


Fig. 4.71. Preferences by men aged 31 to 40 for 291 colours uniformly distributed in the colour space

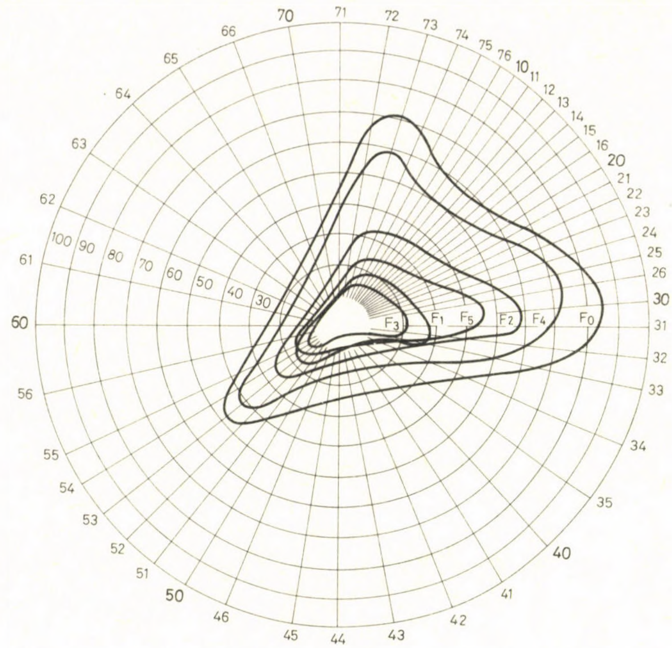


Fig. 4.72. Preferences by men aged 41 to 50 for 291 colours uniformly distributed in the colour space

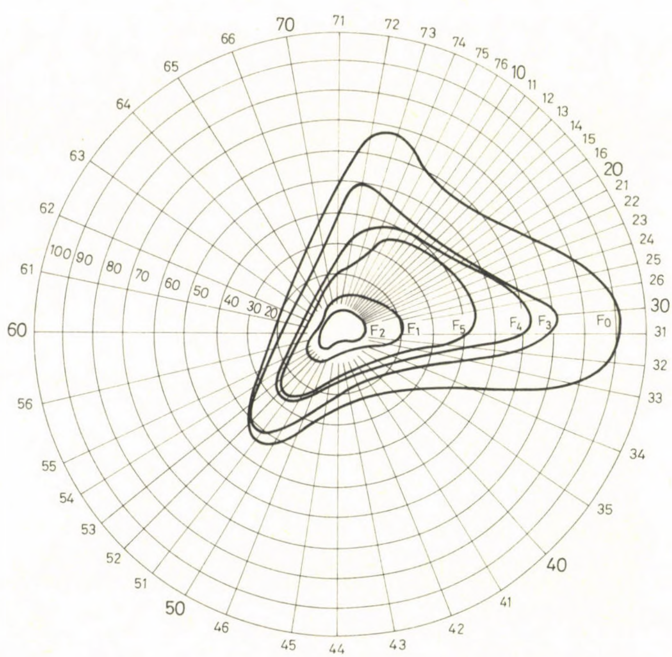


Fig. 4.73. Preferences by men over 51 years for 291 colours uniformly distributed in the colour space

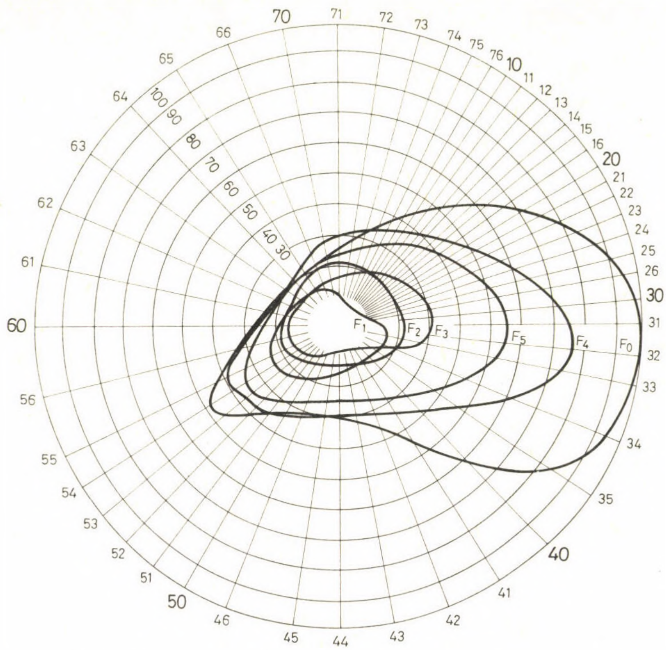


Fig. 4.74. Preferences by girls aged 0 to 2 for 291 colours uniformly distributed in the colour space

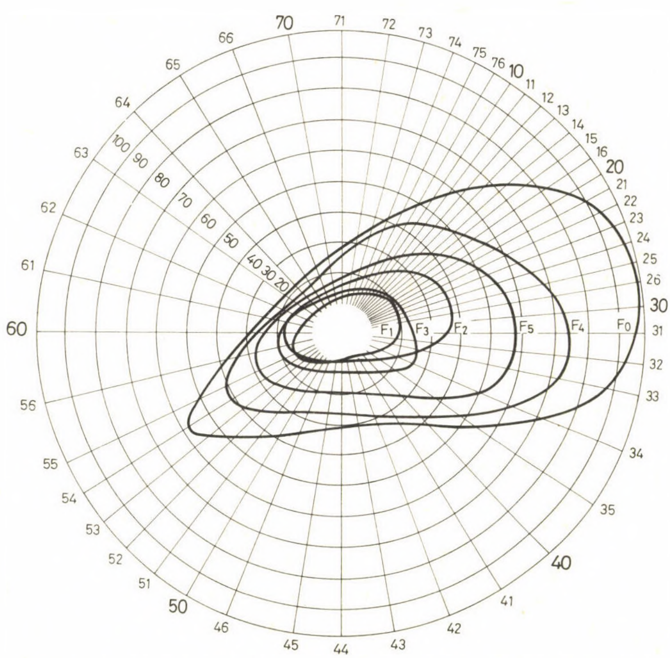


Fig. 4.75. Preferences by girls aged 3 to 5 for 291 colours uniformly distributed in the colour space

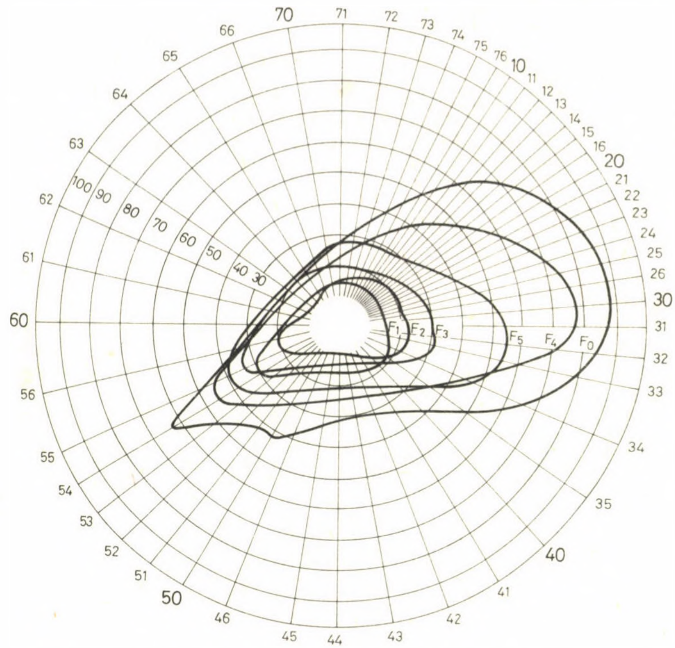


Fig. 4.76. Preferences by girls aged 6 to 8 for 291 colours uniformly distributed in the colour space

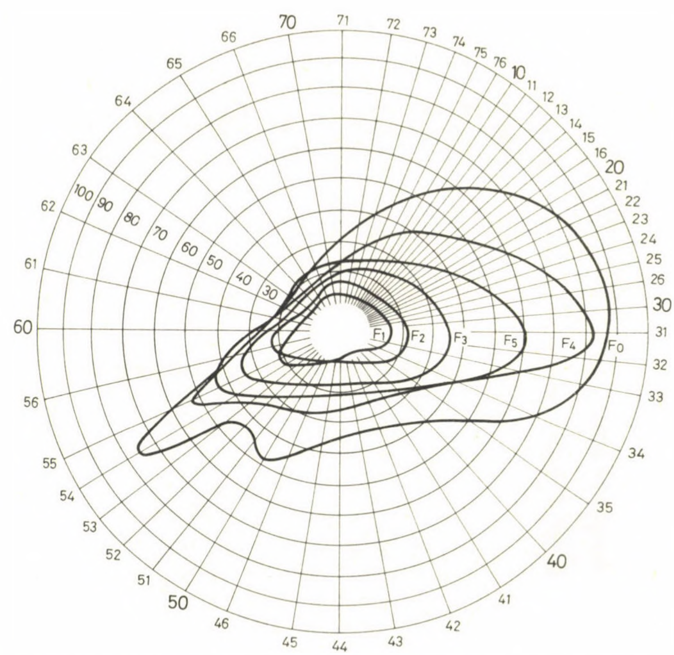


Fig. 4.77. Preferences by girls aged 9 to 10 for 291 colours uniformly distributed in the colour space

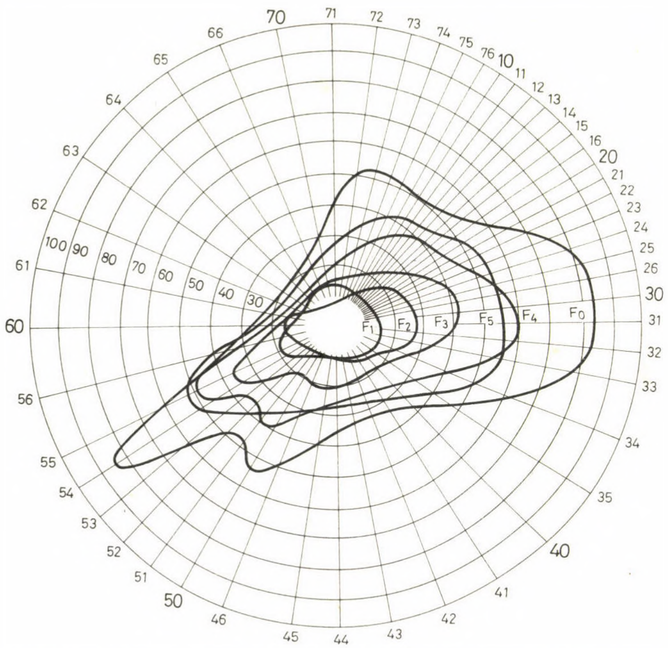


Fig. 4.78. Preferences by girls aged 11 to 12 for 291 colours uniformly distributed in the colour space

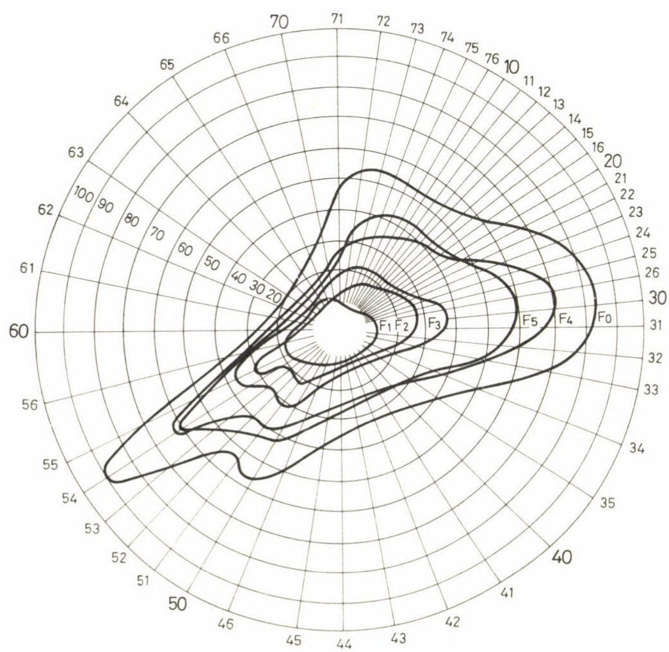


Fig. 4.79. Preferences by girls aged 13 to 14 for 291 colours uniformly distributed in the colour space

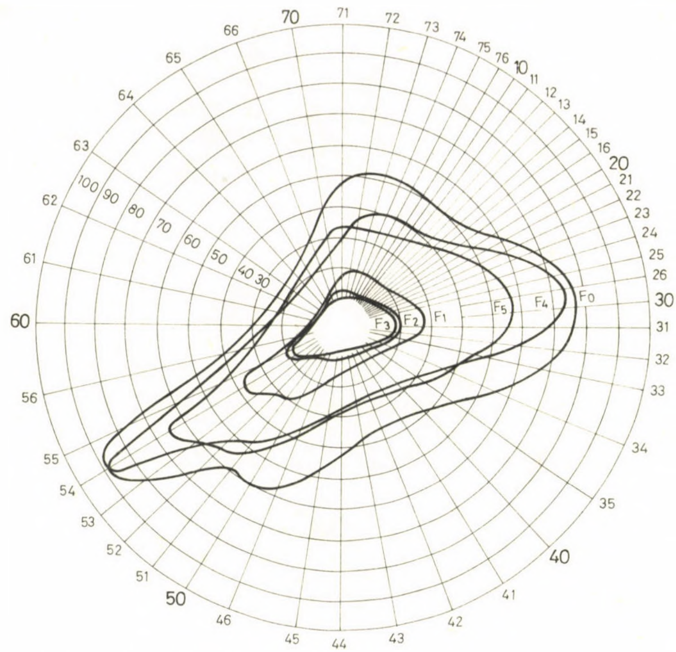


Fig. 4.80. Preferences by girls aged 15 to 16 for 291 colours uniformly distributed in the colour space

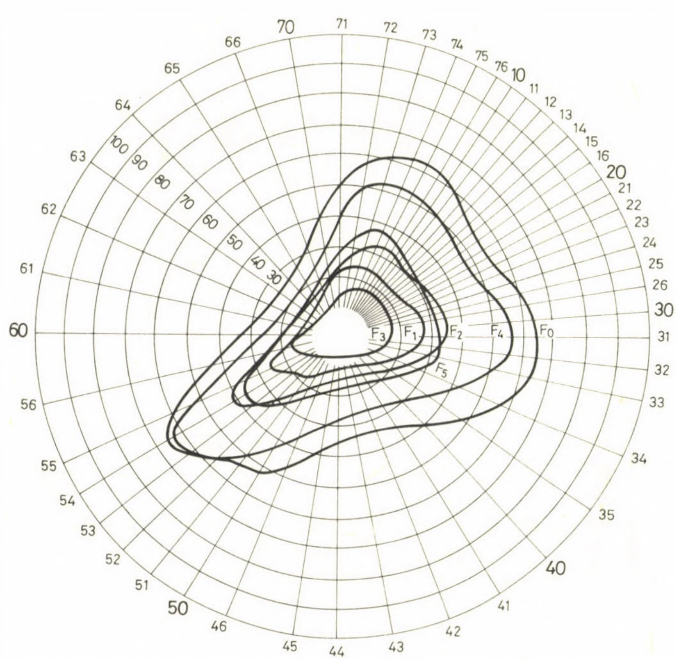


Fig. 4.81. Preferences by girls aged 17 to 19 for 291 colours uniformly distributed in the colour space

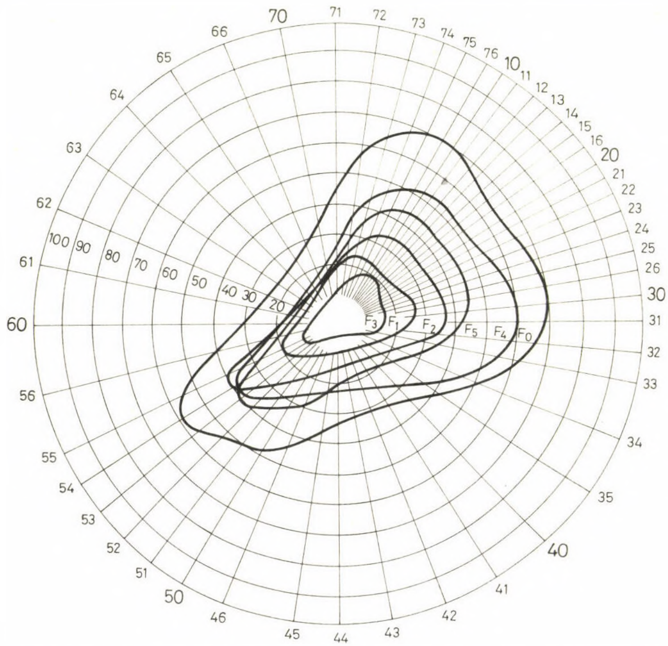


Fig. 4.82. Preferences by women aged 20 to 30 for 291 colours uniformly distributed in the colour space

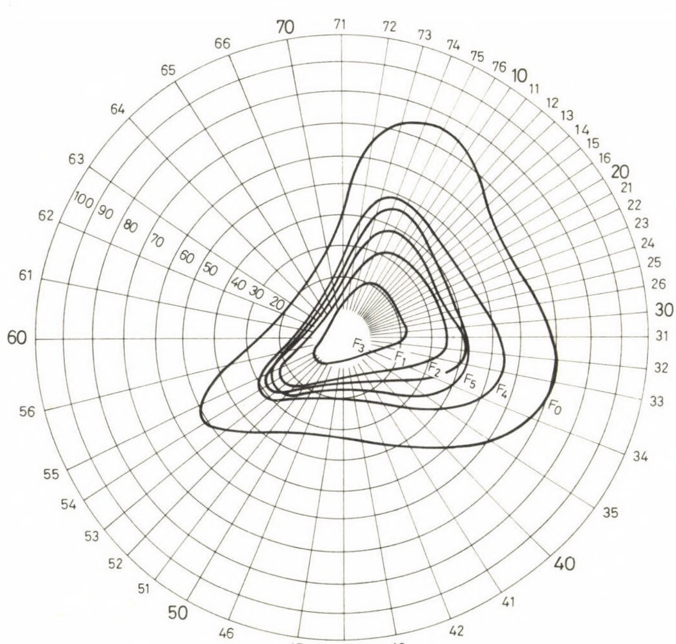


Fig. 4.83. Preferences by women aged 31 to 40 for 291 colours uniformly distributed in the colour space

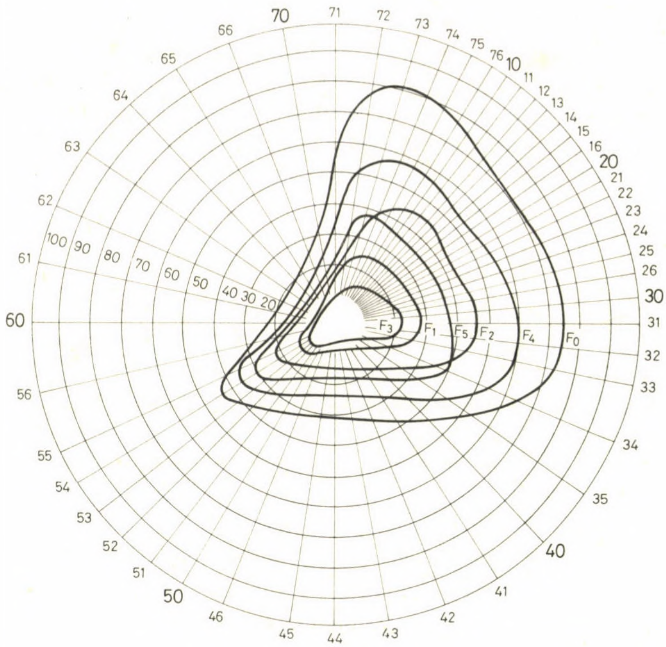


Fig. 4.84. Preferences by women aged 41 to 50 for 291 colours uniformly distributed in the colour space

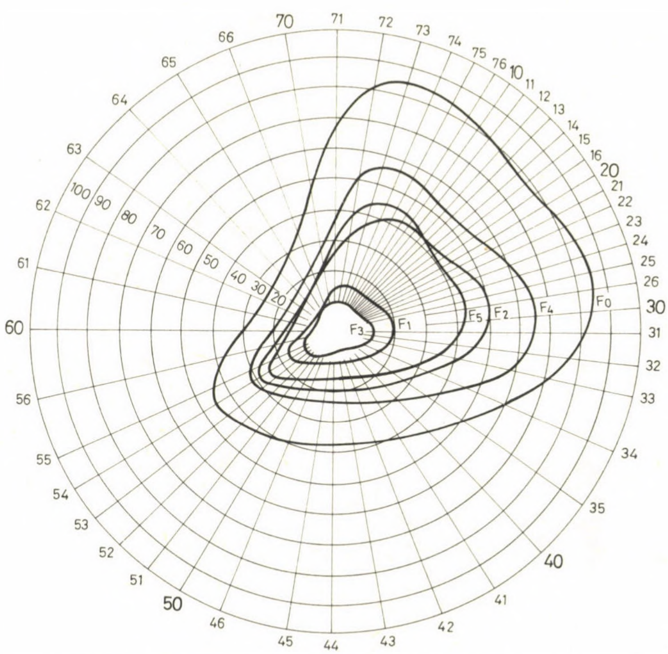


Fig. 4.85. Preferences by women over 51 years for 291 colours uniformly distributed in the colour space

saturated dark colours in any colour domain, while girls prefer medium saturated dark colours to light ones in colour domains red and green. Over 20 years of age, less saturated shades are ever more preferred, mainly by women. Beginning with 30 years, warm green, red and blue prevail in colour selection. When women choose green it is a more yellowish, red more purplish, and blue colder.

Preference values for every colour in colour planes corresponding to 48 Coloroid basic hues are obtained from:

$$P = AT^2 + BTV + CV^2 + DT + EV + F, \tag{120}$$

written for nine data in every colour plane, where P stands for preference, T for saturation, and V for lightness. Coefficients A, B, C, D, E, F have been selected so that section $T=0$ corresponding to the achromatic scale should be equal for every age group. So first coefficients C, E, F have been determined from data for points of white, gray and black, followed by other equations written by means of other points. Coefficients A, B, D have been determined from this redundant system of six equations with three unknowns, on the basis of the condition of least error square sum. It has to be noted that the equation for the most saturated surface colour has been accounted for with a weight factor ten. Interpolation between corresponding colour points of adjacent sections permits us to assign a preference value to every point ot the colour space.

For use in practical colour design, colour preference of a discrete colour for every ten Coloroid lightness units, and every four Coloroid saturation units in every colour plane have been computed, totalling for all the age groups 2248 preference values in each colour plane. Our preference tables contain a total of 107 904 index numbers, of them a set is presented in Appendix. These tables are useful in practical colour design, in particular, in the stage of colour delimitation (see Chapter 7). Adequate information on preferences for various domains of the colour space can be found in the circular diagrams above, which in the absence of tables can fulfil moderate demands. The entire set of tables will be issued as a separate publication.

4.2.13. Colour Preferences in History

Nowadays, there is an increasing tendency to clad historical towns in colours reflecting or expressing the age and original architectural style of buildings. In this case among the aspects of colour dynamics to be considered in colour choice, the historic points of view should prevail. In other words, instead of present day colour preferences, colours expressing the building age have to be selected. Historical ages can be impressively characterized by their colour preferences which originated by interaction between several factors.

Human colour preferences have always had physiological fundamentals. A sufficiently broad selection underlying appreciation of colour perceptions could only be provided by an adequately developed visual organ. Our relation to colours has, however, always been determined by the mentality of the given age, shaping and modulating ancient messages associated with colours. Means permitting the coloration of human environment, that is, paints and natural or artificially coloured materials have been the objective conditions and at the same time, proofs of colour preference, materializing the human desire to rejoice in colours.

It is a proven fact that colour distinction ability of the human eye is in continuous, and rapid development. The number of shades distinguishable to an average present day person much exceeds that of some hundred years ago. The sensitivity of vision can be developed, sensitivity of a painter's eye may be the multiple of that of a non-professional.

Overall definition of an age, the spirit of that age primarily reflects actual social conditions, relation of people to nature, to the world, knowledge and faith, ambitions and desires. An interplay of all these factors shaped relation to, and preference for colours by mankind in historical ages.

Possibilities to express relations to colours have always been delimited by known, available pigments, making them the decisive, objective conditions of colour preference. Originally, coloured minerals and plant juices have been used as pigments for decorating one's surroundings. Semantic messages have also been associated with colours. The longing for self-expression or to rejoice in colours urged man to extend his palette, and to add ever more colours and shades both to his environment and vocabulary.

Our ancestors were willing to bring great sacrifices to take possession of new, beautiful tones. Pigment mines of renown for some attractive pigments were goals of pilgrimage from the remotest points of the known world. Man in antiquity invested perhaps more effort to create a new shade, than the alchemist in making gold, and some pigments were valued higher than gold.

Colour preference in ancient Egypt is presented in Fig. 4.86, Greek, Roman, Mediaeval and Renaissance colour preferences in Fig. 4.87, while those in Baroque, Rococo, and Ottocento periods are seen in Fig. 4.88. It appears that originally, colours of the red domain prevailed, then gradually gave way to blue. Against an increasing preference for green and violet, yellow and orange gradually lost ground.

At the same time, however, variability, that is, the number of shades differing in saturation and lightness increased within the decreasingly preferred colour domains of red, orange, and yellow. For instance, within the red domain, Egyptian Memphis and

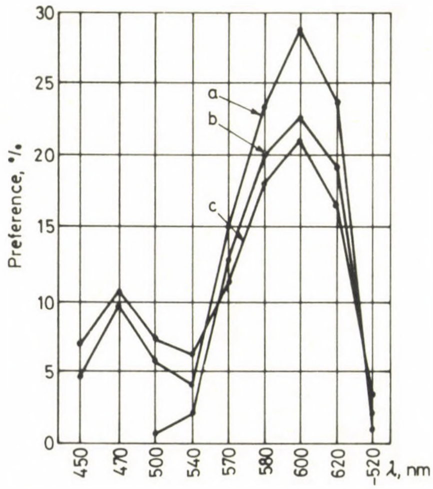


Fig. 4.86. Colour preferences in % in ancient Egypt vs. dominant wavelengths of hues, a) ancient empire, b) middle empire, c) new empire

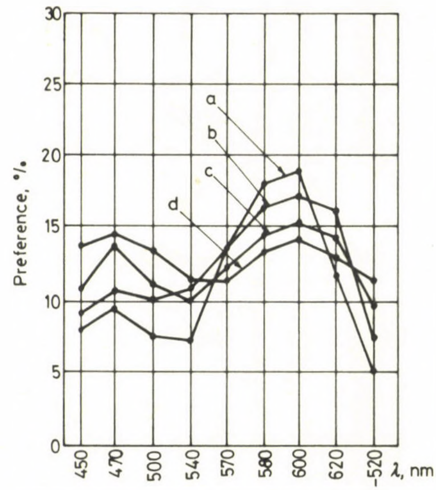


Fig. 4.87. Colour preferences in a) Hellenism, b) Roman age, c) Middle Ages and d) Renaissance. Notations as in Fig. 4.86

henna reds were similar by hue and saturation, as compared to minium, cinnabar and Pontian reds applied in Hellas, let alone the reds used in the Middle Ages, i.e. membrana, minium, cenobrium, carminium, terra rossa, vermiculum, sinopis, which were rather different not only by hue but also by saturation and lightness.

Colour preferences in Classicism and in Romanticism are given in Fig. 4.89. Change of preferences for yellow, red, and blue from ancient Egypt to the twentieth century appear in Fig. 4.90. Whilst preferences for red and blue thoroughly changed through the ages, that for yellow hardly did so. In the course of history, however, it was not only human relation to hues that underwent changes. In the Middle Ages intensive, saturated shades were liked, and so were contrasts, including lightness contrasts. In the Renais-

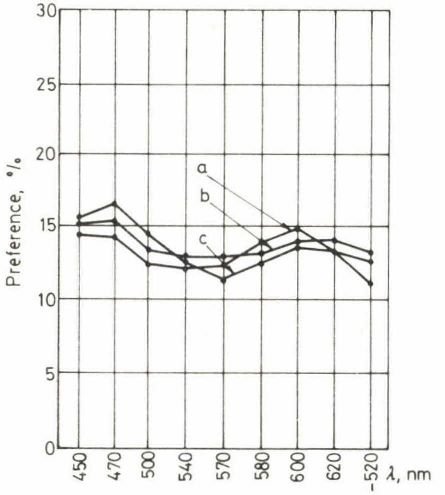


Fig. 4.88. Colour preferences in a) Baroque age, b) Rococo age and c) Ottocento. Notations as in Fig. 4.86

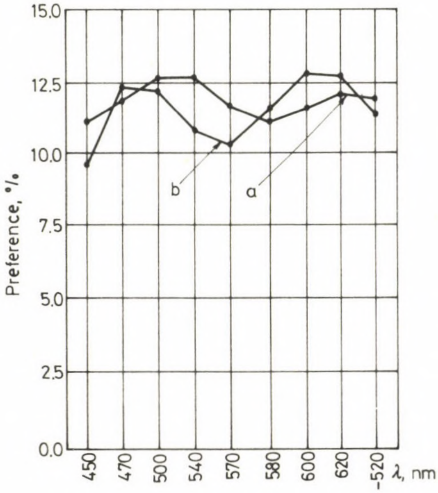


Fig. 4.89. Colour preferences in a) Classicism and b) Romanticism. Notations as in Fig. 4.86

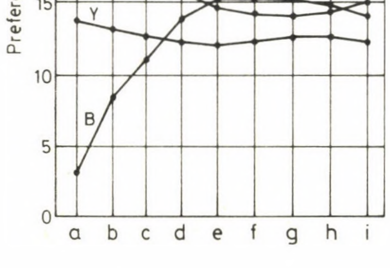
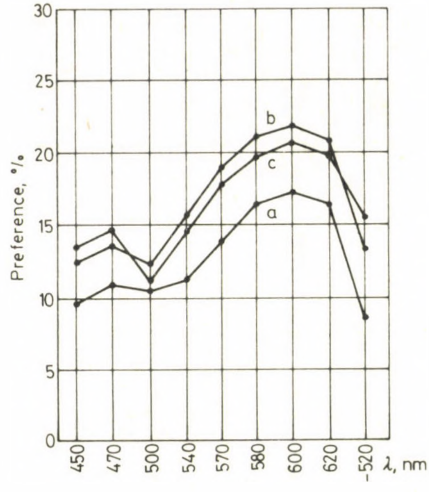


Fig. 4.90. Variation of preferences in % for red (R), yellow (Y), and blue (B) in the European culture complex. Notations along the horizontal axis: a) Egyptian, b) Hellenism, c) Roman, d) Middle Ages, e) Renaissance, f) Baroque, g) Rococo, h) 19th century, i) 20th century

Fig. 4.91. Comparison of colour preferences in % vs. dominant wavelengths of hues in a) the Roman age, b) by present-day boys and c) girls aged 11–12 years



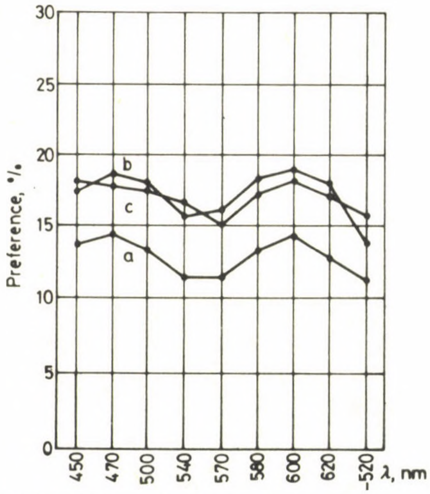


Fig. 4.92. Comparison of colour preferences in a) Renaissance, b) by present-day boys and c) girls aged 17 to 19. Notations as in Fig. 4.91

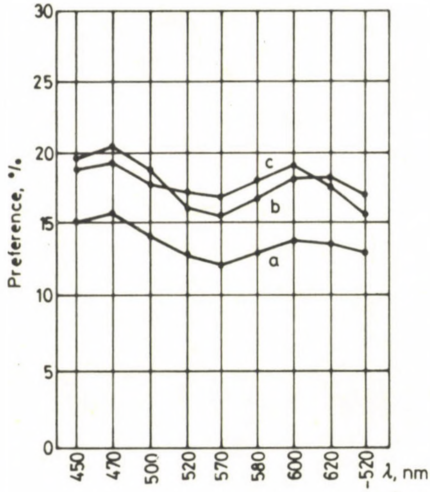


Fig. 4.93. Comparison of colour preferences in a) early 20th century to that b) by present-day men aged 20 to 30 and c) women aged 20 to 30. Notations as in Fig. 4.91

sance, intensive shades gave way to dull shades, and saturation contrast came to prevalence. In the Baroque age, the scales of both saturations and lightnesses were enriched and there was a tendency to highlight architectural elements, such as piers, cornices, courses, and capitals by shades lighter than those of the walls. In Classicism, more saturated tones retreated, while variation of the less saturated colours increased and, in general, colours became lighter. In Romantic and Eclectic architecture, even medium saturated colours were banished, the number of colour varieties abruptly decreased, architectural elements were not distinguished any more by colours, and lightness. Finally by the turn of the 20th century, almost complete greyness became dominant. If colours were used at all, their saturation was nearly zero. Since the mid-20th century, buildings became again more coloured, but the wide choice offered by the paint industry is seldom fully exploited by architects. However, in the colour design of historical town centres, colour preferences in the period of construction have to be taken into consideration.

Comparison between historical and actual colour preferences leads to interesting conclusions. Historical variation of preferences follows the pattern of colour preferences of the individual from childhood to adult age. Figure 4.91 compares preferences by boys and girls aged 11 and 12, to those realized in monuments of the Roman age. Respective Figures 4.92 and 4.93 are compared with colour preferences of boys and girls aged 17 to 19, to those in the Renaissance, and of men and women aged 20 to 30 to those of the early 20th century.

4.3. Colour Association

Environment colour design is expected to consider also the expressive power of colours, that is, association of ideas to certain colour values. Man during his lifetime finds that given objects or natural phenomena bear certain colours, that are, in turn, identified with the object, such as blue with sky, red with flame, orange with sunshine. But colour associations are not exclusive products of individual lives and observations, but also subsist as collective colour sensations of mankind.

4.3.1. Evolution of Present Day Concepts of Colour Association

Already ancient Greek philosophers were aware of consecution of notions in human thinking. Primarily, Aristotle pointed out that a notion was usually followed by a similar, or opposite notion, or one which had occurred with it before. These three kinds of relation—similarity, opposition, or contact in space or time—have later been considered as the basic laws of associations.

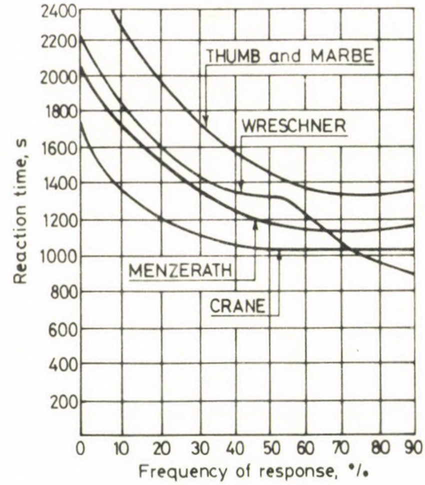
As Warren (1921) stated it, English philosophers of the 18th and 19th centuries started from these Aristotelian ideas to create that hypothetical system of mental events which influenced and still influence, concerning associations, contemporary psychology. These theorems have been expressed most clearly by Brown (1820) and Locke (1700) intending—like some modern psychologists—to develop a psychology independent of physiology.

Experiments on association have been made first by Galton (1880), Wundt (1896), Trautscholdt (1883), Cattel (1886) and later by Bryant (1947). A limitation of their tests was that test subjects answered verbal stimuli by words. Fruitful colour association tests started when experimenters abandoned the earlier practice, and examined only reactions to definite stimuli, organizing experiments so as to yield quantitative results.

Hull (1943) has developed indices for association intensity such as association reaction time, answer frequency, habituation, and generality.

Frequency of associations has been tested by Kent and Rosanoff (1910). Among others, they have found that children seldom answered by opposites, while adults usually did so.

Fig. 4.94. Reaction times of free associations vs. answer frequencies, after different authors. Horizontal axis shows frequency of answers in %, vertical axis shows the reaction time in seconds



CATTEL (1886) was the first to test association reaction times. LUND (1927) measured reaction time from the instant of stimulus to start of answer and found that the sight of a colour elicited an association later than did a verbal concept.

THUMB and MARBE (1901) found more frequent associations to be faster. Reaction times of free associations and answer frequencies have been compared in Fig. 4.94 based on experiments by THUMB and MARBE, as well as by WRESCHNER (1909), CRANE (1915) and MENZERATH (1908).

Definition of colour association is likely to be helped by the analysis of its triple—biological, aesthetical, and symbolic—message.

4.3.2. Biological Message of Colour Associations

The statement that the association message is largely due to a so-called biological command function confronting sensory organs of the associating person, originated from SCHAIE (1961a) and was based on experiments by TINBERGEN (1942) and HEISS (1960). The same was the purpose of tests by WEXNER (1954) who wished to support GOETHE's statements published in 1810, namely that red and orange are stimulant, blue and purple arouse timidity.

Biological messages of colour associations have been tested recently on university students (NEMCSICS, 1977a, e, 1978b), in order to determine the biological message of red associated to the concept of warmth. These tests were made in winter, in a classroom where temperature could be controlled. Test persons (each members of a tutorial group) worked on their problems in red, blue or green light. Room temperature was controlled by the test subjects themselves by turning radiator knobs, so as to be the most agreeable for them under the actual conditions. Students were expected to wear about the same clothing in every test phase. Room temperature was throughout recorded by a concealed instrument.

Results are shown in Figs 4.95, 4.96, 4.97. Times spent by students in the classroom are shown on x-axes, ambient temperatures in °C on y-axes. From the diagram it is clear

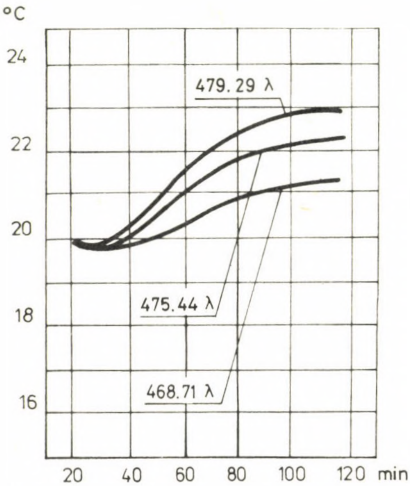


Fig. 4.95. Room temperatures (°C) found to be agreeable by test persons under illuminations by blue lights of different dominant wavelengths vs. time of staying (min)

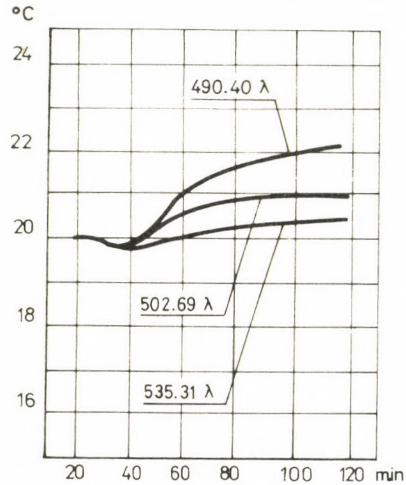


Fig. 4.96. Room temperatures (°C) found to be agreeable by test persons under illuminations by green light of different dominant wavelengths vs. time of staying (min)

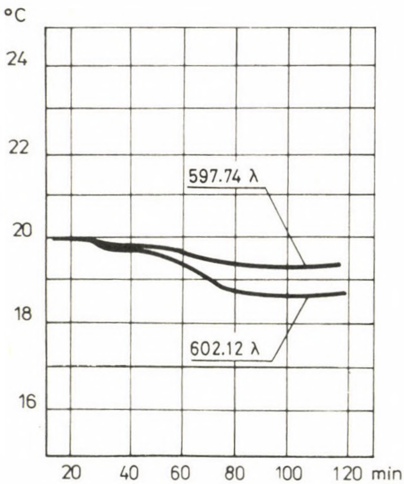


Fig. 4.97. Room temperatures (°C) found to be agreeable by test persons under illuminations by red light of different dominant wavelengths vs. time of staying (min)

that students were more at ease at a higher temperature in blue light, and at a lower temperature in red light. This fact has been interpreted as obvious biological motivation of the association of red to warmth.

4.3.3. Aesthetic Message of Colour Associations

The message of colour associations depends on experience, education of test person, i.e. it is not solely of biological origin, but has also significant aesthetic motives: it is directly related to the environment and is the manifestation of concealed emotions.

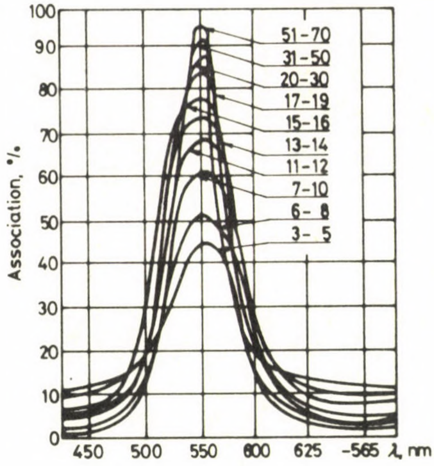


Fig. 4.98. Colour associations by test persons of different ages to the concept of spring vs. dominant wavelength. Curves refer to different age groups

Colour associations are generally combined with sensations from other organs, and therefore their content message results from interactions between empirical and biological features.

This was the basic idea of KARWOSKI (1938) in describing relations between colour and music. BRÜGGEMANN, a conductor and composer, expressed musical scales in terms of colours, assigning colours to scales: C major = white, yellow of sunshine, bright green; G major = achromatic, yellowish green, silver with beige; D major = orange, red-brown, green of the woods; A major = red with light blue, red, crimson (mainly for Mozart); E major = bright silver, metallic brilliance such as gold with red or silver with blue; H major* = orange without bright colours, or orange and violet; F sharp major = bright saturated, clear blue with gold and red; C sharp major = rather indefinite; D flat major = dark gold, brown; G flat major = gloomy, indefinite; A flat major = deep blue, deep brown and ochre; E flat major = gold, greenish gold, light silver with blue and gold; B major = dull ochre, brown, light gray with brown; F major = bright yellow, green, blue with silver gray.

Aesthetic message of colour associations was investigated by WOODS (1956) by assigning concepts expressing emotions and concepts to colour combinations rather than to single colours, making conclusions about how experience accumulating with age and variation of colour associations are connected. The same aspect was investigated in experiments undertaken at the Technical University of Budapest involving fifty thousand test persons aged 3 to 70 years (NEMCSICS, 1978).

In Fig. 4.98 colour associations to the concept of spring recorded in these experiments are illustrated, taking variations with age into consideration. The x-axis shows dominant wavelengths of colours used in these experiments.

* B natural in English notation.

4.3.4. Symbolic Message of Colour Associations

Colour associations are always motivated by the symbolic message associated with the given colour. Symbolic messages may be religious, political, or social in nature. The specific content of symbolic messages is not invariant but is shaped by historical and cultural events and circumstances.

Symbolic values of colours are most typically manifest in meanings obviously connected with colour. In classic colour symbolics as stated by JUNG (1910) red was colour of blood and life, black that of night and death, yellow that of light and hope.

According to LÜSCHER (1970), symbolic message of colours reaches back to human prehistory. Light yellow of the day expresses hope and activity, the dark blue of night rest and passivity. LÜSCHER calls these messages heteronomous, while those of red and green are autonomous. Red is always the expression of outward activity, while green that of self-defense.

In the oldest dream-book that subsisted, the Egyptian dream papyrus from the twelfth dynasty, about 2000 B.C., so-called good dreams were written in brown, and bad dreams in red. Red meant that the dream was seen by the passion-ridden followers of Seth–Typhon, the god of darkness and evil.

As we know it, in ancient Egypt, only yellow, red, blue and green, as well as black and white were vested with symbolic meanings. Spiritual colours were blue and green, standing for Amon and Osiris, respectively (Fig. 4.99).

In classic Hellas, after HIPPOCRATES, four temperaments were distinguished and symbolized by colours. The sanguine temperament was assigned to red, choleric to yellow, melancholic to black, and the phlegmatic to white. The same interpretation occurs in the theory by GALEN on body fluids, of which the four first principles were symbolized by colours. Fire was characterized as red, air as yellow, water as blue and earth as green.

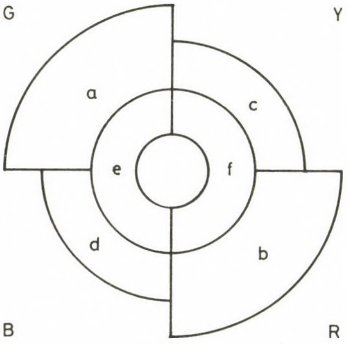


Fig. 4.99. Colour symbology of ancient Egypt. Legend: G green, Y yellow, B blue, R red, a youth, rest, rebirth, Osiris; b evil, passion, vitality, Seth-Typhon; c emotion, d intelligence, Amon; e spiritual, divine; f corporal, human

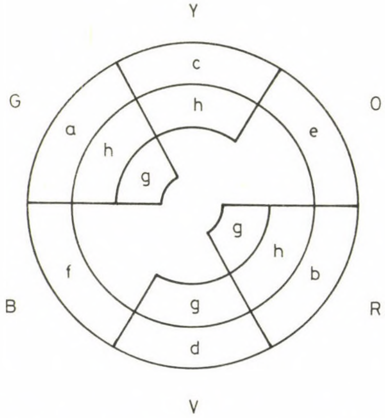


Fig. 4.100. Mediaeval colour symbology. Legend: G green, Y yellow, O orange, R red, V violet, B blue; a peace, fertility, hope; b unrest, love, courage; c glory, light, pride; d sorrow, darkness, humility; e ecstasy, wealth, finiteness; f knowledge, justness, infinity; g liturgic, h magic

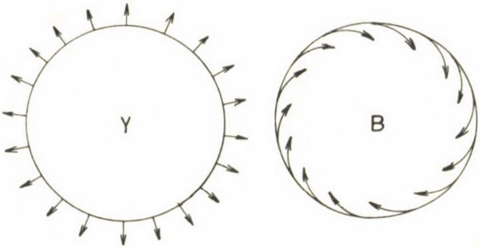


Fig. 4.101. Antagonistic pair of colours yellow–blue after KANDINSKY. Legend: Y yellow, B blue

For them, blue and green meant rest, red and yellow motion. Red was considered as a sensual, green as an antisensual colour.

Mediaeval colour symbolics was a blend of liturgy, black magic and heraldry. Liturgic colours were red, violet, green, and white, while black, blue, yellow, and orange were considered as antiliturgic. Witchcraft had four degrees, symbolized as blackening, yellowing, whitening and reddening,—completed at times by greening. These colour names were keywords intended to reflect the state of mind of the alchemist at different phases of the process. Peacock feather, the alchemists' symbol, referred to four basic conditions of the soul, symbolizing coherence and unity of the four colours of alchemistic degrees. In heraldry, red was the symbol of courage, orange that of constancy, yellow of respect, green of fertility, blue of truth, and purple of dignity. By the late Middle Ages, blue became of importance as a symbol of knowledge. The doctor's hat, rector's mace were blue (Fig. 4.100).

Collection and systematization of present day symbolic messages of colours have been studied both by fine artists and psychologists.

As KANDINSKY, the painter wrote (1955): "Yellow and blue have another movement . . . an ex- and concentric movement. If two circles are drawn and painted respectively yellow and blue, brief concentration will reveal in the yellow a spreading movement out from the centre, and a noticeable approach to the spectator. The blue, on the other hand, moves in upon itself, like a snail retreating into its shell, and draws away from the spectator (Fig. 4.101). Yellow, if steadily gazed at in any geometrical form, has a disturbing influence, and reveals in the colour an insistent, aggressive character. . . . Blue is the typical heavenly colour. The ultimate feeling it creates is rest. . . . Vermilion is a red with a feeling of sharpness, like glowing steel which can be cooled by water. Vermilion is quenched by blue . . . Orange is like a man, convinced of his own powers . . . violet is red withdrawn from humanity by blue. . . . It is consequently rather sad and ailing."

Psychologists have made much more extensive compilations of the symbolic messages of colours, than did KANDINSKY. The best known of them are those by KLEIN (1930), KARWOSKI (1938), MURRAY (1938), ALSCHULER (1943), JELINEK (1951), NAPOLI (1951), WEXNER (1954), HEIMENDHAL (1961), SCHAIE (1961b), SCHACHTEL (1962), SABURO-OHBA (1963), FRIELING (1968) and DÉRIBÉRÉ (1974). It is surprising that representatives of most far away cultures assign similar symbolic messages to colour values to those we do.

The Japanese SABURO-OHBA wrote: "Red is happiness, joy, passion, fight, force, anger, violence, hate, rudeness, madness; orange red is fidelity, honesty, force, horror, temptation; orange is force, happiness, warning, ecstasy, joy; orange yellow is happiness, joy, ecstasy; yellow is radiation, hope, self-revelation, joy, rudeness; yellowish green is hope,

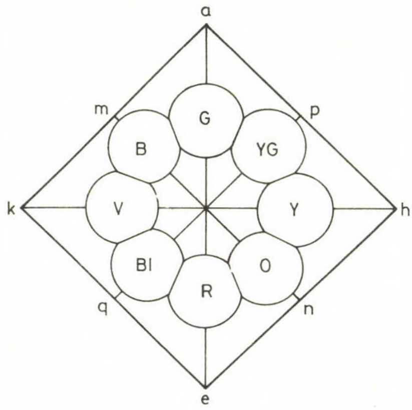


Fig. 4.102. JELINEK's system of colour associations. Legend: G green, YG yellowish green, Y yellow, O orange, R red, Bl purple, V violet, B blue; a antierogen, e erogen, k stupefying, h stimulating, m reassuring, n exalting, p fresh, q anxious

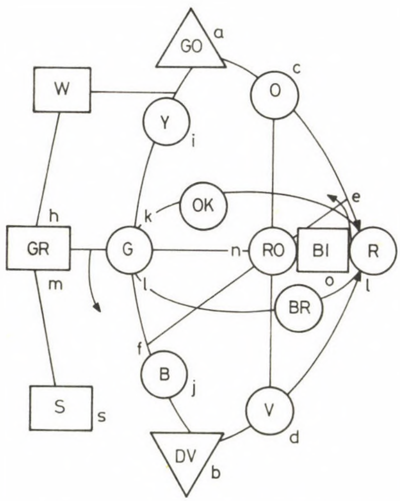


Fig. 4.103. FRIELING's system of colour associations. Legend: G green, Y yellow, O orange, R red, V violet, B blue, OK ochre, BR brown, GO gold, DV dark violet, Bl purple, RO pink, W white, GR gray, S black; a mental radiation, b earth, c self-revelation, d introversion, e activity, f passivity, i radiant light, j spiritual radiation, h rest, k water, l life, m lifeless, n loneliness, o existence, s death

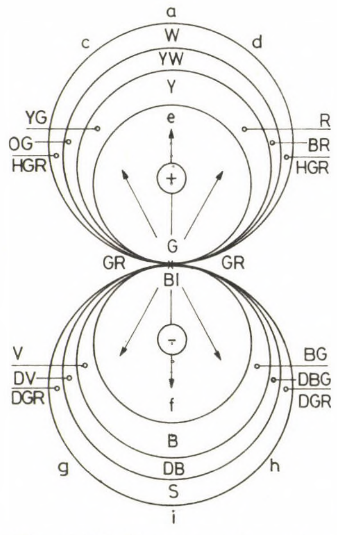


Fig. 4.104. HEIMENDHAL's system of colour associations. Legend: W white, YW yellowish white, Y yellow, YG yellowish green, OG olive green, HG light green, R red, BR brown, HGR light gray, G green, GR gray, Bl purple, V violet, DV dark violet, DGR dark gray, BG bluish green, DBG dark bluish green, B blue, DB dark blue, S black; a liberation, b effort, c hope, d escape, e activity, f passivity, g anger, h birth, i absorption, helplessness

youth, future, freshness, growth; green is peace, youth, hope, safety; greenish blue is mystery, depth, eternity, thought, sorrow; blue is truth, mind, mystery, greatness; bluish violet: mourning, phantasy, mystery, solemnity; violet is sublimity, mystery, phantasy, noblesse; purple is dignity, haughtiness, delight, roughness."

There have been several attempts to systematize these symbolic messages such as colour symbol systems in Figs 4.102, 4.103 and 4.104.

4.3.5. Evaluation of Colour Association Studies

Comparison of colour association studies for a given concept throughout the world made at different times has led to the surprising conclusions that the results of different authors applying different methods were strikingly similar. Let us consider, for example, the colours associated with the concept of merriness on the basis of tests by ALSCHULER, WEXNER, FRIELING and NEMCSICS (1967b, 1970, 1977e) in Fig. 4.105, given by the dominant wavelength. For many authors, red colours express the concept of merriness. It seems, that when starting from the concept, the colour association is always unambiguous.

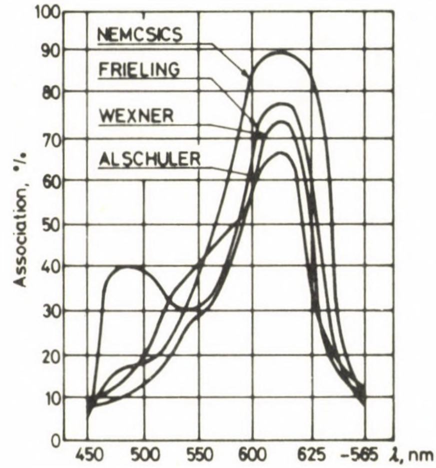


Fig. 4.105. Colour association frequencies with the concept of merriness after different authors vs. dominant wavelengths of hues

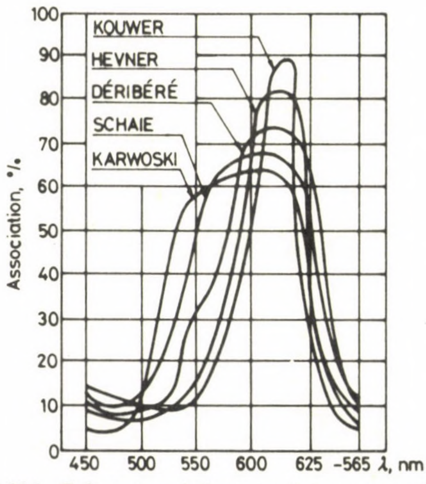


Fig. 4.106. Colour associations to the concept of excitement, after different authors. Notations as in Fig. 4.105

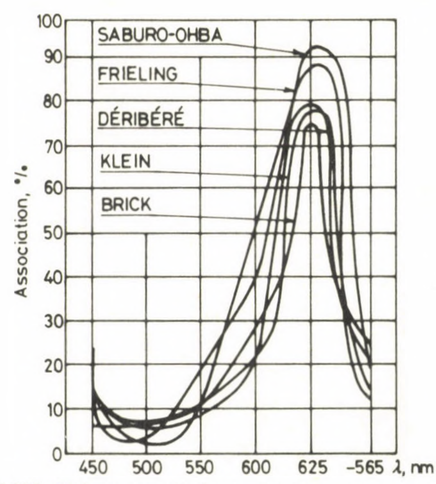


Fig. 4.107. Colour associations with the concept of anger, after different authors. Notations as in Fig. 4.105

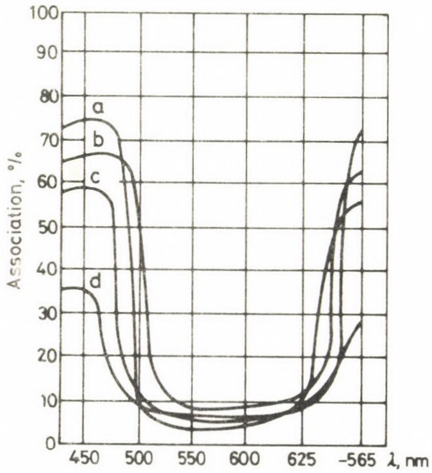


Fig. 4.108. Association with colours of different saturations and lightnesses associated to the concept of silence. a) saturated colours, b) medium saturated colours, c) unsaturated light colours, d) unsaturated dark colours. Notations as in Fig. 4.105

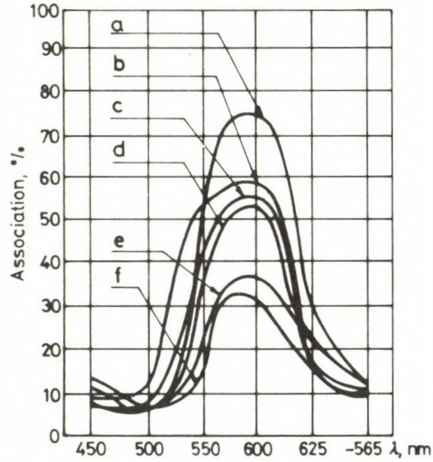


Fig. 4.109. Colours associated with the concept of motion by test persons of different ages. a) men aged 50, b) women aged 50, c) men aged 20, d) women aged 20, e) boys aged 10, f) girls aged 10. Notations as in Fig. 4.105

If, however, Figs 4.106 and 4.107 are looked at, showing—again, based on results by several authors—colours associated with excitement and anger, it appears that colours of the red domain are associated, apart from merriness, also with excitement and anger. Thus, approach from colour to the former relationship is no longer unambiguous. Hence the hue parameter does not suffice to express colour association relations. Nevertheless, most of researchers did not only prefer the hue parameter, but handled it as the exclusive one.

This is supported by diagrams in Fig. 4.108 for colours of different saturations associated to the concept of silence vs. dominant wavelength, based on the Author's tests.

Another mistake often made in colour association experiments was to omit age-dependent variations. Age-dependent features of colour association become apparent from Fig. 4.109 based on our own experiments and showing associations to the concept of motion in different age groups.

In recent years, we have performed colour association tests on about sixty thousand test persons, endeavouring to eliminate the above mentioned shortcomings of earlier tests. Up to now, some four hundred diagrams have been published about our results.

4.3.6. Colour Association Scales

Tones little differing by hue, saturation, and lightness invoke sometimes rather similar, but at other times, quite different associations. This is important for environment colour design, since, while for some colours, any parameter may be modified without altering their emotional message, for others a slight shade variation would alter the association content of the colour. This is why in design practice, knowledge of associations to given, discrete colours is of little use, and therefore one has to compare the frequency of an association to a colour to those of other colours of the colour scale. Accordingly to every colour in the scale a number from 0 to 100 should be assigned, expressing the frequency of association between the given concept and the colour. A series of tests have been carried out at the Technical University of Budapest in order to develop such a scale.

Our test results were aimed at creating a system of colour association values where colour to concept associations are rated along a continuous scale from 1 to 100.

For this purpose, first, rates of colour associations pertinent to 432 points uniformly distributed in the colour space have been determined in three superposed tests. Sites of the 432 points in the Coloroid colour space are the same as described for the colour preference index number system.

In the first test associations with 24 representative points of the colour space, in the second, with 48 points of the continuous colour circle, and in the third, with 432 points in 48 discrete colour planes were recorded.

In the second test aimed at generalizing our results, colour points in sections of 48 Coloroid basic hues, colour association values based on the previous test were assigned by means of a quadratic function with two variables. Interpolation between corresponding colour points in neighbouring sections permitted a colour association value each to every point of the colour space to be assigned. From these data tables for practical use of colour association were compiled with calculated values for 40 to 50 discrete colour points in each of the 48 sections of Coloroid basic hues.

Information on associations ordered to scales permit the comparison of tests made under different conditions and their application in design practice. Frequencies of the concepts merriness, joy, excitement, and anger as association messages according to several authors are shown on hue scales in Figs 4.105, 4.110, 4.106, and 4.107, respectively. With different authors maxima are generally at the same hue for each concept; only

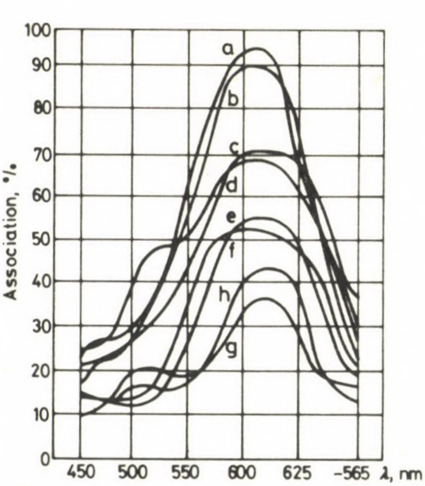


Fig. 4.110. Colours associated with the concept of joy by women and men of different ages, after Nemcsics. a) men aged 50, b) women aged 50, c) women aged 20, d) men aged 20, e) girls aged 10, f) boys aged 10, g) boys aged 5, h) girls aged 5. Notations as in Fig. 4.105

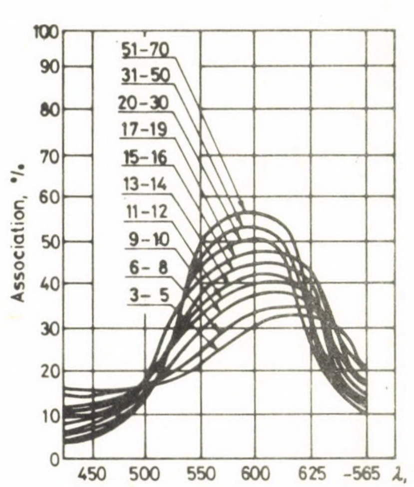


Fig. 4.111. Colours associated with the concept of summer by test persons of different ages, after Nemcsics. Curves refer to different ages. Notations as in Fig. 4.105

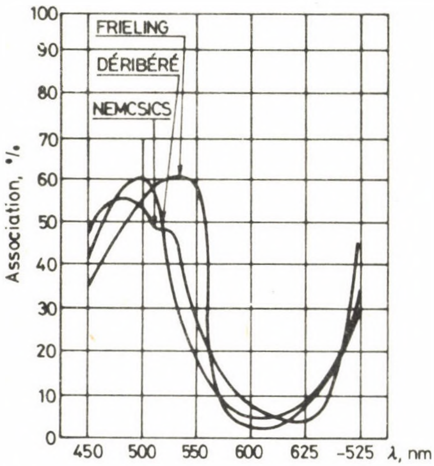


Fig. 4.112. Colours associated with the concept of rest, after different authors. Notations as in Fig. 4.105

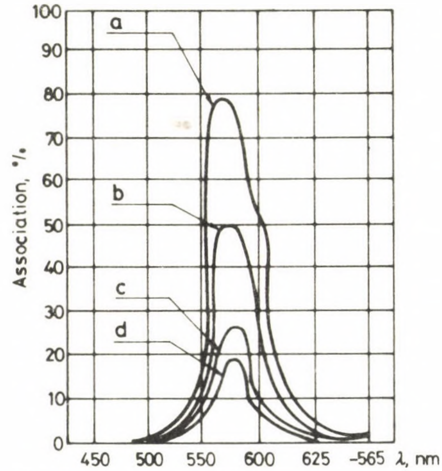


Fig. 4.113. Colours of different saturations and different lightnesses associated with the concept of noise. a) saturated colours, b) medium saturated colours, c) unsaturated light colours, d) unsaturated dark colours. Notations as in Fig. 4.105

the ascents are different. Merriness, joy, and excitement are unambiguously expressed by cinnabar, while anger by madder. Note, however, that orange, yellow, and even some green were associated in a rather high percentage with merriness and joy; they were hardly associated with anger.

Colours associated with merriness are to be preferred in the design of e.g. premises for entertainment, but the designer has to be careful not to express anger. Colour associations of the two concepts are clearly recognizable on the hue scale, but their difference is best perceived on the saturation scale. Colours of merriness are saturated and as light as permitted by saturation, while those of anger are unsaturated and dark.

In a built environment, association with concepts such as spring or summer, is rather evocative. While the hue scale expressing spring is rather narrow (Fig. 4.98), that of summer is much wider (Fig. 4.111) but colour associations with the latter are much less frequent than those with spring colours. Association intensity is seen to increase with age and experience.

For the colour design of different industrial establishments, let alone, of a home, colours expressing motion, rest, silence and noise have to be known. Motion is expressed by orange red, rest by bluish green, but e.g. yellowish green may express both concepts (Figs 4.109 and 4.112). Blue is associated with silence, orange with noise. In respect of these concepts, however, there exists no colour which would express both (Figs 4.108 and 4.113). The figures also demonstrate how much association is affected by saturation and lightness.

Colours associated with concept pairs of joy–sorrow (Fig. 4.114), cold–warm (Fig. 4.115), silent–noisy (Fig. 4.116), nearer–farther (Fig. 4.117) are shown in circular diagrams, with angular coordinates each bearing a Coloroid hue. Frequencies of associations of the colours represented by the radius with the given concept were plotted on the radii. Every radius represents a hue and its six colours, namely the most saturated surface

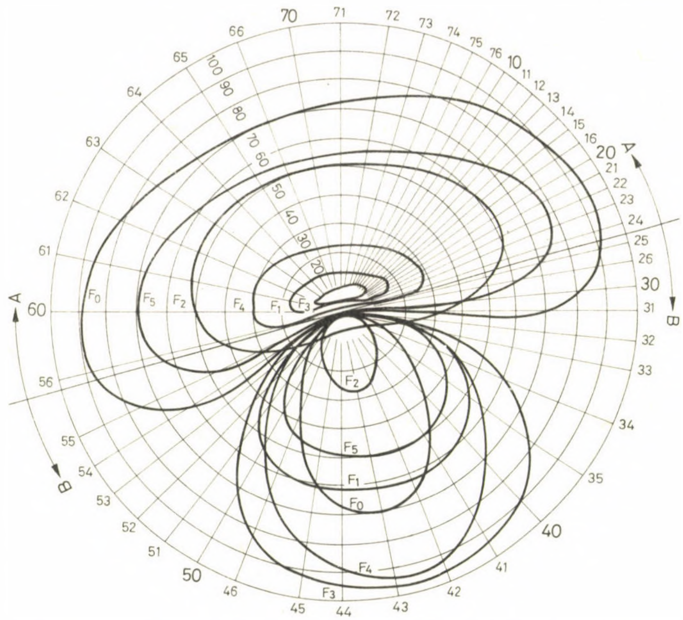


Fig. 4.114. Colours associated with the concepts of joy (side A) and sorrow (side B). Association frequency increases from the centre outwards. Numbers on periphery refer to Coloroid hues. For symbols at curves see Fig. 4.61

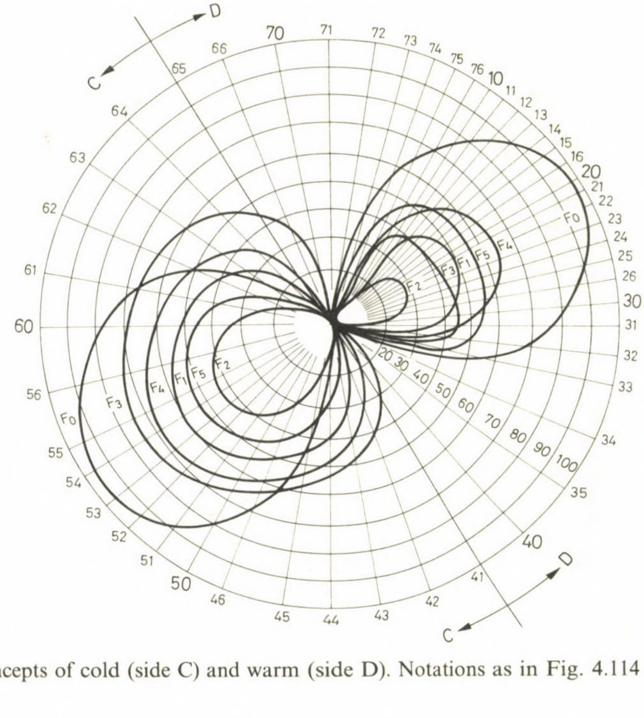


Fig. 4.115. Colours associated with concepts of cold (side C) and warm (side D). Notations as in Fig. 4.114

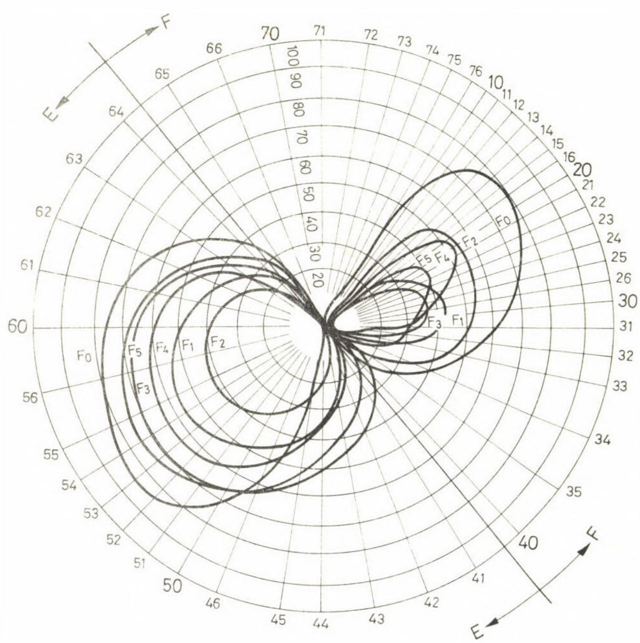


Fig. 4.116. Colours associated with the concepts of silence (side E) and noise (side F). Notations as in Fig. 4.114

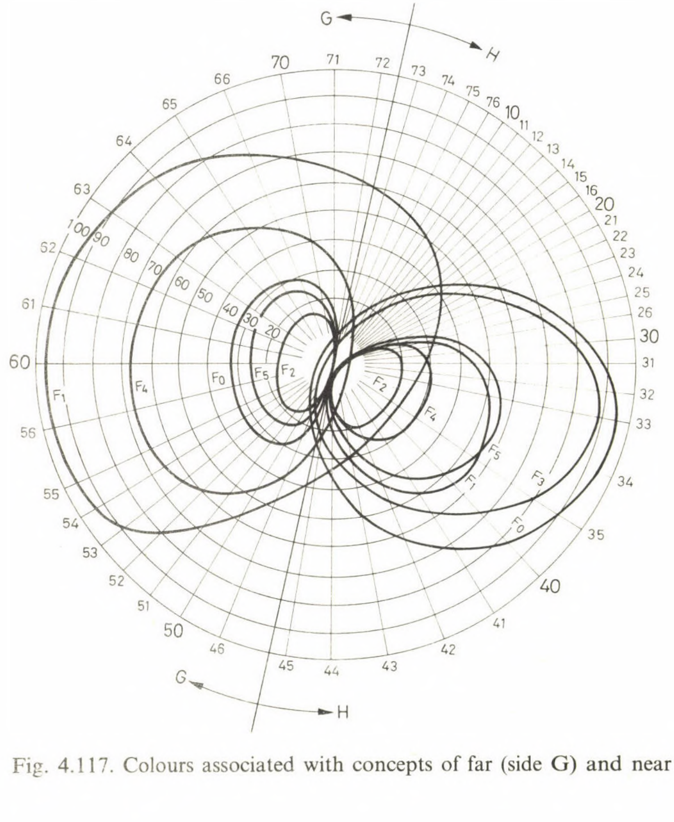


Fig. 4.117. Colours associated with concepts of far (side G) and near (side H). Notations as in Fig. 4.114

colour F_0, an unsaturated colour of the lightness of medium gray F_1, an unsaturated, very light colour F_2, an unsaturated dark colour F_3, a medium saturated dark colour F_4, and a medium saturated, medium light colour F_5. Curves connecting points with the same markings illustrate the relation of surface colours with given concepts.

Let us consider first the pair joy and sorrow. Joy is expressed by saturated colours, sorrow by dull, darker colours. More than half of colours in the Coloroid system are well suited to express joy, first of all reds, oranges, greens, greenish blues, and blues. There is a rather narrow domain available to express sorrow. Of them cold violets seem to be the most appropriate. A domain each of blues and madders seem to be most neutral to express emotions covered by these concepts (Fig. 4.114).

Concerning the pair cold–warm, the warmest colour is saturated orange and the coldest one is saturated manganese blue. The less saturated a colour, the less it is expressive of a warm sensation. The same is true for the expression of cold, except the domains of chromoxide greens and cobalt violets, where colours of lesser saturation are more expressive associations with cold than are saturated ones (Fig. 4.115).

On the other hand, as to the pair silent–noisy, there are much less of "noisy" colours than "silent" ones. Rather wide domains of the colour space are indifferent from this aspect. Noisiest colours are yellow, orange, and red, while the quietest are sky-blue and ultramarine (Fig. 4.116).

Lastly, let us consider the pair of concepts receding and approaching. Receding colours are dull, approaching ones are saturated. The former are the bluish green and green; the latter are red (Fig. 4.117).

Diagrams illustrate the concept–colour relations always in comparison with an achromatic surrounding. In conformity with regularities for contrast phenomena, a coloured environment significantly modifies these conditions.

4.4. Psychosomatic Effects and the Pleasure of Colour

Colour stimuli eliciting different colour sensations, being radiations of different wavelengths, affect the human organism not only through the visual organ. Radiation penetrating the organism may change certain physiological parameters, entraining also psychical alterations. Environmental colours affect learning, the unfolding of abilities, blood pressure, respiration frequency, body temperature—all of importance for environment colour design.

4.4.1. Colour, Personality, Abilities

The beginnings of psychodiagnostics date back to the 19th century. Galton (1880), McKeen and Cattel (1886), later Binet (1910) and more recently Simon (1972) have developed methods to test children's intelligence. The first half of our century witnessed a proliferation of tests. Now there are over 800 different ability and 150 personality testing methods known. Ever increasing precision has been required in the evaluation of tests, and colours have gained increased importance in ability and personality tests. Pioneering work has been done by the Swiss psychologist Rorschach (1942), developing a test method using coloured pictures. Frieling was the first who attempted in 1939 to disclose abilities and personality parameters by colour tests, developing it to the present form in 1949. In the same year, LÜSCHER published his study "Psychology of Colours. Introduction to Psychosomatic Colour Testing", describing his colour test. Simultaneously with FRIELING and LÜSCHER, PFISTER has published his "Colour Pyramid Test", inducing HEISS to publish in 1951, with the coauthorship of HILTMANN his work "Colour Pyramid Test after PFISTER". Among these tests, that by LÜSCHER is the most popular.

In developing his basic colour test LÜSCHER's assumption was that colour selection by the test person expressed his way of living, his psychological and neurovegetative condition, as well as his hormone status. In his test, four possibilities for human behaviour were associated with the four primary colours: blue, green, red and yellow. Blue expresses concentric, heteronomous behaviour, characterized by released sensitiveness, calmness, and satisfaction. Those choosing green exhibit concentric–autonomous behaviour characterized by determination and constancy. Red is the expression for eccentric–autonomous behaviour inciting one to empathy and to vital will to conquer. Yellow expresses eccentric–heteronomous behaviour characterized by expectation to happiness, relaxation and relief.

According to LÜSCHER, his test gives an insight into neurotic disturbances of the patient, stressing that colour selection is primarily not a psychical but a vegetative physiological reaction determined by nervous and hormonal conditions. This is why at some psychophysical clinics in Germany, this test is added to the diagnosis and helps in the selection of the correct therapy.

Personality tests are of importance for the practice of colour dynamics by helping to recognize colours connected to affectivity, cognitive, and behavioural conditions in various stages of human development. These recognitions are of use in the practice of

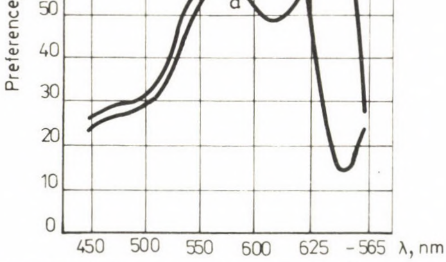


Fig. 4.118. Colour preferences in % of normal (a) and feeble-minded (b) children, vs. dominant wavelengths of different hues after HAMMA

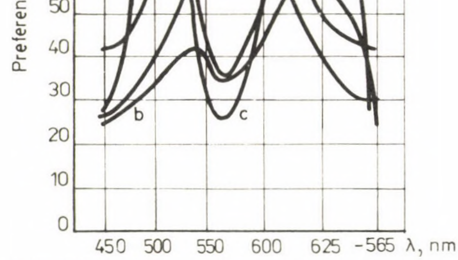


Fig. 4.119. Colour preferences in % of members of a high-altitude therapy expedition by ALBRECHT at different altitudes, vs. dominant wavelengths after KLAR. a) at see level, b) at 2500 m, c) at 4000 m, d) at 5300 m

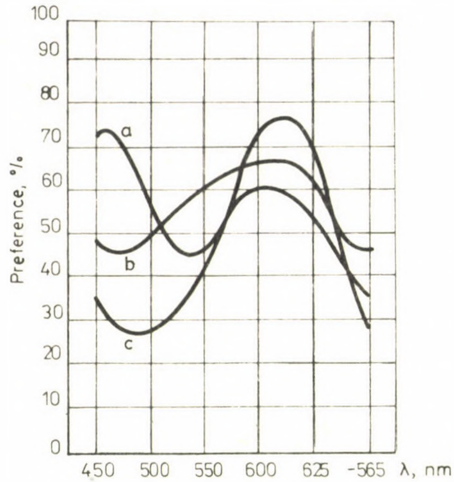


Fig. 4.120. Colour preferences in % of students eminent in different subjects, vs. dominant wavelengths. a) drawing and composition, b) design, c) structural engineering, mathematics, statics

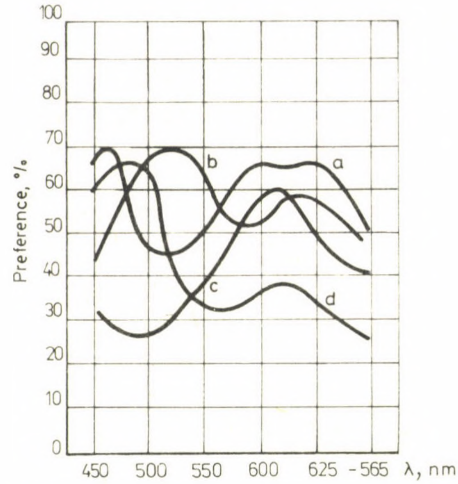


Fig. 4.121. Colour preferences in % of students of different behaviours, vs. dominant wavelengths after Nemcsics. Symbols for axes are those in Fig. 4.118. Legend: a) diligent, b) negligent, c) superficial, d) engrossed

colour design endeavouring to express or modify human attitudes. Relevant test results are illustrated by some figures to follow.

Colour preferences of a hundred normal, and feeble-minded children each aged 10 to 14 were plotted in Fig. 4.118, based on Hamma's tests compiled by Klar (1968).

The survey was done by Lüscher's test and summarized by Klar as: "The two groups of children displayed conspicuously different attitudes to violet, chosen by 28 normal, and 74 feeble-minded children. That is to say, feeble-minded children are much more sensitive and suggestible, which is why they feel an attraction to violet. Firm personalities reject magic, indefinite violet."

Results of colour psychology tests collected during a high-altitude therapeutic expedition in the Andes, guided by Albrecht, are shown in Fig. 4.119. Participants took part, at sea level, in a Lüscher colour test, repeated later at altitudes of 2500 m, 4000 m, and 5300 m above sea level. Test results concerning yellow have been commented on by Klar (1971) as: "At sea level light yellow means primarily animation, future expectation, the desire to widen the horizon. This is completely in agreement with the expectational psychical condition of expedition members undertaking such an important venture. At higher altitudes, expectations obviously diminish, and so does the endeavour to widen the horizon. Yellow drops back from first to fourth place."

Our results with the Pfister–Heiss pyramid test are seen in Figs 4.120 and 4.121. The former diagram shows the attitude to colours of students in architecture, with separate curves for those excellent in drawing, in structural engineering, and in the history of architecture. These curves reveal a correlation between colour selection and field of interest. The latter diagram illustrates relation to colours of thorough vs. superficial and of diligent vs. negligent students. These curves highlight the idea that differences in interest and attitudes have their counterparts in attitudes to colours. It only remains to see how much behaviour can be affected by appropriate environment colours (NEMCSICS, 1977e).

Preference curves for eminent schoolchildren and university students are compared in Fig. 4.122, based on tests by LÜSCHER (1949) and by NEMCSICS (1979a), respectively. These curves are suprisingly similar to those for frequencies of colours symbolizing knowledge in Egyptian and mediaeval colour symbology (Fig. 4.123). According to these figures, blue is both expression for, and symbol of knowledge.

In another experiment, students were seated in compartments with alternating blue and red illumination, or surrounded by these colours. They were given different prob-

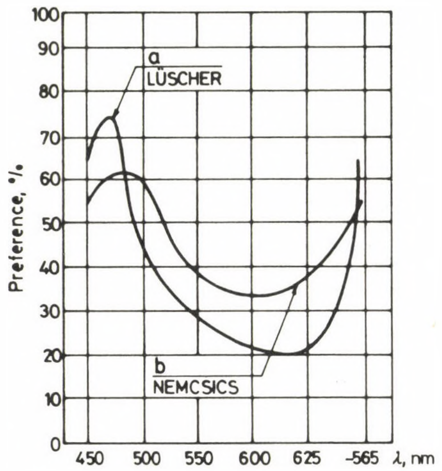


Fig. 4.122. Colour preferences in % vs. dominant wavelengths of a) schoolchildren, and b) university students, with good average marks found in Lüscher tests by LÜSCHER and NEMCSICS. Notations as in Fig. 4.118

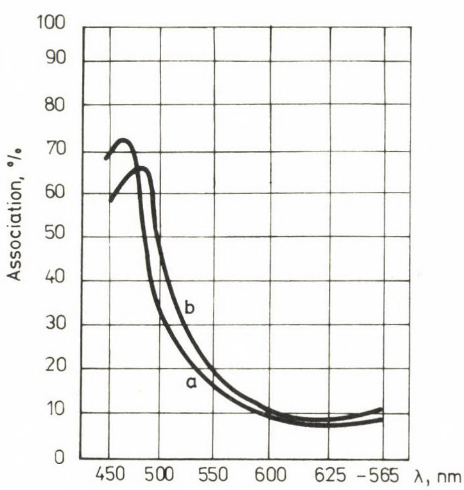


Fig. 4.123. Association frequencies with the concept of knowledge in % vs. dominant wavelengths in a) Egyptian and b) mediaeval colour symbology after BIRREN

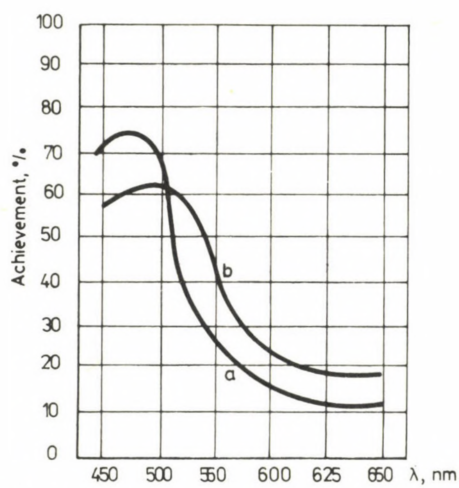
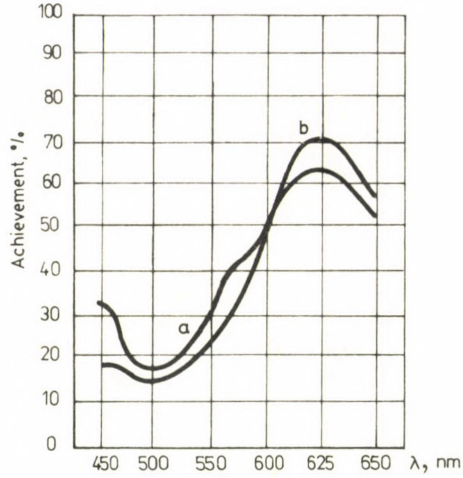


Fig. 4.124. Efficiency in solving mathematical problems vs. dominanat wavelength under illuminations of different wavelengths, after NEMCSICS. a) boys, b) girls

Fig. 4.125. Efficiency in solving problems requiring ingenuity vs. dominant wavelengths under illuminations of different wavelengths, after NEMCSICS a) boys, b) girls



lems requiring e.g. reasoning, logical abilities, absorbed work, and flashes of wit. From Fig. 4.124 it appears that problems requiring absorbed work and logical abilities were solved at the lowest error percentage by students in blue environment, while according to Fig. 4.125, solution of problems requiring flashes of ideas was aided by the red surrounding.

4.4.2. Effect of Colour on Biological Parameters

Red stimulates and excites the nervous system. It increases blood pressure and the number of respirations per minute. Orange improves the functioning of digestive organs, reduces metabolic disturbances. Lemon yellow incites cerebral activity, its greenish shade tranquilizes the nervous system. Green calms the nervous system, reduces blood pressure, dilates blood vessels. Blue has an antifebrile effect; it alleviates pain, reduces blood pressure, pulse and respiration rates. Violet has a favourable activating effect to cardiac functions.

Experiments on the effects of colour on biological parameters were started only about the mid-century. Growth rates of plants have been studied by BIRREN (1961c), and of animals by BISSONETTE (1954) exposing them to lights of different colours (Fig. 4.126). ESHER and DESRIVIÈRES (1964), investigating the stimulating effect of radiation of different colours on warm-blooded animals, have found that red light was highly stimulant (Fig. 4.127).

In an interesting series of experiments, BENOIT (1955) observed the growth of birds' genital glands exposed to radiations of different colours. In the first phase, coloured light affected only the retinae of the animals. Red was found to promote the growth of genital glands. Thereafter nerve tracks connecting retina to the brain were cut. It was found that radiation acted directly on the subcerebral neurovegetative centre, the hypothalamus, and indirectly, to hypophysis, and thereby, to the development of genital glands (Fig. 4.128). Also transmittances of different body tissues to light of different colours were examined (Fig. 4.129).

Hollwich (1964), Tilgner (1967) and Dieckhuse (1974) have investigated effects of coloured radiation on human water balance, sugar metabolism, diencephalic glands, hypophysis, blood composition, hormone metabolism, the vegetative nervous system, and liver functions.

It was shown that colour light, but also coloured environment elicit various, experimentally demonstrable reactions in living organisms. UV light increases productivity; the effect of red to increase blood circulation is manifest also on skin surfaces not directly

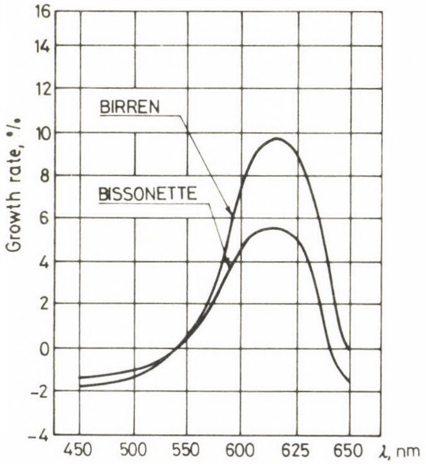


Fig. 4.126. Growth rates in % of plants and animals vs. dominant wavelengths after Birren and Bissonette

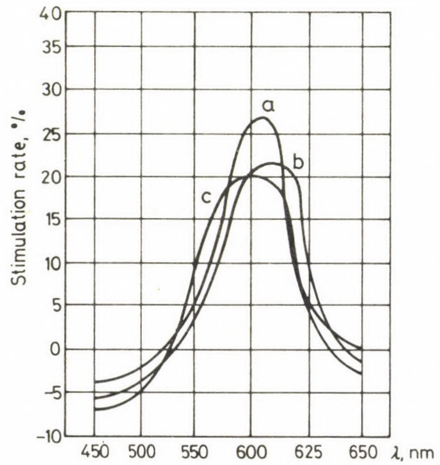


Fig. 4.127. Stimulating effect in % of coloured light vs. dominant wavelengths on warm-blooded animals, after Esher and Desrivières

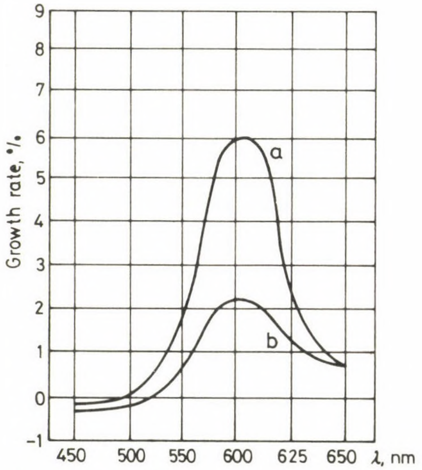


Fig. 4.128. Development of genital glands of birds in % vs. dominant wavelengths after Benoit: a) growth upon irradiation of vegetative retina, b) to growth upon irradiation of the hypothalamus

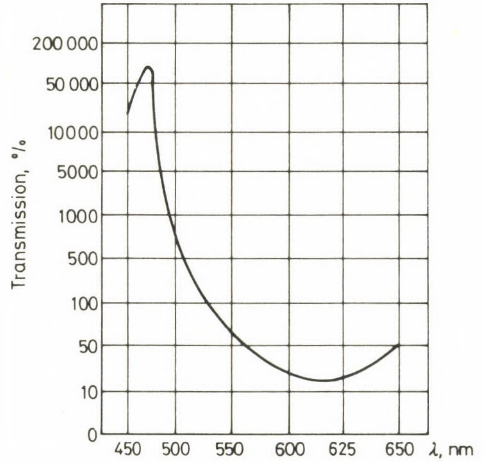


Fig. 4.129. Transmittance vs. dominant wavelengths of body tissues, after Benoit

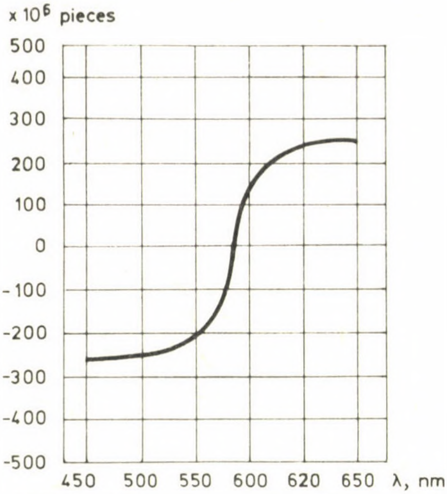


Fig. 4.130. Variation of the number of eosinophile cells in blood vs. dominant wavelengths, after STECK

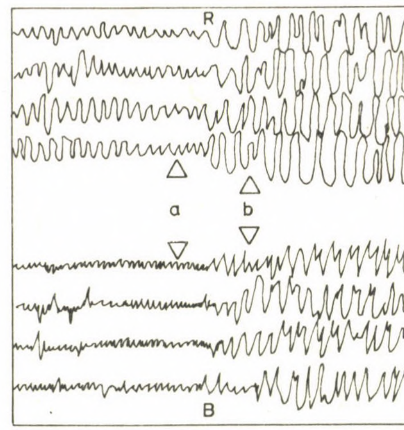


Fig. 4.131. Electro-encephalograms a) with eyes open and b) closed in red (R) and blue (B) environment after by GÉROND and LINDSEY

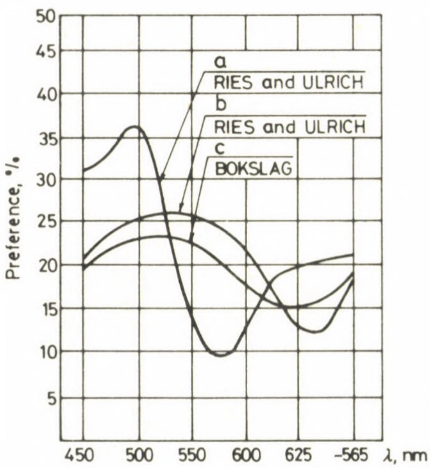


Fig. 4.132. Colour preferences in % vs. dominant wavelength of a) fat, b) dieting and c) healthy women, after RIES and ULRICH, as well as BOKSLAG

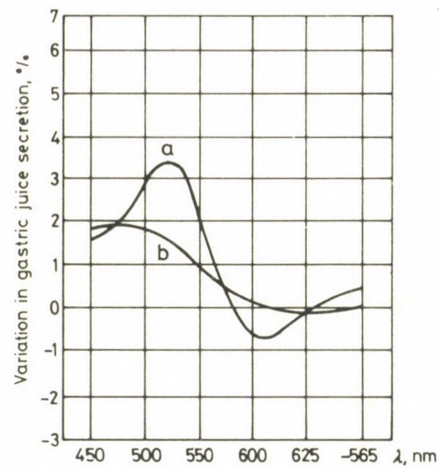


Fig. 4.133. Variations of gastric juice production in % vs. dominant wavelength in production: a) gastralgic patients and b) healthy persons

exposed to radiation. STECK (1972) experimentally demonstrated the effect of visible radiation on eosinophile blood cells. Reduction of the number of eosinophile cells simultaneously affects cortisone secretion by the adrenal cortex, a relation regulated by ACTH (hypophysis hormone) (Figs 4.130, 4.131). In addition to physiological observations, several pathological phenomena arising from the effects of different coloured environments have been reported.

Environmental colour effects also act on gastric and intestinal activities. Red and green environments reduce appetite, and may even be disappetizing, while yellow im-

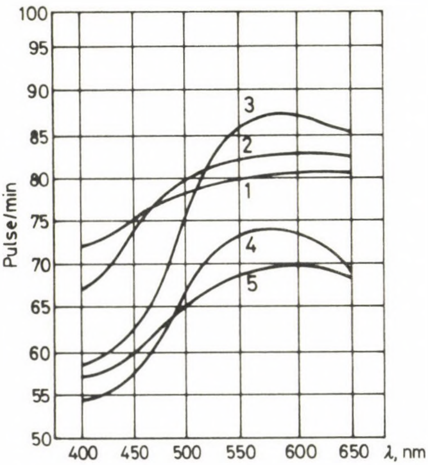


Fig. 4.134. Variation of pulse numbers per minute vs. dominant wavelength of test persons aged 20 to 24. Curver refer to different test persons

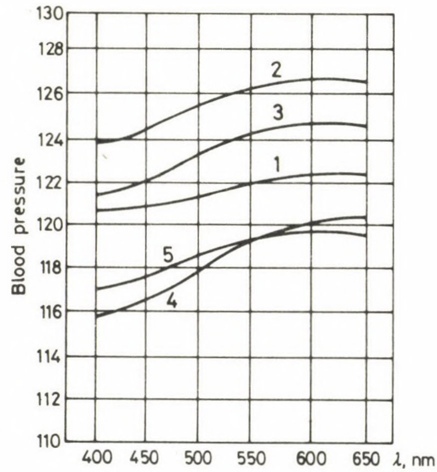


Fig. 4.135. Blood pressure variation vs. dominant wavelengths of test persons aged 20 to 24. Curves refer to different test persons

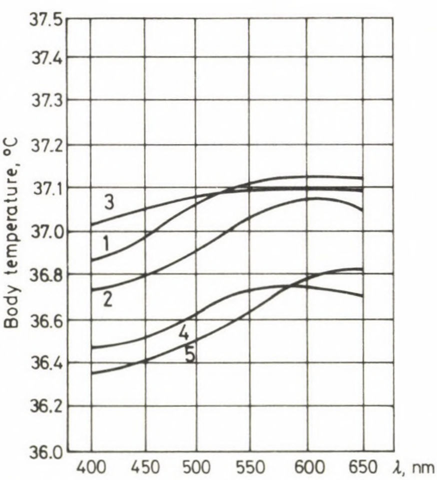


Fig. 4.136. Body temperature variation vs. dominant wavelength of test persons aged 20 to 24. Curves refer to different test persons

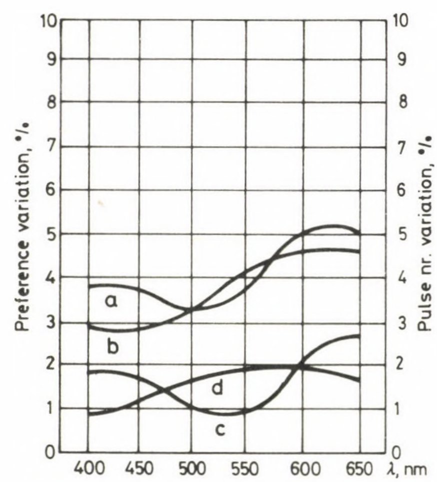


Fig. 4.137. Comparison of psychological and physiological sensitivities to colours manifested in change of preference percentage and blood pressure respectively vs. dominant wavelengths in test subjects aged 20 to 24. a) preferences by women, b) pulse numbers of women, c) preferences by men, d) pulse numbers of men

proves digestion and increases appetite (Fig. 4.132). This has been supported by tests on fat, dieting women by Ries and Ulrich (1959). It was only after the end of dieting that preference curves became similar to those of healthy women (Fig. 4.133).

It has been often observed that inclination to certain diseases or biological, pathophysical parameters can be either impaired or improved by colour effects. Also in tests with students, effects of environment colours on pulse number, blood pressure, and body temperature could be observed (Figs 4.134 to 4.137).

All that has been said suggests that colours in rooms in which we stay permanently are of importance also from physiological aspects. An unfavourable colour environment may add to other defects of the working place. On the other hand workplace defects may also be reduced by proper colour effects. Another conclusion is that colour environment comprises not only colours within the visual field of the room occupants.

5. Relations of Colour, Man and Environment

Man has created for himself a second nature, the built environment. Much of his life is spent in this man-made world. He is not only creator of this environment but also subject to its effects. To make our environment a home-like world, so that it should help—rather than hinder the development of our abilities, and to feel there at ease, requires—among other things—to make use of the power of colours, to investigate relations between colour, man and built environment.

This chapter is concerned with relations inherent in the man-made world not yet considered in this book. Relations between colour and space, colour and function, colour and illumination, as well as colour and ergonomics will be considered, all four relations being concerned with the system of relations between colour, man and environment, functioning, in fact, as a system. Relations between members of the system will be presented in diagrams.

5.1. Colour and Space

"Reality of a building is not its walls and roof but the space we live in"—said Lao Tse centuries ago. But what is space? What is meant by the concept of space? It is a commonplace concept—like material, motion, time—rather problematic for science but appearing self-evident for man as do everyday things.

Space is perceived from the first moment of life, continuously, with ever more sensory organs, yet it is hard to define. Everyday experience shows space in itself to be indefinite, and only mass—its opposite—makes it perceptible and definite for our consciousness. This opposing unity between space and mass postulating each other—following partly from the nature of things, and partly, from the physiological features of perception—decisively affects the possibilities of space creation. Not space itself is perceived but relations between its three-dimensional elements, or at least, between elements with a plastic value, a relation expressed by direction, intensity, and quality of light, surface texture, and colours. Space does not exist in itself but by its effects elicited by these plastic elements. Consequently, it cannot be handled as some morphological pattern. Approach to the problem of architectural space is twofold: that of sensation, and of factors eliciting this sensation, hence, on one hand, the psychical process of space sensation elicited by the actual conditions, and on the other hand, composition, i.e. the spatial order of the eliciting plastic elements.

Composition itself is not restricted to the topological description of spatial elements, its essential features being also surface colours or spectral energy distribution of the light source.

Based on recent results of experimental psychology, the statement may be ventured that only physiological conditions of spatial vision are predetermined. Visual space perception is nothing else than innerved experience. Experiments using various colour saturation and lightness scales have proved that space sensation can be made not only uncertain but also contrarious to the topology of the environment. From the aspect of achieving a desired space sensation, results of these investigations may be a more potent tool for the architect than modification of the space geometry.

5.1.1. The Role of Colour in Modifying Space Perception

Today it is well known to everybody that warm colours seem to bring objects nearer, while cold colours appear to remove them. Again, anybody might have observed that when saturated colours are viewed against a black background, yellow appears to step forward, violet to recede, and the other colours are in between. Conversely, on a white ground, violet emerges with a mass effect, while yellow of similar lightness is repressed (Figs C40, C41). These observations make it obvious that the spatial effect of a colour is always due to interaction with, and dependent on, neighbouring colours. As interesting as these observations are, they offer too little insight into the spatial effect of colours to help the architect in expressing the wanted space sensation. Those concerned with colour, first of all, painters, have known much more about it since centuries ago.

In his "Trattato della pittura" Leonardo da Vinci, giant of the Renaissance, described several observations on the effect of colours modifying space sensation, which have only recently been thoroughly reinvestigated in experimental psychology.

After having discovered line perspective, the Renaissance became interested in colour perspective. As Leonardo put it: "There is another perspective, that of the air: since air differences permit us to recognize at what distances a building stands, even if the buildings stand on the same straight line. For instance, if a great many buildings are seen beyond the city walls that seem to reach to the same height above the walls, and you want to represent them as one being farther than the other then a somewhat hazy air has to be painted, knowing that in such an air, farthest things, e.g. mountains, seem nearly blue, like air at sunrise, because of large air masses between them and the eye. Thus, the first building over the wall should be painted its natural colour, the next one with a fainter outline, more bluish, that which is twice as far, should be made twice as blue, that five times farther five times bluer, and keeping this rule, it may be neatly recognized which one is farther, which one is bigger, and which one is smaller among buildings rising to the same height above the wall."

Following Leonardo's train of thought, several centuries later Itten (1961) concluded from his tests that the scale of the spatial depth effects of the six basic colours followed the proportion of golden section. That is to say, placing orange between depths expressed by yellow and by red, spatial depths expressed by these colours, that is, yellow to orange, and orange to red, are in a proportion to each other like the smaller to the larger distance in the golden section. The same proportion exists between yellow and red, and green and blue, yellow and green, and green and blue.

Again, it was Itten's observation that among cold and warm colours of the same lightness, warm ones tend forward, and cold ones to the depth. Complemented by a light to dark contrast, the cumulative effect is more pronounced. If bluish green and orange red of the same lightness lie on a dark surface, bluish green appears to be behind, and orange red before the surface. Making bluish green lighter, its apparent spatial position will tend to that of orange red.

In their quoted statements, Leonardo and Itten attributed space effect variation to

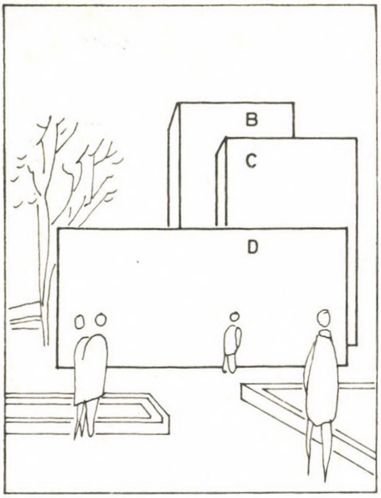


Fig. 5.1. Vertical walls outdoors at different distances from the observer, as colour bearing surfaces

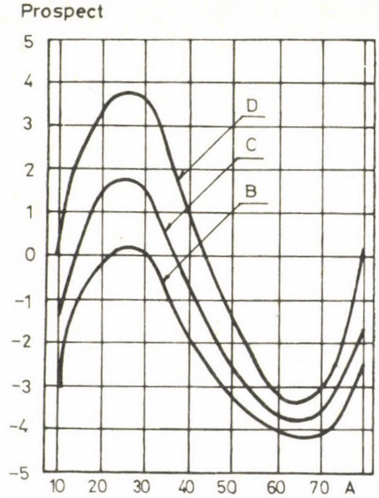


Fig. 5.2. Distance perception modifying effects of different hues on surfaces in Fig. 5.1. in prospect units, taking the medium saturated, medium light colour of hue *A*10 on surface D as reference

hue variation. These are statements which are now well known—although not always applied—by every architect. But variations of other colour parameters may also modify space sensation. As LEONARDO wrote: "If the same colour is at different distances but at the same height, it has to be lightened in the proportion to its distance from our eyes." Elsewhere, concerning saturation, he stated: "Colours in the foreground should be simple, the gradient of their decrease should be in accordance with the gradient of their distances, that is, the closer the object, the more it has to assume the nature of the viewpoint, and the closer the colours to the horizon, the more they adopt the colour of the horizon."

About the combined role of saturation and lightness in modifying space sensation LEONARDO wrote the following: "With increasing distance, first, the outlines of adjacent bodies of similar colours disappear, e.g. of neighbouring oak trees, at the next greater distance, outlines of objects differing by medium dull colours, such as foliage from fields, or abutments, or crumbling hillsides and rocks, while the last to blur are outlines of bodies confined by darkness at their light sides and by light at their dark sides."

To all this ITTEN added: "Saturated colours seem always nearer than dull colours of the same tone value. Adding this relation to that of cold to warm offers even richer possibilities for the apparent spatial location of various colour values." Later he stated: "For the creation of apparent spatial position of colour values, quantities of occurring colours are also decisive. Yellow on red background rises to float before red, but upon increasing the yellow area to exceed the red one, red seems to overtake yellow." (Fig. C42).

These statements refer mainly to free-standing vertical space walls. Based on observations by LEONARDO, FRANCESCA, VAN GOGH, PISARRO, ITTEN, WILSON, BIRREN, FRIELING, DÉRIBÉRÉ, and the Author, Figs 5.1 to 5.4 show variation of the perceived distance from free-standing vertical walls bearing colours of different hues, saturations and lightnesses. As reference was taken the perceived distance from wall D in Fig. 5.1, the nearest to the onlooker, bearing a Coloroid colour A10 of medium saturation and medium lightness.

The rate of decrease or increase of the reference distance perception has been expressed in "prospect" units (NEMCSICS, 1976). Zero point of the psychometric scale introduced for this purpose is the distance perceived from wall plane D under the circumstances outlined. The prospect values plotted are relative values expressing merely tendencies to modification of space perception.

Nevertheless, even the knowledge of tendencies is a valuable information for the designer. Orange of Coloroid hue 24 reduces while cold green of Coloroid hue 65 maximally increases the perceived distance. In case of warm colours, the modification of distance perception is much affected by the distance of the colour bearing surface from the observer, a factor rather irrelevant for cold colours (Fig. 5.2).

Slight saturation differences between unsaturated, or even, very saturated colours hardly affect the distance perception, while even the slightest saturation change of medium saturated colours markedly affects the distance perceived. Thus, in the coloration of e.g. facądes in a street, if colours of medium saturation are to be applied, then only scales of the same hue may be selected. But there is free choice between either unsaturated or very saturated colours (Fig. 5.3). It is not generally known that the increase of distance perception is not proportional to lightness increase (Fig. 5.4).

Concerning colour bearing surfaces of horizontal planes or interiors, much less has been reported in the literature about modifications of the space sensation. Test results are seen in Figs 5.5 to 5.8, space sensation being again expressed in prospect units.

Blues and greens on the ceiling of a room increase space sensation much more than on the floor, while on the floor, colours in the red and purple domains are less depressive

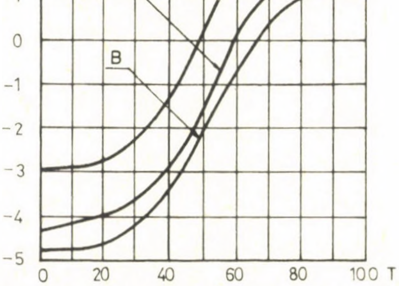


Fig. 5.3. Distance perception modifying effects of colours of different saturations on surfaces in Fig. 5.1. in prospect units, taking medium saturated, medium light colour of hue *A*10 on surface D as reference

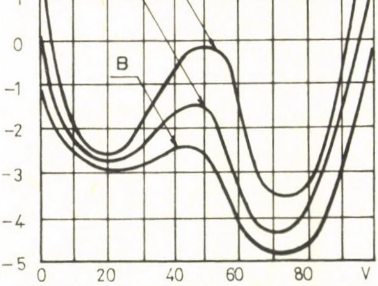


Fig. 5.4. Distance perception modifying effects of colours of different lightnesses on surfaces in Fig. 5.1. in prospect units, taking medium saturated, medium light colour of hue *A*10 on surface D as reference

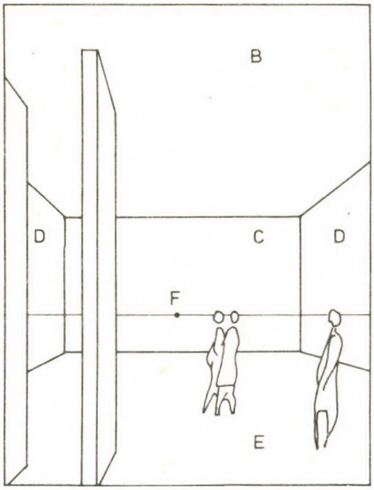


Fig. 5.5. Interior colour-bearing surfaces in different positions to the observer

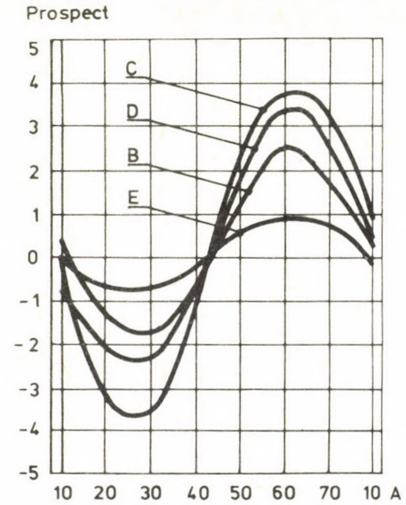


Fig. 5.6. Distance perception modifying effects of different hues in Fig. 5.5. in prospect units

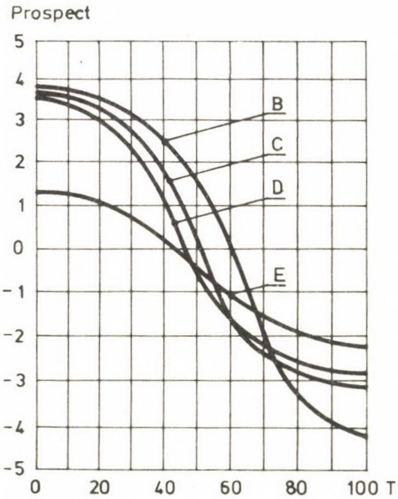


Fig. 5.7. Distance perception modifying effects of colours of different saturations in Fig. 5.5. in prospect units

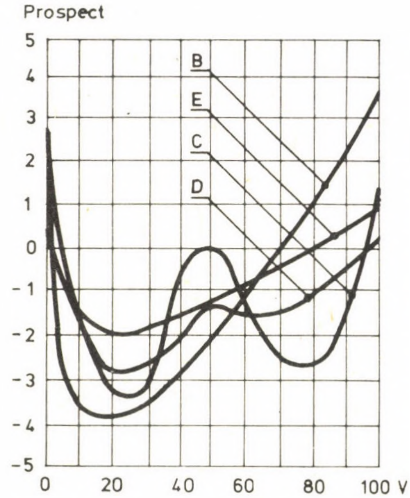


Fig. 5.8. Distance perception modifying effects of colours of different lightnesses in Fig. 5.5. in prospect units

than on the ceiling. In a low room, the ceiling requires less saturated colours than the floor. Depending on the hue, colours of about Coloroid saturation T20 and Coloroid lightness V70 induce the same space sensation modification on the ceiling and on the floor. On walls, the hue of the colour is decisive for the modification of space sensation, while on the ceiling, saturation and lightness are dominant. Thus, colour designers have to concentrate on hue for walls, and on saturation and lightness for the ceiling.

A typical problem encountered in the practice of interior colour design is that in case of constant proportions, in what direction variation of absolute dimensions of a room affects the space sensation modifying effect of various colours. Or, what are the effects of dimensions and proportions of colour bearing surfaces in this respect. Relevant diagrams based essentially on our own observations are seen in Figs 5.9 through 5.12.

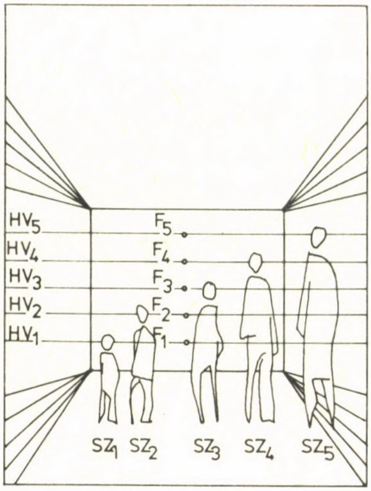


Fig. 5.9. Ceilings as colour-bearing surfaces of rooms of the same width but of different headrooms

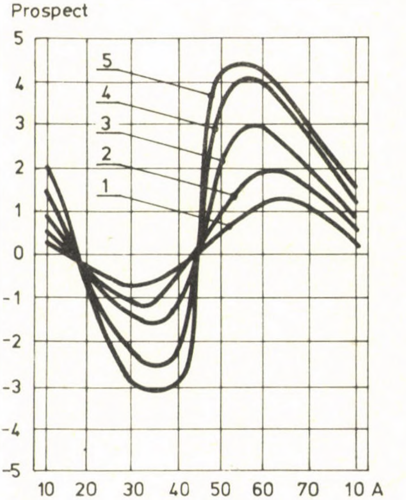


Fig. 5.10. Effects of colours of different hues on ceilings in Fig. 5.9. on increasing the headroom in prospect units

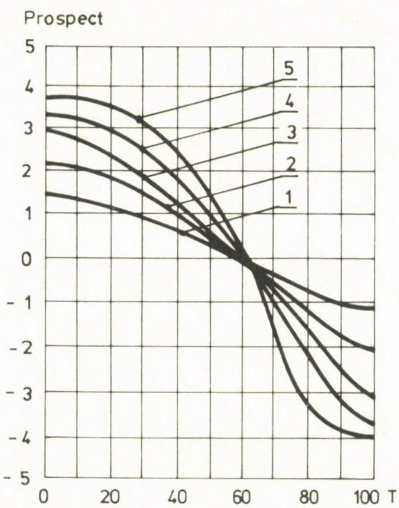


Fig. 5.11. Effects of colours of different saturations on ceilings in Fig. 5.9. on increasing the headroom in prospect units

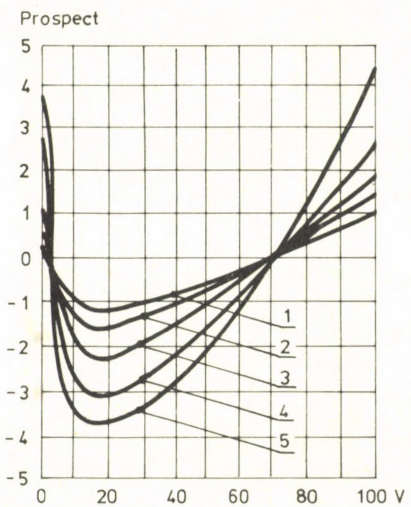


Fig. 5.12. Effects of colours of different lightnesses on ceilings in Fig. 5.9. on increasing the headroom in prospect units

5.1.2. Mass, Building Component, Surface, Form

It is common knowledge that in a home, red upholstery is more momentous than is e.g. a gray one, or that a white dress appears to make the wearer fat, while someone wearing a gray or black dress seems slimmer. But it has also been stated that bulky furniture should not be painted red or any other saturated colour lest it will look even heavier. If the impression of importance or mass of an object is to be enhanced, it should be colored either very light or very saturated.

Our observations concerning objects have been recapitulated in Figs 5.13 and 5.14. Mass of the chair in Fig. 5.13 is felt to be larger or smaller depending on the relation between the colours of the chair and the background. In Fig. 5.14, modification of mass perception with the variation of hues of a chair and its background has been plotted. Modification of mass perception has been rated from 0 to 10 on a special psychometric scale, in "mass" units, 10 masses being the maximum modification of mass perception. On the horizontal axis of the diagram various background hues are marked, the vertical axis shows modification rates of mass perception. The curves show the rates of modification for chairs of different colours. Modification of mass perception is in strict linear correlation with the hue contrast between chair and background. Different hue contrasts result in different mass sensation modifications. Modification is at maximum when a yellow chair is placed before violet background. Mass perception modifications as a function of variations of saturation and lightness of chair and background are shown in Figs 5.15 and 5.16, respectively.

The effect of colours to modify mass perception is of special importance in the colour design of streetscapes and of townscape complexes. Streetscapes of historical town centres usually comprise different building masses. Design is often expected to shape different masses into an assembly of units eliciting similar mass perceptions. Or even, a building lesser by mass but more important by its function or historical value has to be highlighted by eliciting an increased mass perception.

In Fig. 5.17, a streetscape consisting of ordinary buildings is seen. Façades differ by surface areas, being larger or smaller than the average. Deviations have been plotted in

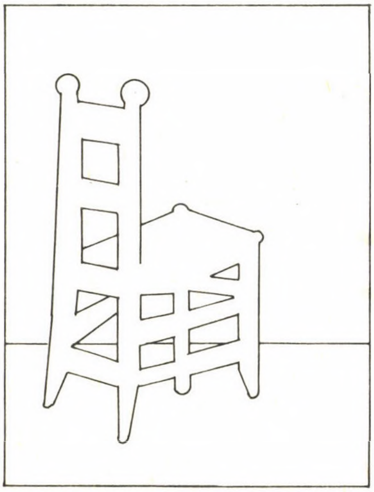


Fig. 5.13. Colour-bearing surface as a mass before different backgrounds

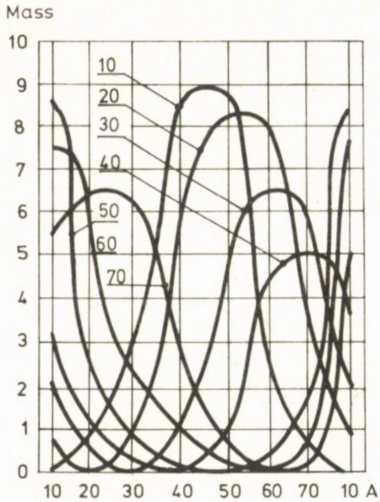


Fig. 5.14. Mass perception in mass units elicited by a chair painted with colours of different hues, before backgrounds of different hues, as in Fig. 5.13. Horizontal axis shows hue of the background colour, vertical axis the magnitude of modification of mass perception. Curves refer to chairs of colours of different Coloroid hues

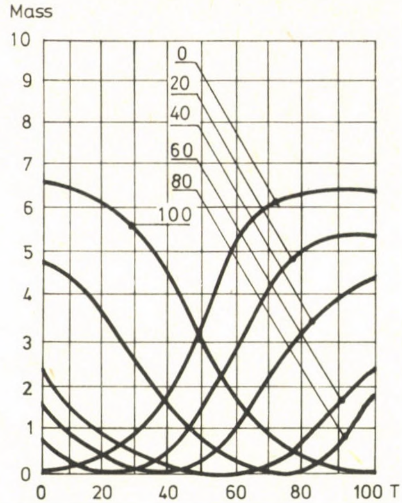


Fig. 5.15. Mass perception in mass units elicited by a chair painted with colours of different saturations, before backgrounds of different saturations, as in Fig. 5.13. Horizontal axis shows saturation of the background colour, vertical axis the rate of modification of mass perception. Curves refer to chairs of colours of different Coloroid saturations

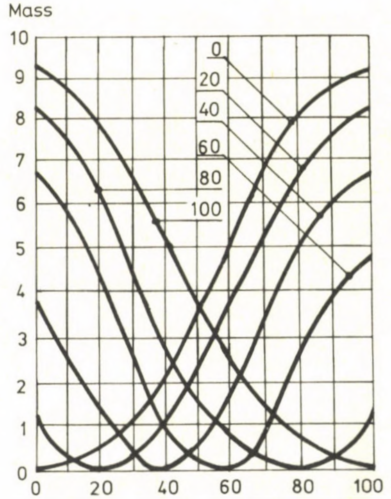


Fig. 5.16. Mass perception in mass units elicited by a chair painted with colours of different lightnesses, before background of different lightnesses, as in Fig. 5.13. Horizontal axis shows lightness of the background colour, vertical axis the rate of modification of mass perception. Curves refer to chairs of colours of different Coloroid lightnesses

an emphasis diagram, so that the designer may know which building in the street has to be given a more saturated or a lighter colour to alter the mass effect, or perhaps a hue deviating from its environment.

The skyline may have as background the blue of a fair sky, or the gray of an overcast sky, altering the effect of different hues, saturations or lightnesses on the mass sensation. Modifications of mass sensation for facades of different hues, saturations and lightnesses

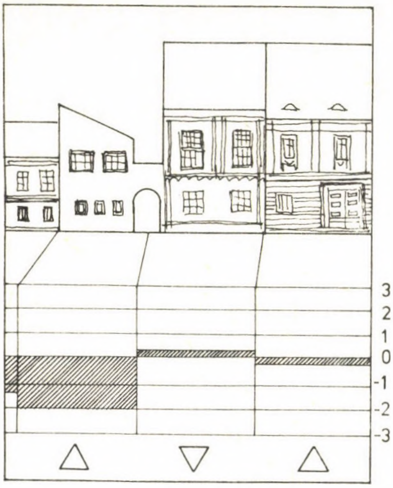


Fig. 5.17. Construction of an emphasis diagram for balancing surface proportions of a streetscape by colour

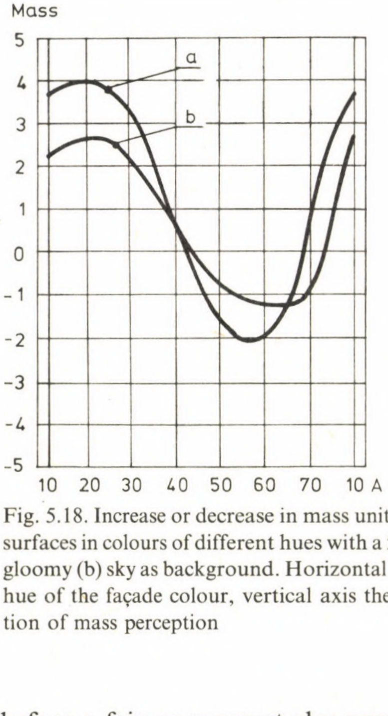


Fig. 5.18. Increase or decrease in mass units of façade surfaces in colours of different hues with a fair (a) and gloomy (b) sky as background. Horizontal axis shows hue of the façade colour, vertical axis the modification of mass perception

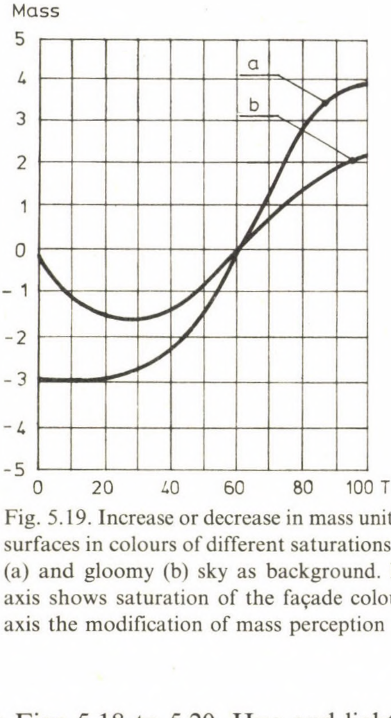


Fig. 5.19. Increase or decrease in mass units of façade surfaces in colours of different saturations with a fair (a) and gloomy (b) sky as background. Horizontal axis shows saturation of the façade colour, vertical axis the modification of mass perception

before a fair or overcast sky were plotted in Figs 5.18 to 5.20. Hue and lightness are effective mainly before a fair sky, while saturation mainly before an overcast sky.

There are different relations between building components, such as courses, pillars, doors and windows, which are in different relations between each other and with the wall surfaces. In addition to function, these components carry aesthetic messages; both can be expressed by colours. Unimaginative streetscapes are enlivened and are given a message, if a proper relation between colours of window casements, cornices, and the walls is established. Colour relations by hue, saturation, and lightness between building components and wall surfaces are plotted in Figs 5.21 to 5.24. Clearly it is advantageous to have hues of door and window frames, courses and footings akin to that of the wall, but of rather different saturation and lightness. On the other hand, hues for door and window casements and sashes should preferably differ from those of the walls.

Appearance of coloured surfaces is much affected by surface texture and material. The colour bearing surface may be perfectly smooth, coarse or granular. Different surface textures have a different optical appearance, and hence elicit different sensations.

Colour is markedly affected by surface texture. This fact becomes clear upon changing the texture of the coloured surface within the same group of colours. Let red, yellow and

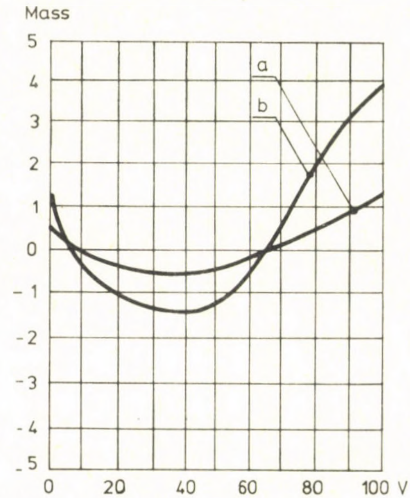


Fig. 5.20. Increase or decrease in mass units of façade surfaces in colours of different lightnesses with a fair (a) and gloomy (b) sky as background. Horizontal axis shows lightness of the façade colour, vertical axis the modification of mass perception

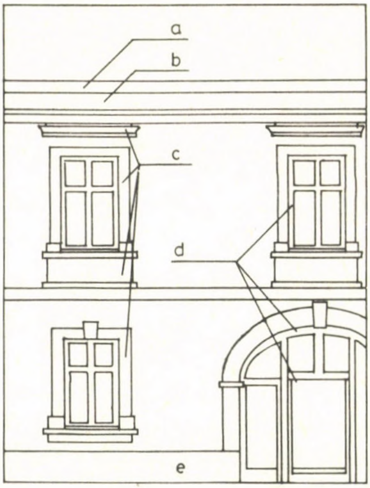


Fig. 5.21. A façade with features: a) gutter, b) cornice, c) course, d) casement, sash, e) footing

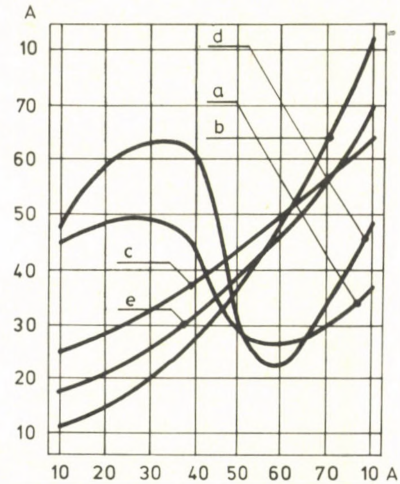


Fig. 5.22. Hues fitting the courses in the façade in Fig. 5.21 matching walls painted to colours of different hues. Horizontal axis shows wall colour hues, vertical axis the hue of the course colour

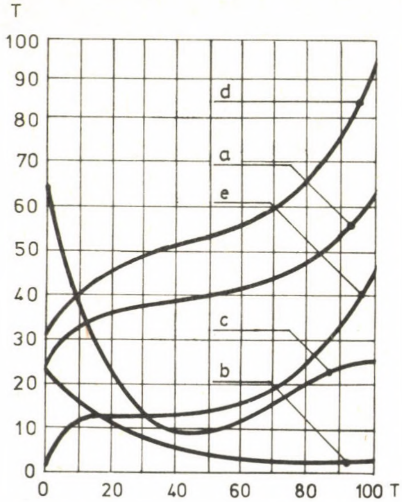


Fig. 5.23. Saturations of courses in the façade in Fig. 5.21, matching walls painted to colours of different saturations. Horizontal axis shows wall colour saturations, vertical axis the saturation of the course colour

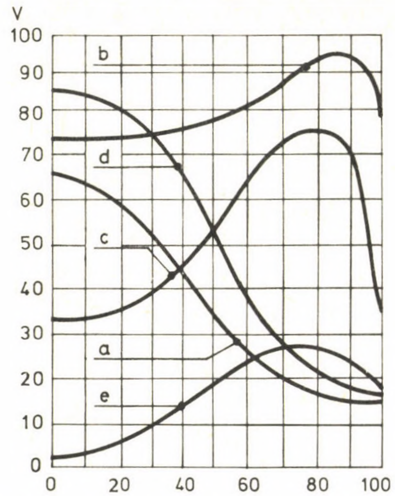


Fig. 5.24. Lightnesses of courses in the façade in Fig. 5.21, matching walls painted to colours of different lightnesses. Horizontal axis shows wall colour lightnesses, vertical axis the lightness of the course colour

blue stripes be painted on a surface. Covering one of the yellow stripes by a silk band of the same colour, the overall effect will dramatically change, due to different surface of silk. Let us make another test by painting a smooth sheet of paper and a surface of fresh plaster with the same green. Now a yellow circle should be painted onto the green paper, while a smooth yellow disc should be stuck onto the green plaster slab. The colours are the same in both cases, but messages of the two combinations will be quite different. Compared to the pleasant, lively plaster surface, the smooth paper will have a boring and featureless appearance.

The quality of textiles, silk or velvet, timber or marble, or other objects raises peculiar optic effects. Surface texture of materials lends special dynamism to colours. Timbers produce varied, warm colour effects. Stone gives a cold impression and so do colour values associated with stone. Tweeds are loose and light, and feel at ease with unsaturated, light colours. On the other hand, velvet is dense, heavy, and respectable and is impressive, mainly when dark coloured. For space creation architecture utilizes an assembly of forms and colours. Therefore it is instructive for the designer to contemplate relationships between forms and colours. Let us examine the relation between messages of some basic figures and colour values.

A square is characterized by two pairs of parallel straight lines, horizontal and vertical, symbol of material, weight, definiteness. For instance, among Egyptian hieroglyphs, the square stood for a plot of land. Figures containing perpendicular lines bear heavy stresses. A square is the counterpart of red. Both symbolize material. Both express what is heavy, opaque, static.

A triangle represents an angle, a diagonal—in general, an intersection. It has an agressive effect, typical of all diagonal configurations such as the rhombus, trapezium, sawtooth. The triangle is also an expression of aggressive thinking, thus it has to combine with yellow to express fully its message.

The circle, rotation around a centre, performs a closed motion. Rather than by a hard, stretched, opposite motion typical of the square, the circle is characterized by continuous, relaxed motion; the circle, just as blue, symbolizes thinking. Thus, a circle performing a continuous, closed motion has blue as its counterpart. Associative relationship between given colour values and configurations is not restricted to the pairs square and red, triangle and yellow, or circle and blue, but it exists also between a wide range of planar or spatial forms, and various colour values.

5.1.3. Appearance

Appearance of a building depends on several factors, one of which is colour. Colour is not only the dress of a building but an integral part of architecture. Function, structure, form, and colour are inseparable, which means that colour of a façade, the harmony formula of a streetscape, or colours of a city cannot arise from an arbitrary decision. Colour selection is inseparable from architectural creation. Function influences structure, structure form, and form colour. Obviously, the process of creation is much more complex than to assume such a single, hierarchic sequence of actions. Colour is directly related not only to form but also to structure and function, and also to all the close and far environment of the building.

It was necessary to point all this out since nowadays, more than ever before, man wants to see his environment, his entire built world, in visual unity, inducing him to adopt integrated colour design and repainting not only of streetscapes but even of whole districts. And this is all right, because our environment badly needs a considerate, unified, architecture-derived intervention reflecting the visual approach.

By now, authentic colour traditions associated with regions, architectural styles, and given functions have been almost completely neglected giving way to many different, concurrently existing philosophies of colour design. Colour has often become a means of self-expression of the artist, or it is present only as the natural colour of the building material. Some architects either confuse a streetscape with a painting, or believe in the existence of "pure" forms and pure architecture, independent of colours. What is more, in our day possibilities of coloration have become almost unlimited. There is not only a choice of harmonizing earth pigments of a particular region available, but an infinity of shades are offered by the chemical industry. To what use? Some of our towns are deprived of colours, are gray, and bleak—others are too coloured, showing a gaudy and confusing picture. This can be helped by designing building coloration taking environment, function, and the system of their structure and form into consideration.

Our wider environment involves geographic features. A mediterranean sunlit environment stimulates white, and light tones. A white building before a blue sky sparkles with freshness, at the same time suggesting stability. But in a northern, foggy landscape, the same colour has an uncertain appearance lost in its surrounding. It seems fresh, and clean only if combined with intensive, fiery colours. In sunless regions, on façades highly saturated colours in contrasted pairs are at ease. Red, orange and yellow are revived by sunshine, while blue and green show better in shadow. Orientation is therefore an important point, mainly in the coloration of façades in a streetscape. In knowledge of the geographic location of a building, façade insolation can be exactly determined around the year—of course, not only for the sake of coloration but also to determine the heat balance of the building, and eventually, to design sunshields.

To determine the insolation of a building, the ecliptic diagram at the geographic latitude of the building site (Fig. 5.25) and a shadow angle meter (Fig. 5.26) are needed. An ecliptic diagram constructed for a given latitude comprises projections of imaginary sun paths, time lines and altitude lines (concentric circles cutting out equal latitude angles

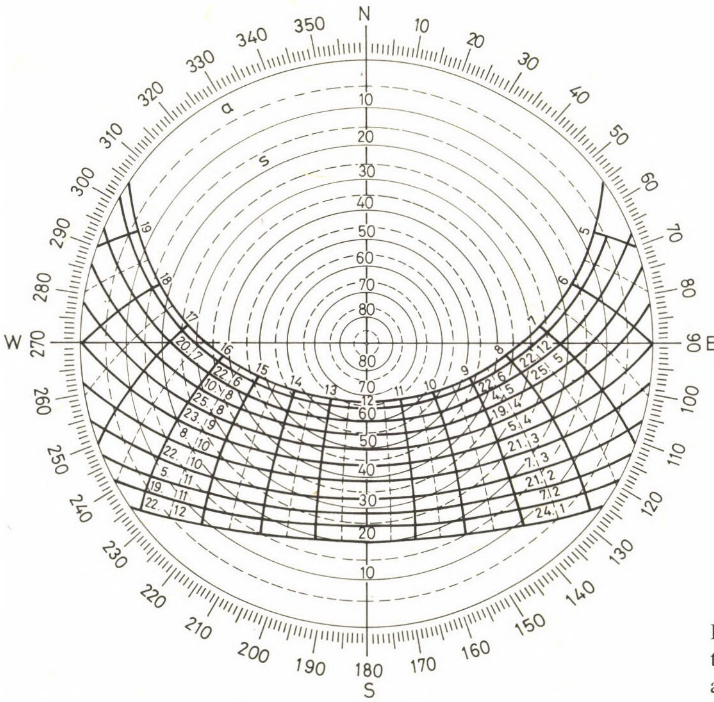


Fig. 5.25. Sun path diagram for the geographic latitude of 46°; a sun azimut, s sun altitude

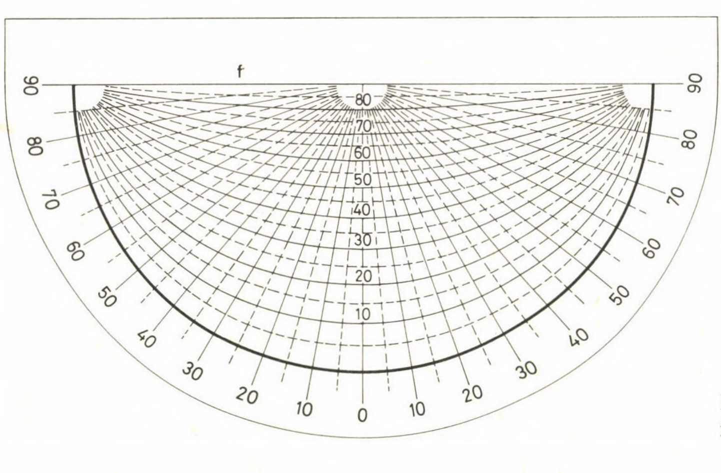


Fig. 5.26. Shadow angle meter; f façade plane

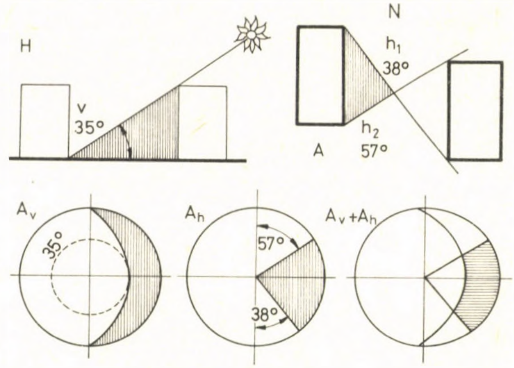


Fig. 5.27. Determination of overall insolation by shadow mask construction. Legend: H façade view of a building complex, A ground plan of building complex, N north, v vertical shadow angle, h_1 h_2 horizontal shadow angles, A_v vertical shadow angle mask, A_h horizontal shadow angle mask, $A_v + A_h$ overall shadow mask

on the sky). A circle with outside graduation marks the horizon plane, circular basis of the sky, its centre represents the position of the imaginary observer. Perimeter graduation indicates sun azimuth, i.e. the horizontal projection angle from the north pole. Arcs intersecting the horizon circle, the sun traces are sun paths at an arbitrary but typical day of the year each: horizontal projections of the sun paths traced on an imaginary skyvault (KUBA, 1975).

The shadow angle meter helps to read shadow angles off the solar diagram without any construction or calculation. To determine the vertical shadow angle, the base line of the shadow angle meter is placed on the solar diagram oriented as the building façade, coincident with its perimeter. The previously determined solar altitudes are read off by means of arcs in the shadow meter, rather than by altitude lines of the solar diagram. The result will be the vertical shadow angle (angle of incidence) of the examined façade for the given position of the sun. This procedure is the same for any orientation.

For example, out of two north-south oriented buildings parallelly aligned, let us determine the insolation of that sited to the west (Figs 5.27, 5.28). Duration of insolation can be read off the solar diagram by marking out extreme sun positions along the contour lines of the building to be seen from the examined façade. These extreme sun positions can be constructed by connecting by straight lines selected points of the examined façade and characteristic points of the shading skyline. Intersections of these straights with the vault of the sky will be the extreme sun positions. In possession of the spatial angles of these points, counterparts in the diagram of intersection points can be marked. Connecting these points yields the counterpart in the diagram of the shading object, loci of extreme sun positions such that from points beyond them, no sun beam can reach the façade. The figure encompassed by this line and the perimeter of the diagram is the shadow mask. The shadow mask covers that area in the diagram, which is screened on the sky by the other building standing in way of sunshine before the given façade. The insolation period can be read off the free sun paths between shadow mask and the diameter coinciding with façade orientation. A shadow mask is advisably constructed in two steps, beginning with diagram counterparts of horizontal, then of vertical outlines of shadow, then assembling the resulting figures to a complete shadow mask.

Appearance of a façade much depends on whether courses are kept in the wall colour (Fig. C43). Emphasis may be partial or for all protruding parts. In case of a rich

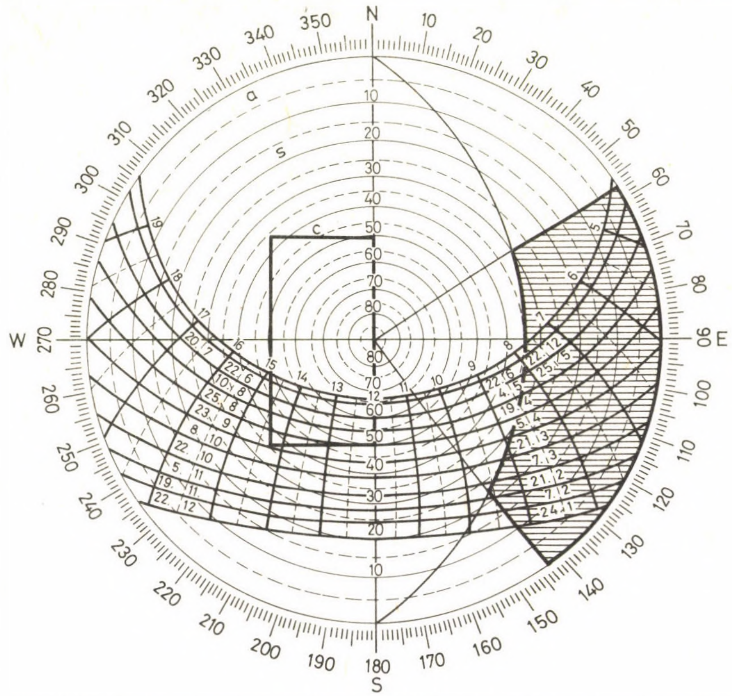


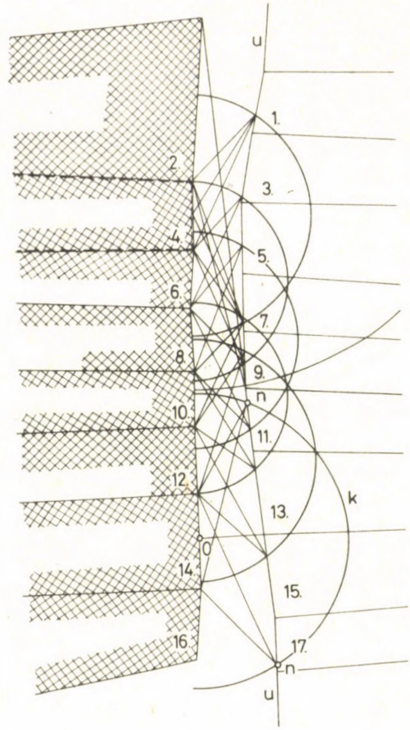
Fig. 5.28. Insolation period can be read off the nonoverlapped section of sun paths between shadow mask ($A_v + A_h$) and diameter pointing to the façade orientation (N–S). c is the outline of building at ground level

architecture, courses may be given several different tones. Wall and course colours need not to be of the same hue, but all courses should be. Let saturations and lightnesses of the applied colours follow the recommendations of this book concerning colour harmonies. A building gives quite a different impression and in most of the cases as more stable, and reassuring one if its wall surfaces are of darker and more saturated colour, than its courses (Fig. C45). Lighter courses point out by means of their colour that they are nearer to the observer than the wall.

Depending on the richness of architecture, colours of either the walls or the courses are more characteristic of the building (Fig. C46). In certain cases, it depends on the angle of aspect of the façade, mainly in narrow streets, whether the essential colour information is borne out by the courses or by the wall. If the angle of aspect on the façade is not less than 30°, and courses do not jump out by more than 8 cm, visual importance of wall colours overrides that of the courses. Optimum angle of aspect may be determined by adjusting the span of compasses to two and a half times the largest dimension of the façade, then drawing a circle with the point of compasses stuck into the middle of the façade line (Fig. 5.29). Intersections of the arc with the street line are optimum façade sight points.

Colour may emphasize the structure of a building. Medium saturated shades suit enhancing courses and levels. Colour emphasis of functional structures lends stability to the appearance of a building (Fig. 5.30). Coloration of parapets, balconies or other features leads to horizontal, vertical, or even, diagonal division of the façade (Fig. 5.31).

Fig. 5.29. Construction of optimum viewpoints n of looking at the façade. Optimum viewpoints n are cut from the street line u–u by a circular arc k traced by compasses stuck at point 0, with a span of 2.5d



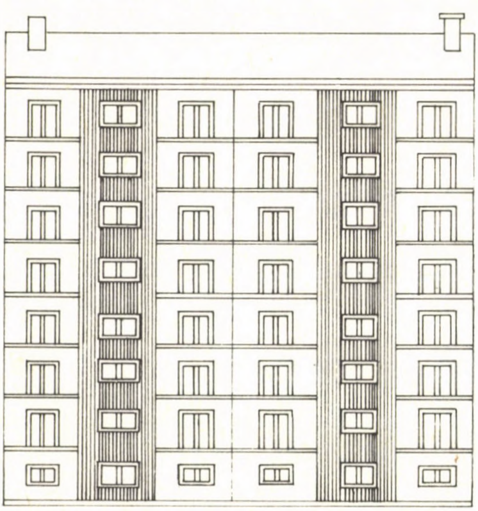
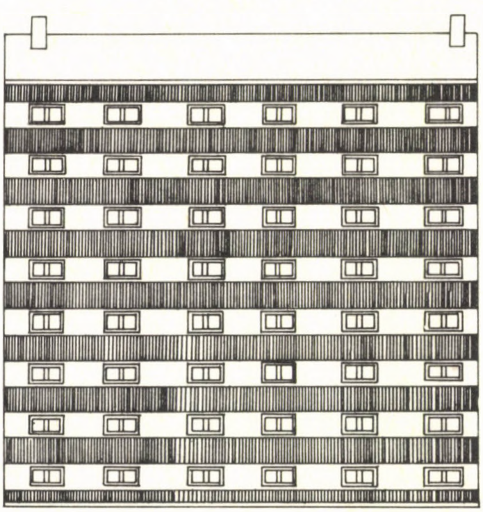



Fig. 5.30. Appearance of a multistorey strip house is fully altered by horizontal or vertical division of wall surfaces

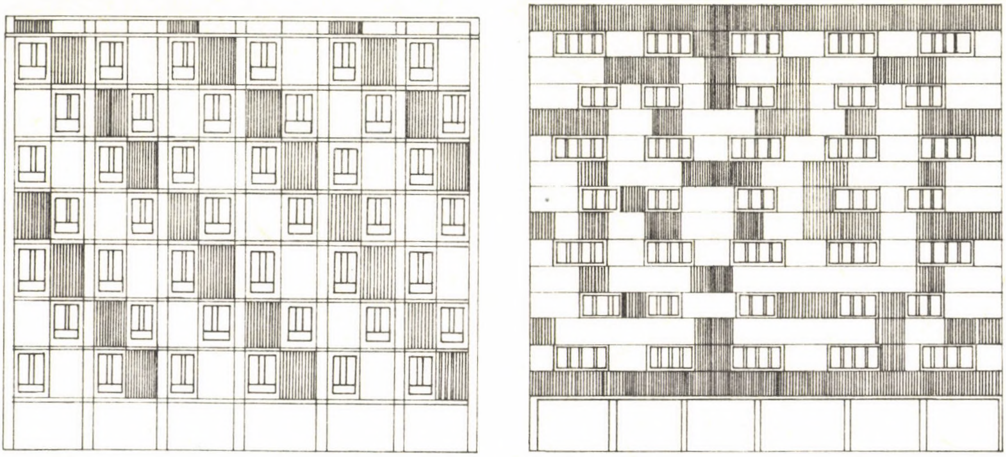


Fig. 5.31. Some possibilities to visually divide a façade

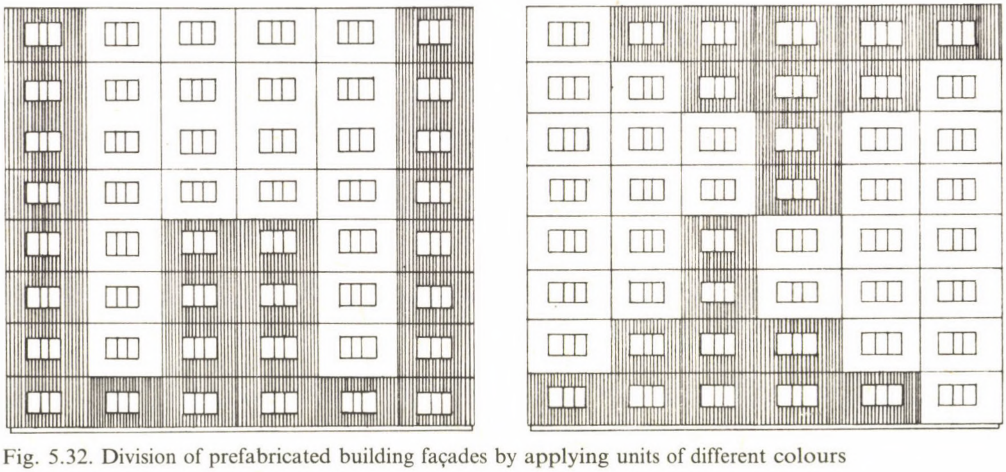


Fig. 5.32. Division of prefabricated building façades by applying units of different colours

Structural unity may be entirely decomposed by applying a random pattern of patches or one contradicting the structure.

Colour suits to stress architectonic features, to emphasize or subdue the rhythm of a row of windows. It is always pleasing if colours of doors and windows differ from walls not only by hue, but if saturations and/or lightnesses are also substantially different. An interesting method of façade coloration is by stable or unstable, staggered or other spot rhythms. Thereby the building may be given either a massive and poised, or an airy, weightless appearance.

Dull shades are to be preferred on façades with a rich variety of forms, while more saturated colours fit those of a simpler design. Façade coloration may point out the coherence between functionally coherent building parts, visually emphasizing doors and windows of functional importance (Fig. 5.32).

Balconies and loggias must not be given colours which when reflected inwards exert detrimental psychic or somatic effects. Again, in selecting colours for façades, psychosomatic effects of the colour have to be reckoned with, especially if it is overwhelming in the visual field of tenants in neighbouring houses.

The more fiery the colours of a façade or a complex of buildings, the more important it is to disrupt highly saturated surface colours by rhythmically repetitive achromatic or nearly achromatic façade components. For instance window casings painted white in an English red façade assume this role. In residential areas, communal buildings should be distinguished by their colour from living quarters. It is not against this distinction to have a connecting colour of a rather dull tone, rhythmically repeated both on residential houses and communal buildings. Dark, dull colours do not suit exposed concrete, or gravel concrete surfaces.

5.1.4. Interiors

Only those interiors exert a pleasant space effect which meet one's need of orientation. Entering a room—be it a living room or a huge workshop hall—eyes immediately scan its walls, then columns supporting ceiling and floor. If spatial boundaries of the room are not immediately felt, haphazard spatial elements obstruct the view, if spatial relations are felt confusing then our fundamental need of orientation is frustrated, and one feels uneasy. Spatial effect of a room is unpleasant if it is too high compared to its area, if at entry, intersection of opposite ceiling and wall is outside the visual cone of 45°. In turn when this intersection line is within the 30° visual cone, the room is too low to be pleasant.

Similar problems of spatial effects may be solved by coloration, and colour can help in several other problems too, as shown below.

Some colours are not equally welcome on all surfaces of an interior. In general for the walls a harmonic mean between floor and ceiling colours is felt to be pleasant. A wall colour darker than that of the floor is less attractive. Our feeling of stability is perfectly disturbed by a floor given the lightest colour, and one feels depressed in a room with a dark ceiling (Figs C47 to C49).

Wall and floor colours affect our impression about dimensions of a room (Fig. C50). Walls of wide, low halls need saturated colours, enhancing the feeling of volume. If columns in the hall have colours of the same lightness and saturation as that of the walls, an uncomfortable spatial effect arises, making our orientation in space uncertain. For high headrooms, clustered pillars, and continuous bars, colours should differ in lightness from those of walls and ceiling. For very large halls, e.g. hangars, the feeling of stability is reassured by intensive, saturated colours for the supporting structure (Fig. C51).

Architecturally undivided, extensive interiors should be preferably divided by rhythmically recurrent colour patches, helping to sense space depth. The room is raised by vertical spot rhythms, lowered and lengthened by horizontal ones (Figs 5.33, 5.34).

Colours are very suitable visually to distinguish functionally separate parts of a room. Within one room, a different colour should pertain to each of the functions. This problem may emerge in hotel halls accommodating different functions. Traffic rooms should also be distinguishable by colour. Deep window casings of old buildings should never be painted to the wall colour. It is advantageous to paint them white. Thereby not

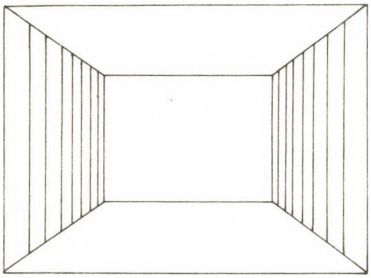


Fig. 5.33. Vertical stripes increase the headroom

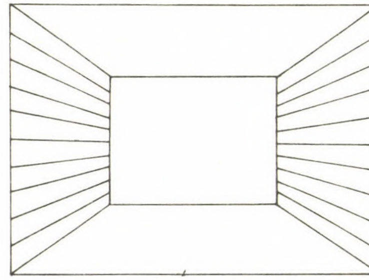


Fig. 5.34. Horizontal stripes lengthen the room and depress its headroom

only wall edge and substance are separated, sensing thereby the wall mass that is reassuring, but more light, and not a coloured one, will be reflected from the white surface inwards.

For interior colouration the orientation of building windows should also be considered. In a room facing north, little blue has to be applied, and so has red to be avoided in a room facing south.

Intimacy of an interior may be emphasized by wallpaper. Large patterns, with saturated colours should not be applied in small rooms, since surfaces with strong colours make our environment disquieting and chaotic and disturb the visual appearance of furniture. Vertical strips elevate, horizontal strips lengthen the room.

5.2. Colour and Function

Human environment may be considered as a system, since man and environmental elements are mutually determinant in any sense—an interrelation concerned with demand of man for his environment.

The idea of demand of function for the built environment originated from the important recognition of biology in the 19th century, namely that subsistence and development of living beings is ensured by the flexibility of their organs, and adaptation to modified functions. This recognition has been formulated by Lamarck in his law: "form follows function".

Function of the built environment is based on social demand, necessity raised to a social level. Within the system of man and elements of his environment, structural relations are defined and sustained by complex functions. This complex function is composed of three types of functions: utility, aesthetic, and informative.

Utility function is understood as designation and purpose of environment elements. Aesthetic functions bring about properties of environment elements which enable one to experience utility functions. Informative functions involve properties of environment elements by which their functions, uses, and operation become understandable for man.

In environment colour design, and in general, in architecture, this complex approach has developed only recently, although its beginnings may be traced back to Labroust, French pioneer of cast iron constructions who wrote in 1830 in a letter: "In architecture, form has to adapt itself to the intended function of the building."

This idea has been further developed by the Belgian Van de Velde (1962) a pioneer of functional design early in this century. He advocated organic relations between art and life. In the same period, a scientific approach to architecture began to emerge, mass production and mechanical technology penetrated architecture, joined by standardization and an endeavour to unify and coordinate dimensions. All this opened up new vistas of functionalism.

The most prominent representants of functionalism have been Le Corbuiser and the Bauhaus. The manifesto of functionalist architecture was issued in 1925, while in 1932, Sartoris published his comprehensive work "Elements of Functionalist Architecture". At that time even the greatest personalities have only been concerned—among the multitude of human activities—with material–biological functions, with directly deducible space demands, abstracting them out of the complex relations of demands. The trend was set by statements such as that by F. L. Wright (1957), namely "function is the inner, determinant side, the very nature of the given work".

These preliminaries underlie the present day approach to environment colour design, considering the totality of utility, aesthetic, and informative functions as the system of demands.

Environment colour design has to serve the expression of the complex function of environment elements. Various functions of colour-bearing environment elements are strictly interrelated and are prone to change into each other, a characteristic to be considered in the methodology of environment colour design as a design process. It is necessary to develop design methods suitable for simultaneous and differentiated consideration and coordination of these components.

Colour function components of environment colour design as a design process can be deduced from the man to colour relations. The man to colour relation cannot be regarded in an abstract way. Colours are always associated to some object, phenomenon, or process, implicating, in turn, into this relation their complex functions. In this respect, theory of environment colour design has been concerned with the possibility to express function by the colour of the environment element. It can be stated, for instance, that more saturated colours of the colour space, with longer dominant wavelengths, act dynamically, hence suit to express functions involving dynamism. The less the saturation of these colours, the lower their dynamism. The greater the hue, saturation, or lightness differences between members of colour complexes to express a function, the more dynamic is the function expressed by them. Intensity of the expression of function is more affected by variation of lightness differences than that of saturation differences. Again, it is found that a function is expressed not so much by a single colour than by a complex of several colours. Accordingly, the expression of function by the environment elements contributes to harmony relations of colours borne by the element, and Coloroid colour harmony relations may be combined with function expression indices.

Disclosure of the rules of function expression cannot rely solely on visual information, since it is physiologically possible that stimuli perceived by one of the sensory organs should create perceptions normally transmitted by another sensory organ.

5.2.1. Utility Function of Colours

Environment is the space for human activities aimed at satisfying human demands. Since the beginnings of society, architecture has been expected to meet human demands. Analysis of, and reckoning with functions necessarily took place in every period, even if functional demands have significantly changed and developed through the ages. Scientific analysis of functions and a conscious, integrated attention to all the requirements could not, however, develop earlier than in our age, at a higher level of social development. This has led from early functionalism, the narrow interpretation of function, to an extended, wide-range functional approach, to the complex consideration of the integer system of relations inclusive demands, requirements, and the colour environment.

Of course, this functional approach itself is undergoing development although in its germs it has been present in every stage of development throughout the development or architecture, and recently, in environment colour design. Nowadays, however, it has become more conscious, unambiguous and scientific, and it has risen to be an important factor of our up-to-date approach. Relationship between structure and function in architecture has been recognized, and this knowledge unavoidably affected environment colour design. The ideas of environment colour designers have to be directed by modern scientific thinking.

Activities in various areas of our built environment have become extremely differentiated. Functions have become so manifold, that categorization is not only difficult but may lead to misunderstandings. Nevertheless, functions need to be categorized, otherwise relations between functions and colours cannot be delineated and the role of colours in the utility function of the environment cannot be studied.

According to the activities accommodated, our environment can be divided into working spaces, community spaces, living spaces, and traffic spaces.

The most important part of our life is spent in working spaces. It is there that abilities are expanded, and where we are exposed to most of the environmental effects. Here colour emerges essentially as an ergonomic necessity. There are a great many different working processes, but each has its definite colour demand.

The widest group of working spaces comprises production plants, but there are also research and design institutes, various administrative, financial, statistical institutions, offices, education institutions, services, workshop, as well as hospitals and medical consulting rooms.

In an industrial plant the visual environment also has to express function. This environment is, however, very complex. Enormous halls are full of a heterogenous mass of machinery and equipment, entangled—seemingly at random—by air ducts, pipes, hoses, conduits, a condition still worsened by flashing lights, dust, smoke and noise. Spatial perception of such a room may induce spatial alienation, which means that the confines of the surrounding room cannot be perceived, one feels as a minute being dropped into the middle of an unfriendly environment, and all this elicits psychological stress. The sight of complexity may reduce productivity and for example may result in warning signals not being noticed.

Colours may contribute to reducing this confusion by a design which creates a certain structural order in the visual field. A way to achieve this is to apply intensive colours on control elements of clean, simple forms, so that their complex should constitute a definite structural pattern.

Recently, development of production technologies has surpassed the typical sight of machinery scattered in a conventional workshop hall. Now all this is replaced by automatically controlled production lines, large-size production and transport equipment, with colours dominating the working environment. Thereby surrounding walls and floors are only the background to the colour dynamic design of modern industrial spaces. The possibility of alleviating noise, dust, heat, vibration, and other harmful effects arising in technological processes by colour dynamic means is of increasing importance.

Colour design has to inform also about the consecution of technological processes and so assumes an organisatory function.

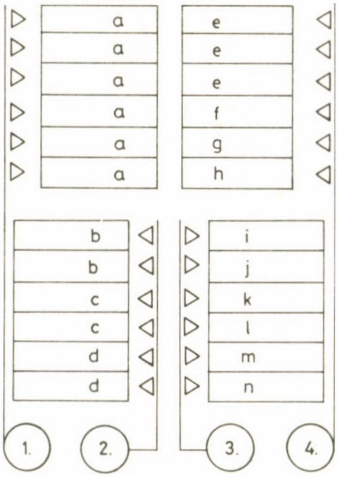


Fig. 5.35. Rooms in industrial plants grouped according to functions: a) workshop, b) preparation, c) store, d) delivery, c) office, f) keeper's lodge, g) kitchen, h) boiler house, i) corridor, j) staircase, k) WC, l) bath, m) dressing room, n) canteen

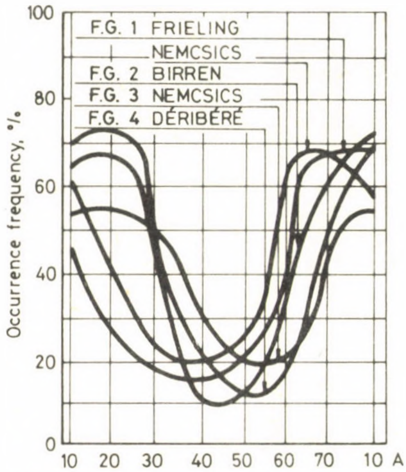


Fig. 5.36. Hues for colour bearing surfaces of rooms of different function groups in industrial plants, as suggested by different authors. Horizontal axis shows the parameter of the given hue, vertical axis the frequency percentage

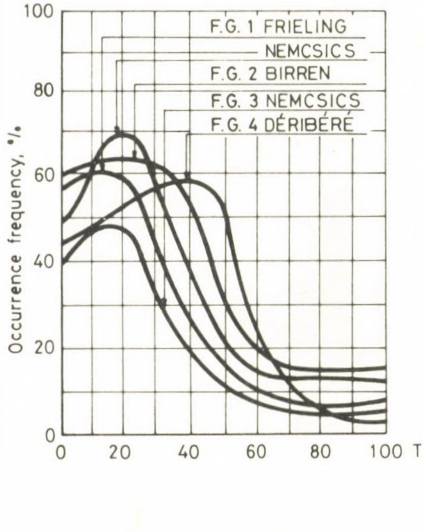


Fig. 5.37. Saturations for colour-bearing surfaces of rooms of different function groups in industrial plants, as suggested by various authors. Notations correspond to those in Fig. 5.36

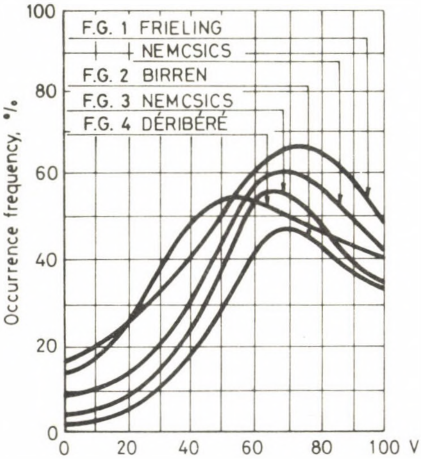


Fig. 5.38. Lightnesses for colour-bearing surfaces of rooms of different function groups in industrial plants, as suggested by various authors. Notations correspond to those in Fig. 5.36

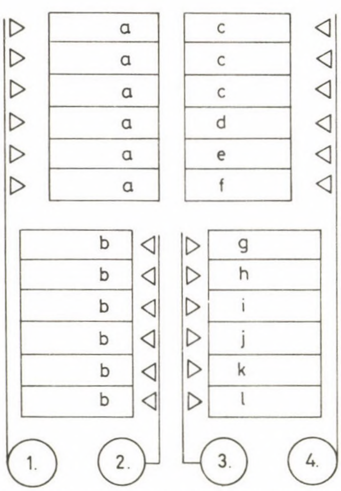


Fig. 5.39. Grouping by function of rooms in schools: a) classrooms, b) lecture rooms for natural sciences, languages, arts, gymnastics, etc., c) headmaster's office, warden's office, teacher's room, d) doorkeeper's lodge, e) kitchen, f) boiler room, k) WC, l) canteen

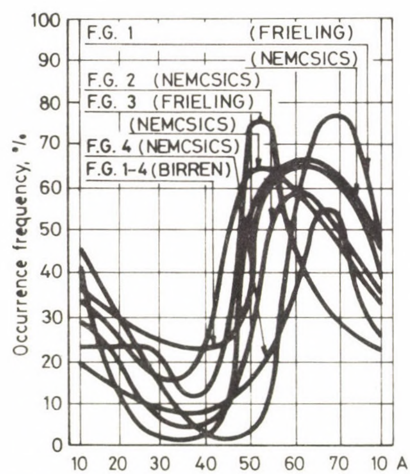


Fig. 5.40. Hues suggested for colour-bearing surfaces in school rooms of different function groups by different authors. Notations correspond to those for Fig. 5.39

Based on published data colour relations optimal for the person operating the function groups in industrial plants are seen in Figs 5.35 to 5.38. Rather than reflecting theoretical conclusions concerning the level of four function groups of a production plant, the diagrams show statistical averages relying on colour formulations in practical and/or published colour designs by Dérîbéré, Frieling, and Nemcsics. Although the designs underlying the diagrams have been made in different countries, in the USA, Germany, France and Hungary, the curves are rather similar, although function groups within the plants can be sharply distinguished, especially concerning hues. In rooms, workshops of the first function group, bluish green, yellowish green, and yellow prevail. Rooms of function groups 2 and 3 may contain also orange and some red. It is, however, typical for any group that participation of violets and cobalt blues is insignificant. In any room, colour saturations are moderate, while lightnesses are high.

In Fig. 5.39 rooms in schools have been grouped according to their function. Figures 5.40 to 5.42 show statistic averages of hues, saturations, and lightnesses for different function groups, based on designs by different authors. Curves are of rather similar character, but are quite different from those for production plants in preceding diagrams. There is an increased proportion of blues, bluish greens, but less of oranges and reds. This seems evident in view of what has been explained in previous chapters, namely that oranges and reds stimulate physical activities, while blues, and bluish greens assist

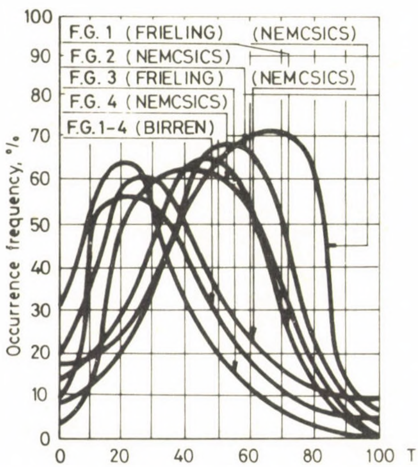


Fig. 5.41. Saturations suggested by different authors for colour-bearing surfaces in school rooms of different function groups. Notations correspond to those for Fig. 5.39

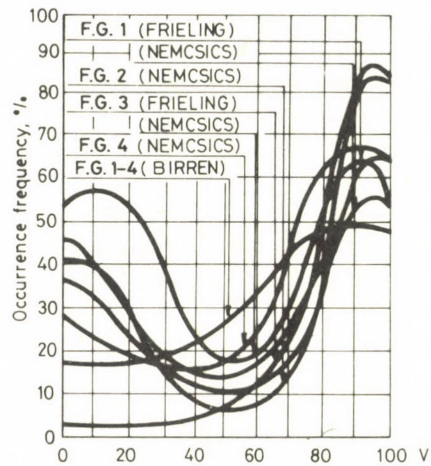


Fig. 5.42. Lightnesses suggested by different authors for colour-bearing surfaces in school rooms of different functional groups. Notations correspond to those for Fig. 5.39

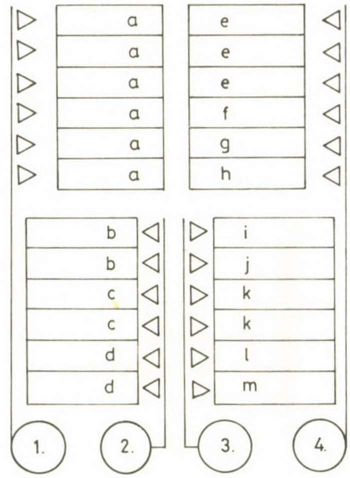


Fig. 5.43. Hospital rooms grouped according to functions: a) ward, b) surgery, c) examination room, d) laboratory, e) offices, consulting room, nurse room, f) gatekeeper's lodge, g) kitchen, h) boiler house, i) passage, j) staircase, k) waiting room, l) WC, bath, m) dining hall

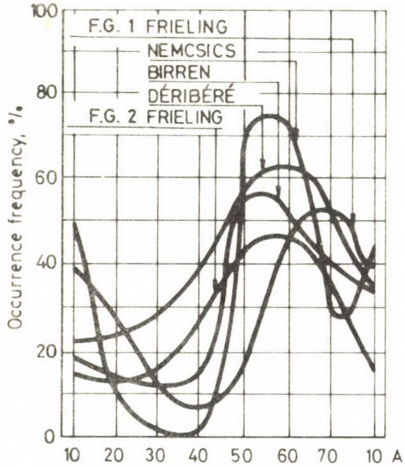


Fig. 5.44. Hues suggested by various authors for colour-bearing surfaces in hospital rooms of different functional groups. Notations correspond to those for Fig. 5.36

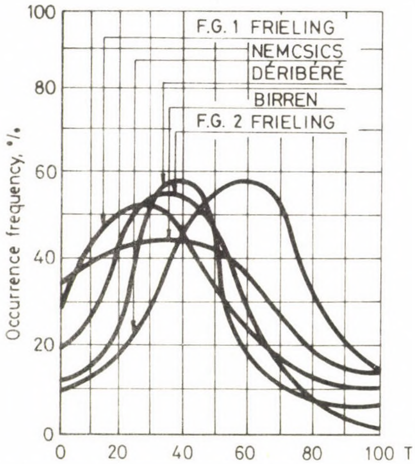


Fig. 5.45. Saturations suggested by various authors for colour-bearing surfaces in hospital rooms of different functional groups. Notations correspond to those for Fig. 5.36

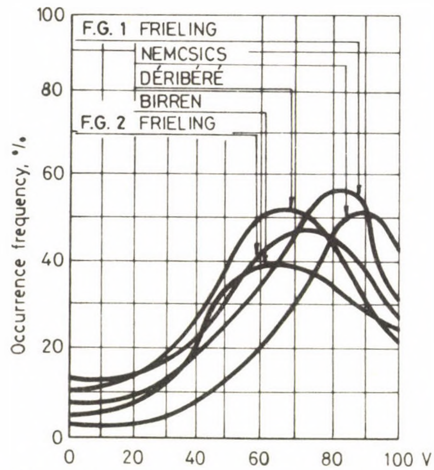


Fig. 5.46. Lightnesses suggested by various authors for colour-bearing surfaces in hospital rooms of different functional groups. Notations correspond to those for Fig. 5.36

mental activities. Colour design of schools often applies saturated colours, and light colours are also not exclusive.

In Figs 5.43 to 5.46 curves of statistical averages—based again on designs by several authors—represent hues, saturations, and lightnesses of colours in some hospital rooms of different function groups.

Functions of hospital buildings are very special. For some people, it provides accommodation for a shorter or longer but nevertheless limited time, while for others it is a working place. Therefore demands of both groups have to be respected not only concerning construction and equipment, but also coloration. The more so since these demands are sometimes contradictory.

In most cases, the state of mind of a patient is *a priori* somewhat abnormal. The lonely, worried patient, so to say forcedly dragged from his habitual environment, is in need of being addressed and protectively accommodated by his new environment. On the other side the work of the medical staff requires a great deal of concentration and excessive colour effects may distract their attention, or even disturb his work. These anomalies have led to the absurd dispute among colour dynamists as to whom should priority given in the hospital ward.

In a hospital, honouring of the utility functions can be done according to different aspects. Coloration should help orientation. Applying a certain colour for doors of rooms with identical or similar functions may eliminate much uncertainty. Doors not for patients may be coloured so as to convey this information. Proper colour design may express connections between rooms. Any obtrusive colour sensation has to be avoided in examination rooms and surgeries. In bathrooms, natural colour effects of sun, sand, and water have to be mimicked. It is, in turn, bad if green reflected onto the face of the patient in front of the mirror, makes him look pale and sick or else, by simultaneous contrast red or orange exert a similar effect. But in rooms frequently contaminated by blood, green should be applied as complementary to red. Ward walls possibly need cheerful, warming, approaching, but not very saturated colours. Eventual chromotherapic effects have to be exploited. A febrile condition in itself yearns for a cool environment. In condition of depression, a multicoloured environment has to be preferred. In a labour ward or an intensive care unit, a positively reassuring coloration has to be applied.

Also spaces for community life—including theaters, houses of culture, libraries, various sports establishments, restaurants, party offices, and churches—may have several functions. These are environments with the oldest tradition of conscious colour design.

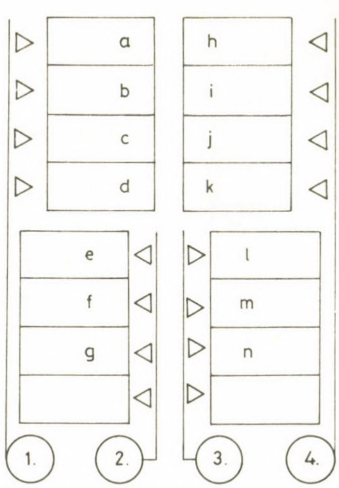


Fig. 5.47. Grouping by functions of rooms in homes: a) bedroom, b) dining room, c) living room, d) nursery, e) study, f) atelier, g) hobby workshop, h) bathroom, i) WC, j) kitchen, k) pantry, l) entrance hall, m) passage, n) staircase

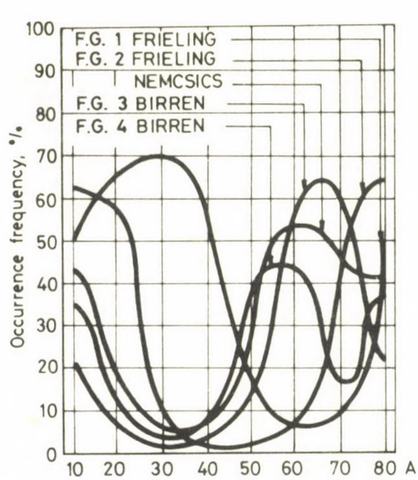


Fig. 5.48. Hues suggested by different authors for colour-bearing surfaces in rooms of different functional groups in homes. Notations correspond to those in Fig. 5.36

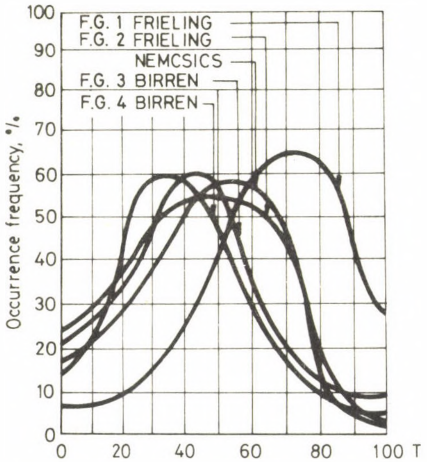


Fig. 5.49. Saturations suggested by different authors for colour-bearing surfaces in rooms of different functional groups in homes. Notations correspond to those in Fig. 5.36

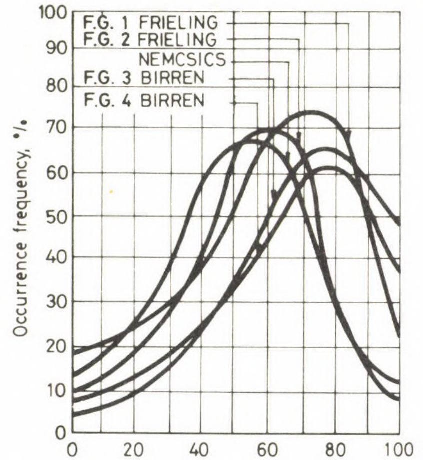


Fig. 5.50. Lightnesses suggested by different authors for colour-bearing surfaces in rooms of different functional groups in homes. Notations correspond to those in Fig. 5.36

An important field of colour dynamics is the colour design of homes. LE CORBUSIER was the first to insist on a thorough analysis of functions of a home, on the careful organization of the ground plan, correct space proportions, elimination of wanton elements, the best possible service of man's physical and mental needs, rational organization, and reliability like that of a machine. "A home is a dwelling machine"—he would say. Essential requirements for a home are a considerate definition and analysis of, distinction between space demands for, and right connections between rooms to be used for sleeping, hygiene, cooking, eating, and living, orientation as needed for different functions, further a built-in furniture, an "all-round" kitchen equipment, central heating, and forced ventilation. Relations between them and colouration in a home are illustrated by the diagrams in Figs 5.47 to 5.50, giving statistical averages for hues, saturations and lightnesses of colours borne by surfaces of rooms of different function groups in a home, based on designs of several authors.

Some aspects of functions of a home are emphasized, others are omitted in workers' hostels, students' hostels, hotels, where colour design cannot be entirely based on principles recognized for functions of a home.

Functions not dealt with here include those of commercial establishments, shops, department stores, market halls.

Transport facilities include not only terminals and waiting halls but also vehicle interiors.

5.2.2. Aesthetic Function of Colours

Just as any work of art, every element of our environment, and the environment itself, is an inseparable unity of content and form. Just as human environment is a space for human functions, environment elements serve somehow the realization, accomplishment, and completion of human functions, and by all that they fulfil their own function. Thus, our environment is up to its aesthetic function if it expresses its utility function in conformity with unity of content and form—where content is the utility function, and form is the shape and colour of the elements.

The essential condition of an aesthetic effect is unity between content and form, as so defined. Furthermore, the objects forming the content of the environment, or indeed the entire environment, are essentially functional. It follows that the integral expression of content can be realized by the harmonious functioning of all the components of the entire space. The practical–utility and spiritual–mental components of function are interdependent. The mental arises, and is inseparable, from practical. Now we cannot any longer believe that the aesthetic form of an object or space should be possible without knowing its function. Neither is it believed that there exist universal aesthetic formulae applicable in every case, or that it is possible to force upon the environment any fine colour harmony without knowledge of its function. In environment colour design, we have also to consider how much importance is attributed to its practical functions from the point of view of our human life as a whole. That is to say, any work and activity has its emotional, mental, and spiritual attachments. Therefore each object, tool or space claims some of these attachments, depending on its role, importance, and function in our life.

Form becomes a necessity in the course of a "function experience", imprinting on our consciousness a harmony sensation as inseparable unity between content and form. Of course, the sight of a colour complex may give aesthetic pleasure, but when separated from content and function of the space, this pleasure is rather superficial, as it does not offer a full space sensation.

Fig. 5.51. Functionally essential surfaces in an industrial workshop hall: 1) ceiling; 2) wall; 3) wall; 4) door casing; 5) door leaf; 6) pier; 7) machinery, equipment; 8) air ducts and air conditioning equipment; 9) floor

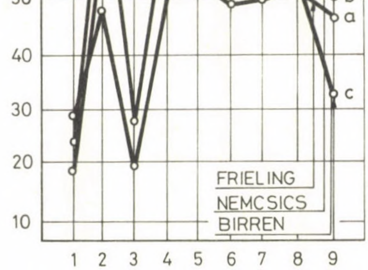


Fig. 5.52. Hues suggested by different authors for colour-bearing surfaces in a textile mill (a), a machining workshop (b), and a precision mechanic workshop (c). Numbering of colour-bearing surfaces on the horizontal axis according to Fig. 5.51; the vertical axis shows the Coloroid hue scale

To be able to create a form expressing the message of the built environment, the designer has to be acquainted with relationships between environment structures, the so-called composition relationships, such as that of material–function–form, conditions of space effects, or the role of space–time–motion in an environment.

It is in our time that colour dynamics has become a conscious creative activity, a science searching out relations and interactions between colour, man, and environment, but also an art recreating the environment in possession of and by means of newly disclosed relationships.

Colour dynamics is expected to investigate with the aid of colour aesthetics the role of colour relations in the expression of function.

An environment of correct colour design expresses its function, meets the requirement of unity between content and form, i.e. it has an aesthetic function. Hues, saturations and lightnesses of colour bearing surfaces in industrial establishments are seen in Figs 5.51 to 5.54, based on colour designs by BIRREN, FRIELING and NEMCSICS. Differences between a textile mill, a machining workshop, and a toolmaker's workshop as aesthetic qualities are primarily borne out by walls, door leaves, and door frames. Differences are manifest as differences in hue on walls and door frames, while as saturation and lightness differences on door leaves.

Hues, saturations and lightnesses of colour bearing surfaces in classrooms for forms 5 and 8 to express functions are seen in Figs 5.55 to 5.58, after colour designs by FRIELING and NEMCSICS.

Colorations in surgeries, examining rooms, and wards expressing functions, also after colour designs by different authors, were plotted in Figs 5.59 to 5.62.

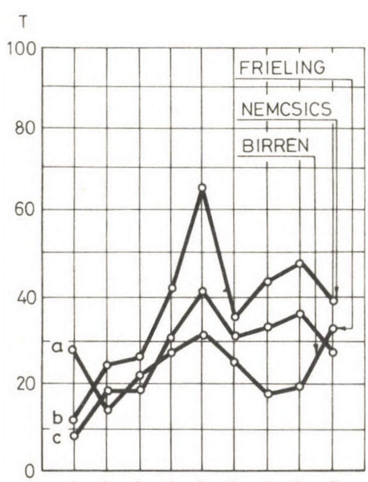


Fig. 5.53. Saturations suggested by different authors for colour-bearing surfaces in a textile mill (a), a machining workshop (b), and a precision mechanic workshop (c). Numbering of colour bearing surfaces on the horizontal axis according to Fig. 5.51; the vertical axis shows the Coloroid saturation scale

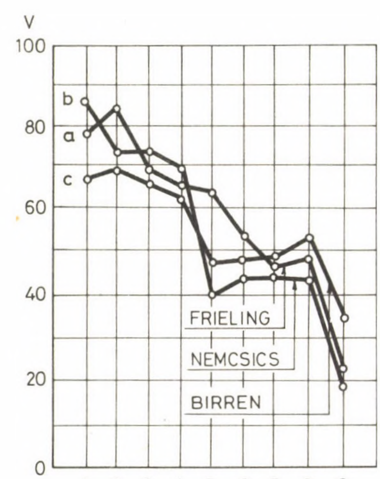


Fig. 5.54. Lightnesses suggested by different authors for colour-bearing surfaces in a textile mill (a), a machining workshop (b), and a precision mechanic workshop (c). Numbering of colour bearing surfaces on the horizontal axis according to Fig. 5.51; the vertical axis shows the Coloroid lightness scale

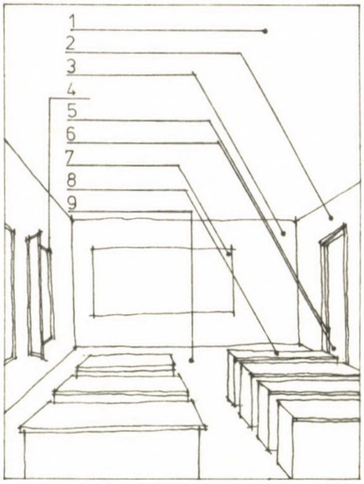


Fig. 5.55. Functionally essential colour-bearing surfaces in a classroom: 1) ceiling; 2) wall; 3) wall; 4) window casing and leaf; 5) door casing; 6) door leaf; 7) blackboard; 8) benches; 9) floor

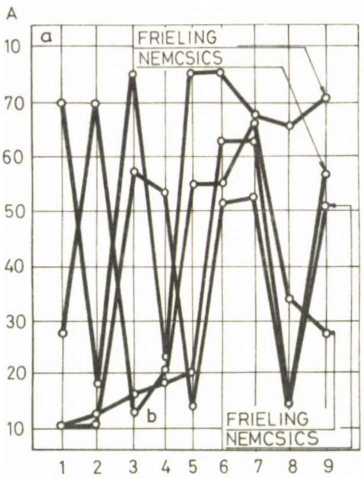


Fig. 5.56. Hues for colours suggested for classrooms of forms 5 (a) and 8 (b) in primary schools by Frieling and Nemcsics. Numbering of colour-bearing surfaces on the horizontal axis according to Fig. 5.55; the vertical axis shows the Coloroid hue scale

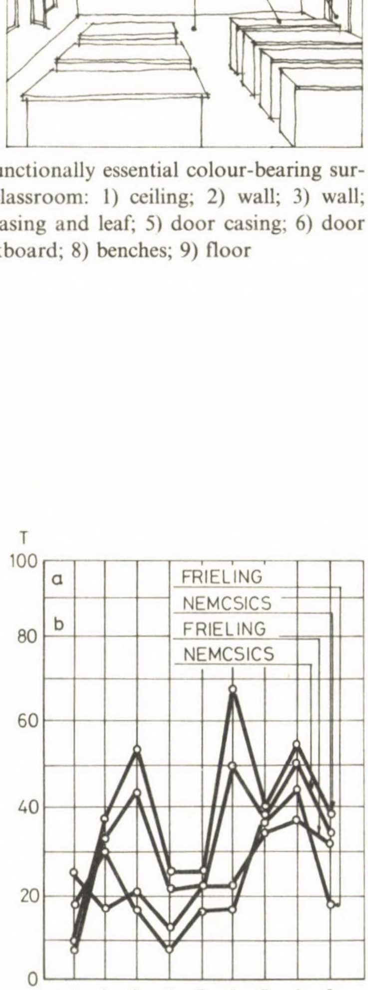


Fig. 5.57. Saturation for colours suggested for classrooms of forms 5 (a) and 8 (b) in primary schools by Frieling and Nemcsics. Numbering of colour-bearing surfaces on the horizontal axis according to Fig. 5.55; the vertical axis shows the Coloroid saturation scale

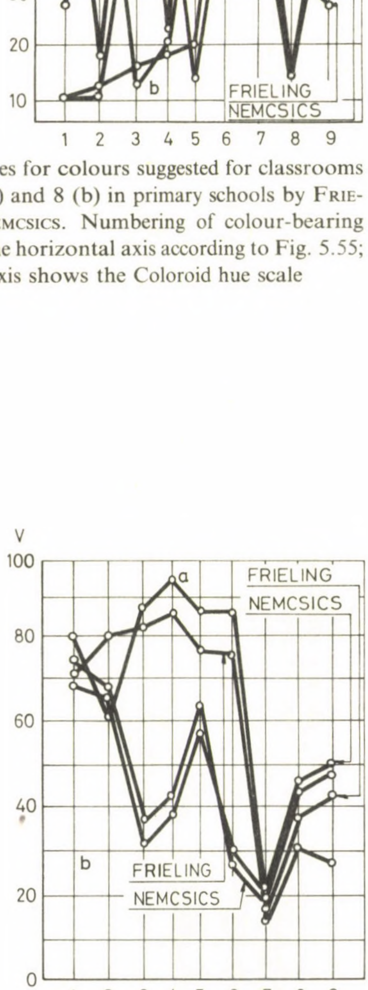


Fig. 5.58. Lightnesses for colours suggested for classrooms of forms 5 (a) and 8 (b) in primary schools by Frieling and Nemcsics. Numbering of colour-bearing surfaces on the horizontal axis according to Fig. 5.55; the vertical axis shows the Coloroid lightness scale

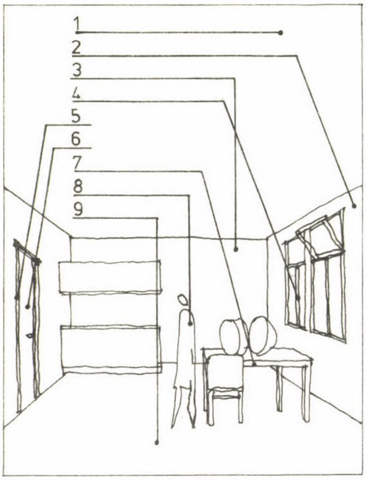


Fig. 5.59. Functionally essential colour-bearing surfaces in a medical examination room: 1) ceiling; 2) wall; 3) wall; 4) window; 5) door casing; 6) door leaf; 7) furniture; 8) coat; 9) floor

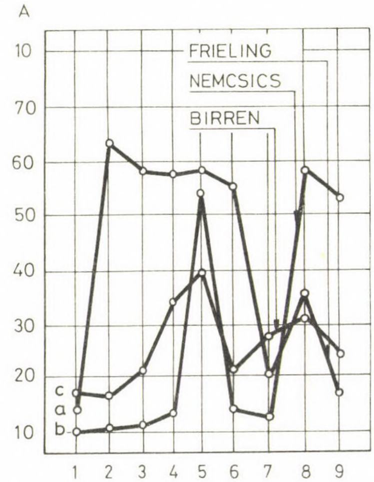


Fig. 5.60. Hues for colours in a surgery (a), an examination room (b), and a ward (c) suggested by different authors. Numbering of colour-bearing surfaces on the horizontal axis as in Fig. 5.59; the vertical axis shows the Coloroid hue scale

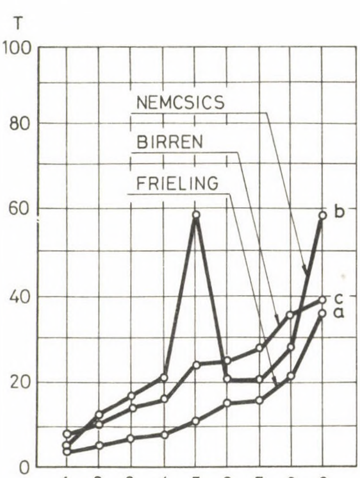


Fig. 5.61. Saturations for colours in a surgery (a), an examination room (b) and a ward (c) suggested by different authors. Numbering of colour-bearing surfaces on the horizontal axis as in Fig. 5.59; the vertical axis shows the Coloroid saturation scale

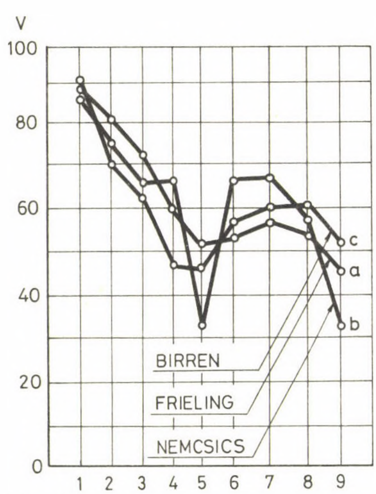


Fig. 5.62. Lightnesses for colours in a surgery (a), an examination room (b) and a ward (c) suggested by different authors. Numbering of colour-bearing surfaces on the horizontal axis as in Fig. 5.59; the vertical axis shows the Coloroid lightness scale

5.2.3. Informative Function of Colours

Information functions of environment serve to interpret for man the functions, the ways of utilizing and the operation of the environment and its elements. An important part of the informative functions of the environment is expressed by colour information. Depending on the message, colour information may be interpreted as logic information, or as artistic or aesthetic information.

Logic and aesthetic information are carried by the same elements, but a different structure belongs to every form of message. They can be characterized partly by their different visual systems, by the differentiation of their complexity and structure, and partly by the psychical differences of their messages. Message is transmitted by highlighting, contracting and grouping some visual codes in the information-bearing surface or space, while disregarding others. A group of colours attracts attention when it excels by regularity and its structure is well recognizable. Recently, the analysis of these relations has been tackled with the methods of semiotics. Although these studies mostly concerned other than visual structures, the results can also be applied to colour dynamics.

Logic information is by standard codes; they are practical, strictly mental, and transmit knowledge. They prepare decisions of receivers, and control their behaviour and attitudes. Logic information is transmitted e.g. by internationally agreed safety colour signals. Locations of these colours in the CIE diagram are seen in Fig. 5.63. For instance green means information, orange warning, red prohibition, blue instruction. A special field of built environment is traffic. Traffic signal colours were plotted in Fig. 5.64. Recently, colours indicating various technological processes have been standardized, as seen in Fig. 5.65. A special field of technology is the colour signals of pipeline colours. Colour signals for the fluid carried have been standardized, including different uses of the same fluid. For instance, there are different signal colours for drinking water,

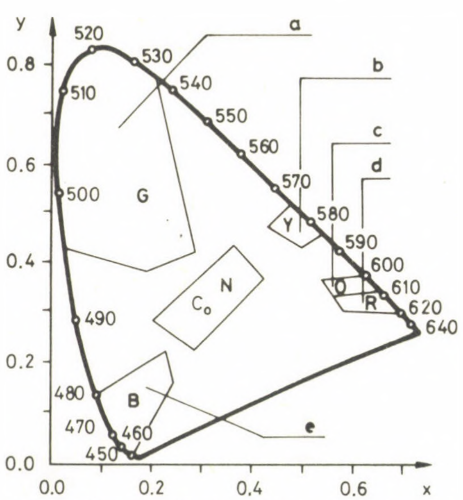


Fig. 5.63. Safety signal colours in the CIE diagram: a) information, b) warning, c) prohibition, d) fire, e) instruction, N neutral complementary domain, Y yellow, O orange, R red, B blue, G green

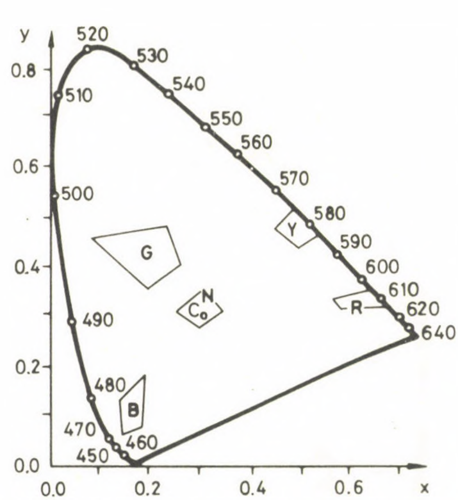


Fig. 5.64. Traffic light colours in the CIE diagram: Y yellow, R red, B blue, G green, N neutral complementary domain

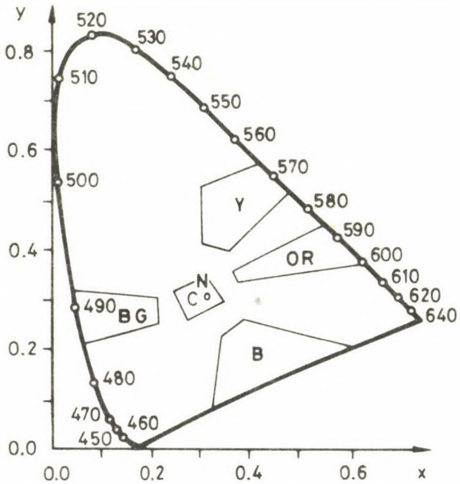


Fig. 5.65. Technology signal colours in the CIE diagram: Y yellows; OR orange reds; B purples and violets; BG bluish greens; N neutral complementary domain

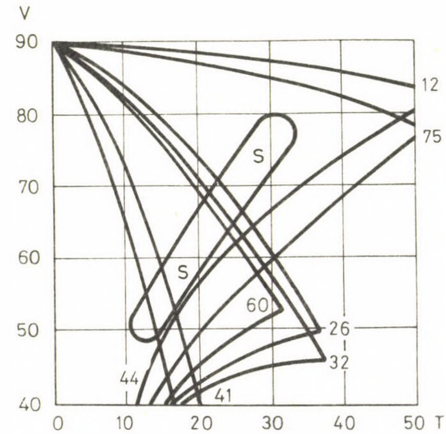


Fig. 5.66. Signal colours (S) to distinguish pipelines in Coloroid sections. Horizontal axis shows the Coloroid saturation scale, vertical axis the Coloroid lightness scale. Numbers represent Coloroid hues

for utility hot water, condensing water, hot water for heating, soft water, neutralizing sewage, and other applications. Pipeline colours in the given Coloroid sections are seen in Fig. 5.66.

Colour information of aesthetic content is mostly emotional. It expresses inward conditions, and the wish to exert mental, and emotional effects based on a common semantic knowledge. Because of their operative and recording functions, visual codes are not only carriers of the message, and social ideas of the colour designed space as a work of art, but may also display the attitude typical of the artistic subject and culture. It follows from all this that colour dynamics creates complex colour conditions and puts them into a coloured world, thereby it has a manifold message, that is, it both expresses and moulds human consciousness and emotions. In other words, environment colour design is an artistic activity on a large-scale, a piece of art existing in built space, and as such, it has not only to cope with its specific iconic task but also to meet the special conditions of colour dynamics.

5.3. Colour and Illumination

Built environment is taken notice of through the visual appearance of environment elements, the built space. Appearance is internationally meant as given photometric, chromatic and reflection characteristics of the space. This means in practice, that articulation of the space, forms of space elements, surface texture and colours are perceived as a function of intensity, quality, and direction of illumination. Sight of a space informs about the environment only in dependence of illumination.

Visual informative elements of a colour environment are wall, floor and ceiling surfaces, and objects situated in this space. But in a wider meaning, the concept of built space comprises also the outside environment seen through the window. Thus, a sight comprises threedimensional elements, as opaque or translucent material structures. Lighter and darker spots arise on surfaces by reflection, producing different colour sensations. These phenomena may be of importance in forming our view about the built environment.

The condition that an intended space effect of the environment should develop in the observer is adequate visibility of environment elements. Informative elements of space design can be properly assimilated only if visual observation is unimpeded. In case of disturbed vision, attention is distracted, leading to early fatigue, poor concentration, and indisposition, and the environment is rejected.

Undisturbed perception can be secured only in the stable domain of perception, which is identical with the final state of mean adaptational luminance. Mean adaptation luminance is a resultant of luminances of inner and surrounding fields. Luminance of the inner field is that needed for performing a task in space. Information domain for performing the task is concentrated in the inner field. Luminance of surrounding fields depends on light distribution over wall, floor and furniture surfaces, including table tops, shelves, floor, lights, windows, and the outer environment. Thus, environmental, and in a wider sense, peripheral luminance domains are of importance for sensing the space effect.

Figures 5.67 and 5.68 illustrate visual field domains, correlating luminance of inner and surrounding fields under stable perceptional conditions. For a given luminance of the inner field based on visual requirements, in conformity with the relationship plotted in the diagrams, surrounding and peripheral luminance and their domains can be computed as:

$$L = E\varrho \,, \tag{121}$$

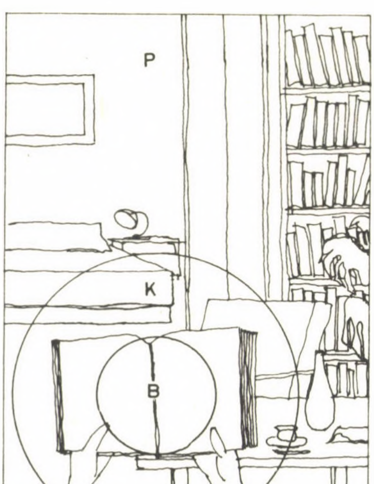


Fig. 5.67. Visual fields of a reading person: B inner visual field, K environmental visual field, P peripheral visual field

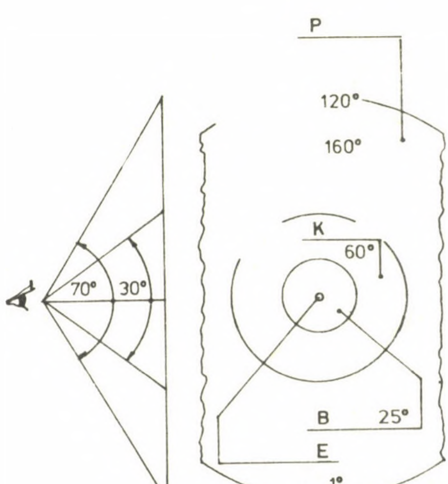


Fig. 5.68. Schemes of different visual field ranges. Peripheral visual field P is vertically 120°, horizontally 160°, environmental visual field K about 60°, inner visual field B about 25°, and precise visual field E about 1°

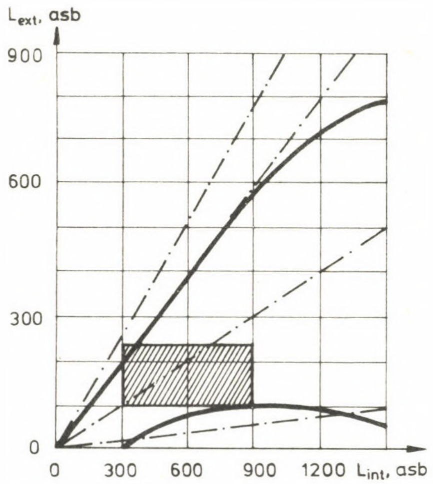


Fig. 5.69. Sensitivity to differences associated with light densities in the inner and environmental visual fields. Horizontal and vertical axes show light densities of inner and outer fields respectively, in asb units

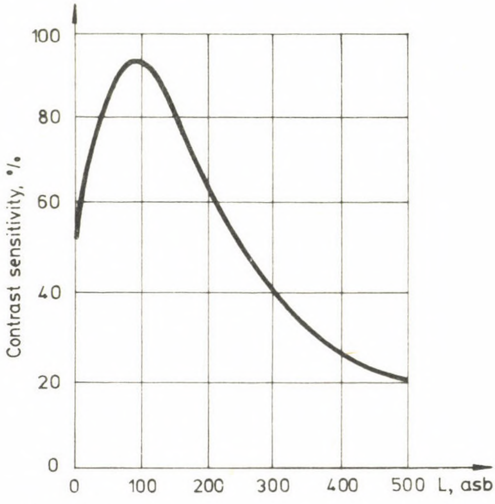


Fig. 5.70. Contrast sensitivity vs. environmental light density. In the centre of the visual field, light density is 100 asb. Horizontal axis shows environmental light density in asb, vertical axis contrast sensitivity

where L is luminance in asb; E is illuminance intensity in lx; ϱ is the reflection factor. According to this relationship, luminance incident on the eye is defined by values dependent on illumination and on material structure.

Illumination depends on quantity, quality and direction of radiant energy. Material structure influences reflection. By varying reflection factors, different light impressions can be produced at a constant illumination intensity.

Environmental field surfaces occupying much of the visual field influence the value of mean adaptational luminance, and are decisive for stable perception (Fig. 5.69) (Bartenbach, 1976). Variation of contrast sensitivity vs. environmental luminance is seen in Fig. 5.70 assuming in the inner visual field a luminance of 100 asb.

5.3.1. Effect of Luminous Intensity on the Appearance of Colours

Built environment consists of surfaces differently reflective under both natural and artificial illumination. The observer sees these surfaces and perceives light produced by them. Eyes react to luminances on the surfaces, rather than on illumination. Let us illuminate a room with white furniture and walls by a given luminous intensity, and then, by the same luminous intensity, rooms of the same size and arrangement, but with different colours on their surfaces. The room with the least reflective surfaces will be found to be the darkest. In rooms including surfaces of different colours, illumination has to be adjusted differently to give a room a pleasant impression.

A healthy man is at ease in daylight, or at a corresponding illumination. Of course, also darkness after sunset is accommodated to, one can be satisfied by much less light from artificial light sources. Illumination levels of our environment are extremely different: 100 000 lx at full sunshine, 10 000 lx in the shadow of vegetation, 2500 lx at a window facing north, 300 lx in the middle of a room facing north, and 60 to 120 lx in a room well illuminated by an artificial light source. Optimum illumination has been experimentally determined by BODMAN (1976) at 1800 lx. Recognition time vs. illumination intensity continuously varies with age, as illustrated by Fig. 5.71. For the same recognition time, a higher luminous intensity is needed at a more advanced age.

It has been tested what luminance conditions are the best in work. Mean and maximum luminances B_m and B_{max}, respectively, in the visual field have to be related by

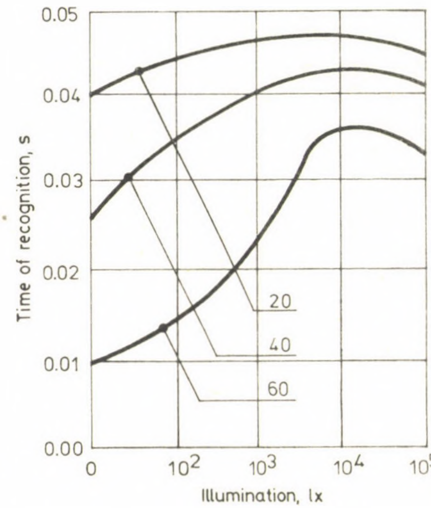


Fig. 5.71. Correlation of recognition time, illumination level and age. Numbers on curves give the age of test persons

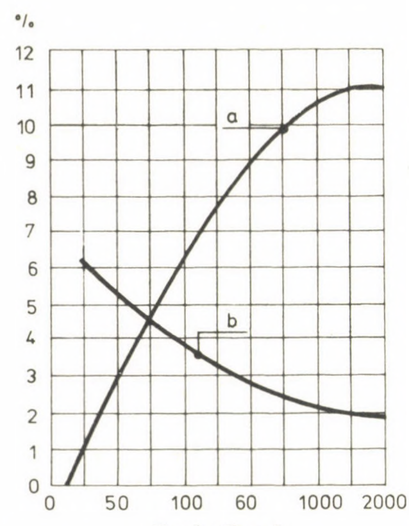


Fig. 5.72. Variation of productivity (a) and susceptibility to fatigue (b) vs. illumination level

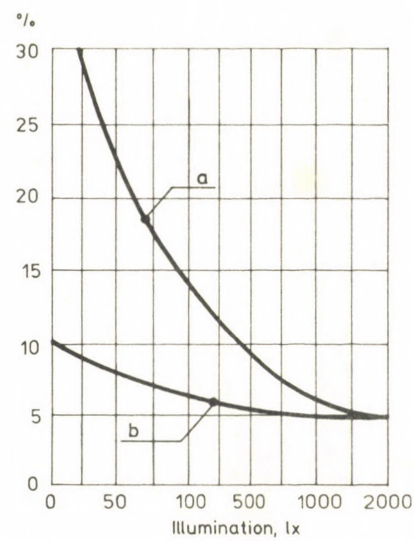


Fig. 5.73. Variation of waste percentage (a) and frequency of accidents (b) vs. illumination level

the inequality:

$$B_{max} : B_m \leqq 40 \tag{122}$$

otherwise a discomfortable dazzling arises.

The effect of a higher light exposure level on work performance and on fatigue is seen in Fig. 5.72, that on spoilage and on number of labour accidents in Fig. 5.73.

Since the advent of electric lighting, the level of artificial illumination has continuously increased. This increase has been different for rooms of different functions in the past 40 years. Figures 5.74, 5.75, 5.76 show variations of illumination levels from 1925 to 1975 in a surgery, a ward, and a hospital laboratory, in a studio, a bedroom, a kitchen, and a staircase; in a precision workshop, a sorting room, a machine tool workshop, and a packaging hall, respectively. Recently, in most countries, illumination levels for different working processes and for rooms of different functions have been specified in standards. Illumination requirements are rather different between countries but are converging.

CIE Publication No. 29.2 contains recommendations for illumination levels in rooms of different functions, such as:

passages in buildings of different functions	50– 100– 150 lx
workplaces, laboratories, libraries	200– 300– 500 lx
classrooms, offices, conference halls	300– 500– 750 lx
special workplaces, drawing rooms, laboratories	500– 750–1000 lx
workplaces, studios having to do with colours	750–1000–1500 lx.

Recently, in determining illumination levels in interiors, light demands increasing with age have been taken into account. Where occupants have rather different ages, light demand is specified for an average age. Variation of light demand referring to 40 years of age are plotted in Fig. 5.77 after tests by Jansen (1965).

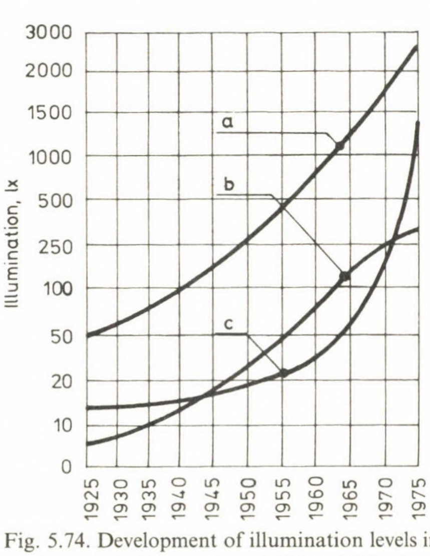


Fig. 5.74. Development of illumination levels in hospital rooms in Europe from 1925 to 1975. a) surgery, b) ward, c) laboratory

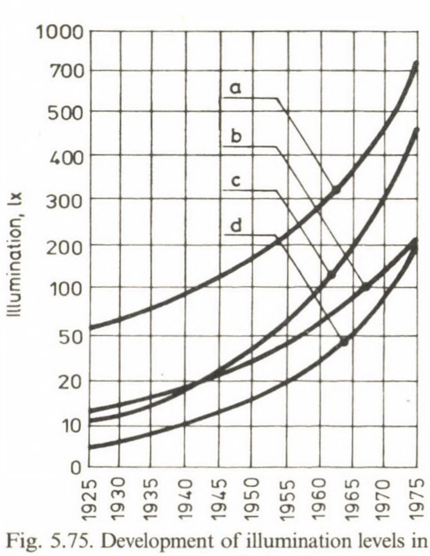


Fig. 5.75. Development of illumination levels in homes in Europe from 1925 to 1975. a) study, b) bedroom, c) kitchen, d) staircase

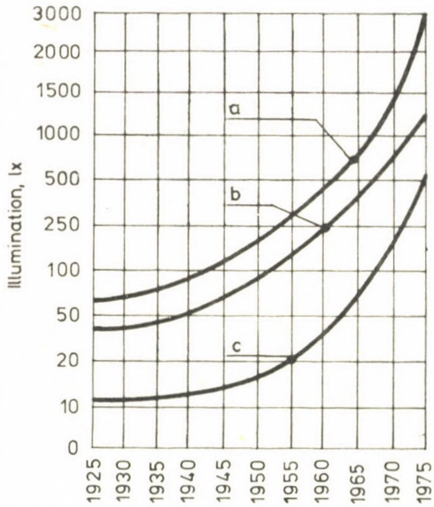


Fig. 5.76. Development of illumination levels in plants in Europe from 1925 to 1975. a) precision assembling, selection, b) machine tool workshop, c) packaging

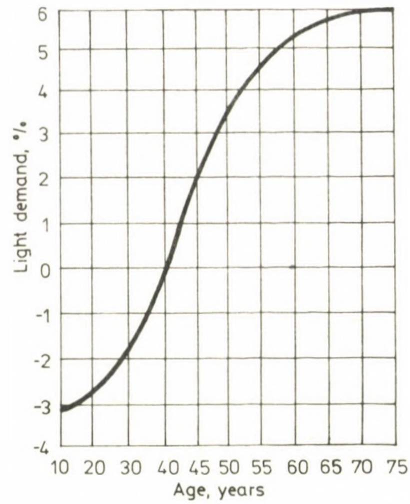


Fig. 5.77. Age-dependent illumination needs as a percentage of the demand of men aged 40. Horizontal axis shows age, vertical axis the light demand percentage

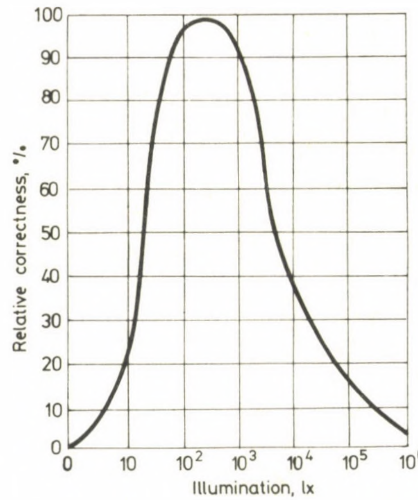


Fig. 5.78. Relative correctness of sensing colours as a function of illumination intensity

Until recently, little regard has been paid to the observation that with increasing illumination level surface colours are seen not to be only lighter but also more fallow*. It has been supported by experiments that eliminating the phenomenon of colour constance by applying reference surfaces, the same surface may be seen as white or dark gray, pink or dark brown, depending on the incident luminous intensity. Change of luminous intensity acts differently on every colour. In a strong light red and yellow are

* In the sense of pale-yellow or brownish yellow.

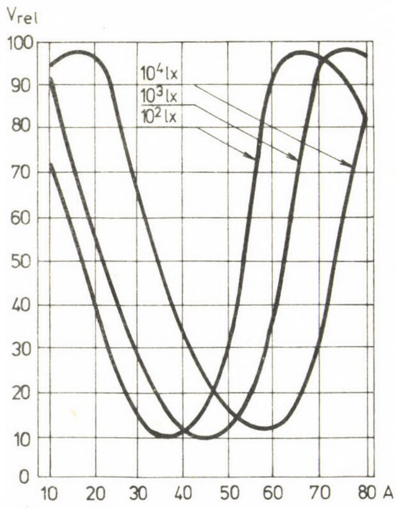


Fig. 5.79. Variation of relative lightnesses of the most saturated colours in the Coloroid colour solid as a function of illumination intensity

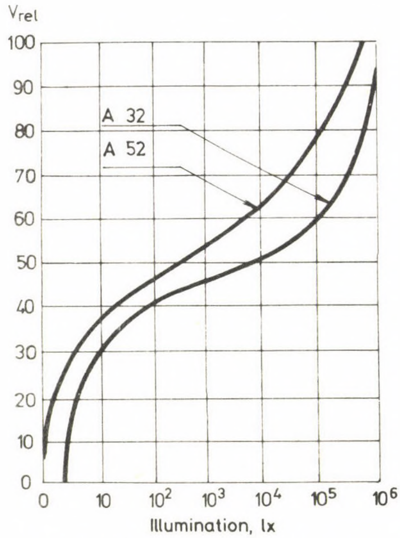


Fig. 5.80. Variation of relative lightnesses of red (*A*32) and blue (*A*52) vs. light intensity

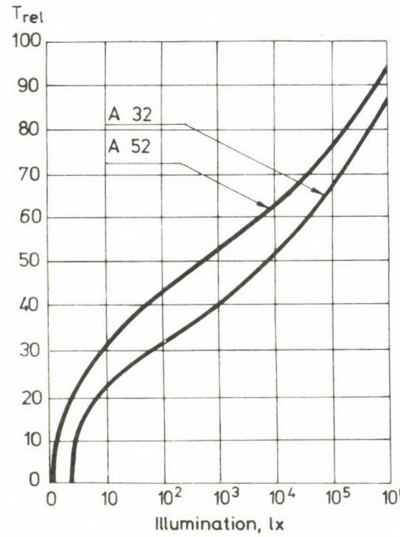


Fig. 5.81. Variation of relative saturations of red (*A*32) and blue (*A*52) vs. light intensity

less fallow than are blue or bluish green. With decreasing illumination level, reds fallow sooner than do blues. The same colours in different luminous intensities are shown in Figs C52 and C53.

Relative correctness of perception of colours in a space with varying illumination level is seen in Fig. 5.78. Variation of relative lightnesses of the most saturated colours of the Coloroid colour solid with the variation of luminous intensity in the room is shown in Fig. 5.79, after tests by Nemcsics. Figures 5.80 and 5.81 show variations of relative lightnesses and of relative saturations, respectively, of colours in the room as a function of luminous intensity.

5.3.2. Effect of Illumination Quality on the Appearance of Colours

Quality of radiant energy from light sources is decisive for environment colour design. The most essential difference between light from artificial light sources and sunshine consists in the spectral power distributions of the emitted energy (Fig. 5.82). Depending on the spectral power distribution of the emitted energy, coloured surfaces in the environment have different appearances. That is, surrounding objects are seen in more or less different colours depending on the quality of white light emitted by the given light source. This fact is the more important for environment colour design since interiors are increasingly illuminated by artificial light sources.

In the last decade, artificial light sources underwent dramatic development. To the family of incandescent lights, almost unchanged since the late '30s, were added halogen incandescent lamps emitting by now 32 lm/W, at colour temperatures up to 3400 K. The assortment of fluorescent lamps has been enriched by true-to-colour types of different colour temperatures. Also development of high-pressure mercury lamps passed the level where they could be applied only in places undemanding to colour. At present, colour-corrected or metal vapour lamps, and recently, metal vapour admixed high-pressure mercury lamps have become competitive for interior illuminations. Even the ancestral sodium lamp has been revived, its efficiency amounting to nearly 150 lm/W, and its recent, high-pressure varieties, Lucalux and Ultralux lamps emit light in a wider spectrum than did their classic ancestor, the sodium spectral lamp.

This development has not yet slowed down; experiments are going on to replace iodine and bromine filled halogen lamps by fluorine lamps promising still better efficiency. Eventually tungsten may loose its dominance among incandescent lamps, and recently, incandescent lamps with selective emission in the visible spectrum have been developed.

In the field of strip lights there is a quite spectacular development in two directions: recent, so-called three-strip lights both utilize energy much more efficiently and render

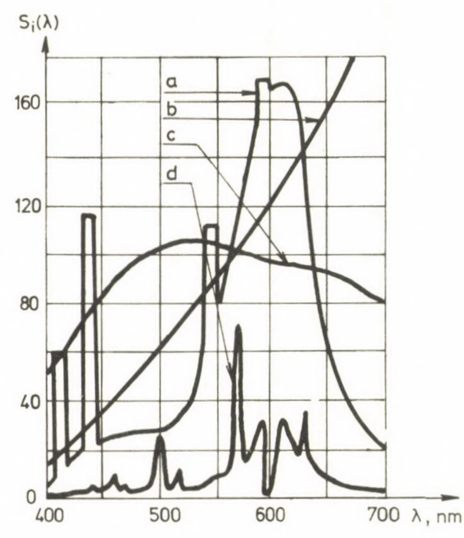


Fig. 5.82. Spectral power distributions of some light sources. a) white strip light, b) incandescent lamp, c) sunlight. d) high-pressure sodium lamp

colours much better. Silica wool filled strip lights are now similar in size to incandescent lamps, at a much better light efficiency.

Available artificial light sources generally produce nearly white light; colours are about the same as for a black radiant. Therefore the colours of these light sources are characterized by the so-called next or correlated colour temperature.

Part of the CIE diagram is seen in Fig. 5.83, where curves connecting positions of black bodies at different temperatures, and straight lines connecting points of identical correlated colour temperatures were plotted. Incandescent lamp spectra are close to the black body spectrum, so for incandescent lamps, this single numerical value adequately describes the light source. Part of the CIE diagram locating colours from incandescent lamps of different white lights is seen in Fig. 5.84.

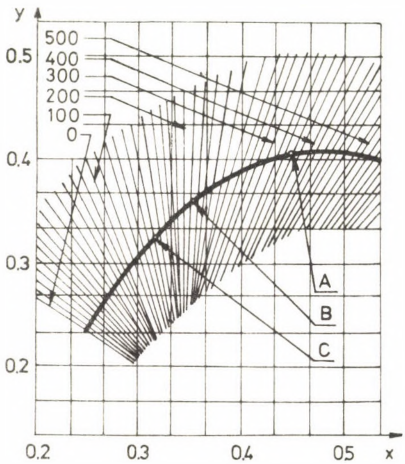


Fig. 5.83. Correlated colour temperature and its illustration in the CIE diagram. Straight lines intersecting curves for Planck radiants are transformed of normals in the *uv* diagram. Points A, B, C correspond to standard light sources

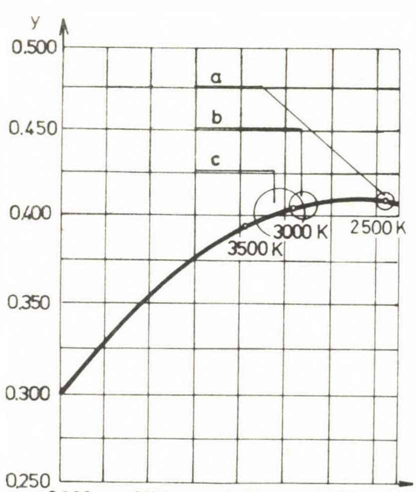


Fig. 5.84. Loci of incandescent lamp colours in the CIE diagram: a) vacuum lamps, b) gas-filled lamps, c) halogen lamps

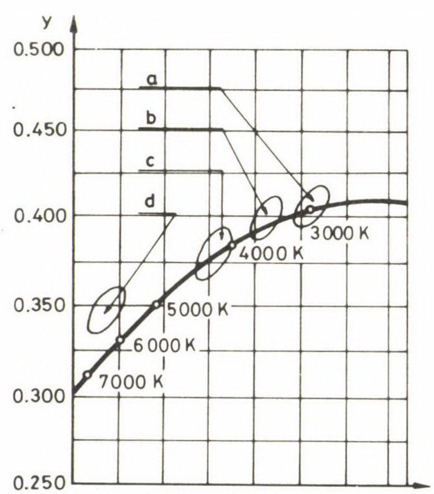


Fig. 5.85. Loci of ASA standard strip light colours in the CIE diagram: a) warm white, b) white, c) cold white, d) sunlight

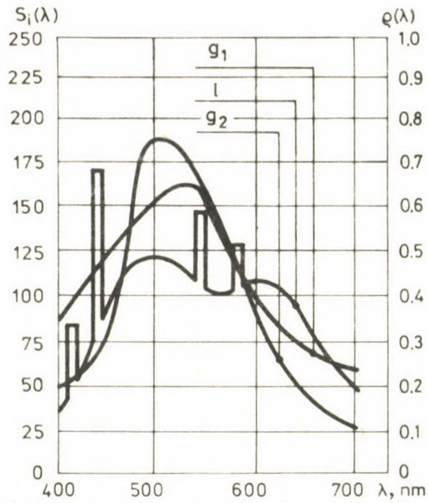


Fig. 5.86. Colour of a green surface illuminated by a strip light: l spectral power distribution of strip light, g_1, g_2 wavelength dependences of surface reflectivities

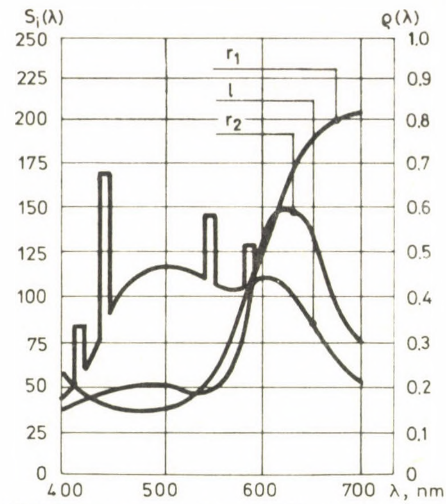


Fig. 5.87. Colour or a red surface illuminated by a strip light: l spectral power distribution of strip light, r_1, r_2 wavelength dependences of surface reflectivities

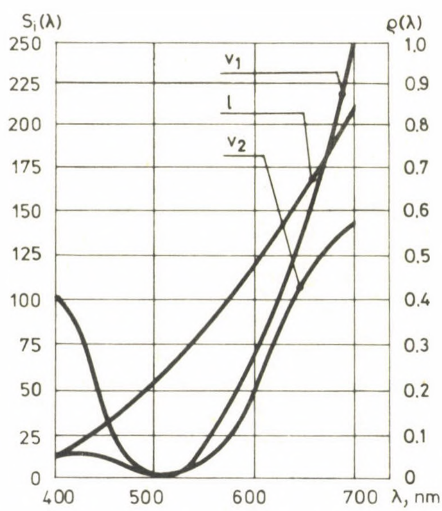


Fig. 5.88. Colour of a violet surface illuminated by an incandescent lamp: l spectral power distribution of incandescent light, v_1, v_2 wavelength dependences of surface reflectivities

Development of various luminescent gas discharge lamps required, however, a closer definition of light sources. Loci according to ASA standard for various kinds of strip lights in the CIE diagram are seen in Fig. 5.85.

Colour sensation elicited by coloured surfaces in the environment is determined, as an objective factor, by the spectral distribution of energy incident on the eye. Spectral distribution—that is, colour—of the energy reflected from that surface is determined, on one hand, by spectral energy distribution of the light source, and on the other hand, by the selectivity to radiations of different wavelengths (reflection curve) of the coloured surface. Spectral energy distributions of light reflected by different selective surfaces illuminated by the same strip light and by the same incandescent lamp were plotted in Figs 5.86, 5.87, and Figs 5.88, 5.89, respectively.

Since surfaces of the same colour illuminated by different light sources act as different secondary light sources, also their psychophysical and psychosomatic effects, important for environment colour design, are different. As a consequence, of course, colour rendering by light sources of different spectral energy distributions affect not only colour

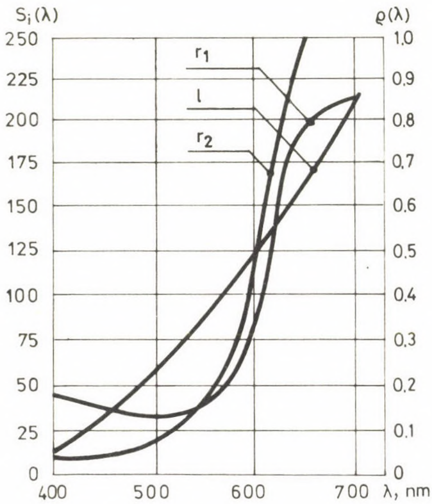


Fig. 5.89. Colour of a red surface illuminated by an incandescent light: *l* spectral power distribution of incandescent light, r_1, r_2 wavelength dependences of surface reflectivities

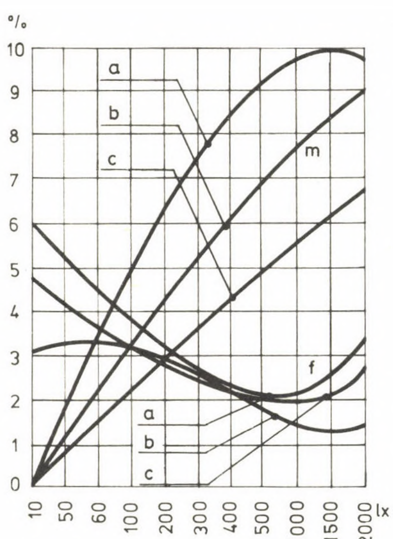


Fig. 5.90. Dependence of productivity (m) and fatigue (f) on the level of illumination by incandescent (a), sodium (b), and mercury vapour (c) lamps. Horizontal axis shows illumination, vertical axis the power percentage

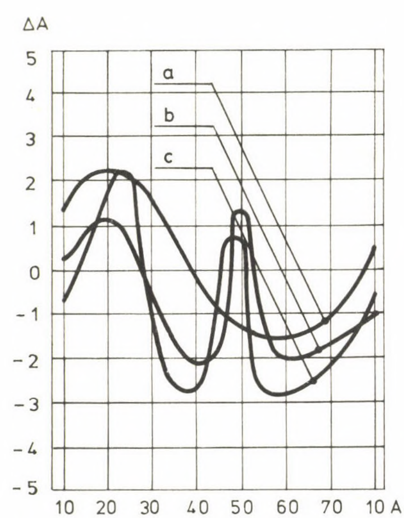


Fig. 5.91. Hue variation of environment colours illuminated by incandescent light (a) and by two different strip lights (b, c). Horizontal axis shows Coloroid hues, vertical axis the deviation from the surface colour in sunlight in Coloroid *A* units

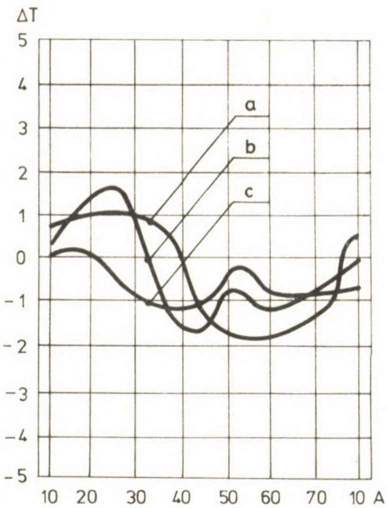


Fig. 5.92. Saturation variation of environment colours illuminated by incandescent light (a) and by two different strip lights (b, c). Horizontal axis shows Coloroid hues, vertical axis the deviation from the surface colour in sunlight in Coloroid *T* units

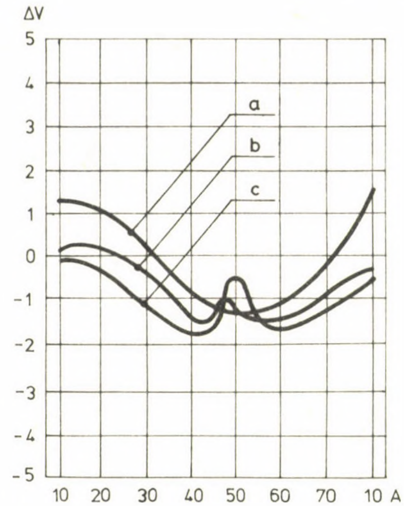


Fig. 5.93. Lightness variation of environment colours illuminated by incandescent light (a) and by two different strip lights (b, c). Horizontal axis shows Coloroid hues, vertical axis the deviation from the surface colour in sunlight in Coloroid *V* units

appearance, but also biological parameters of the room occupants, and—last but not least—their efficiency.

Variations of productivity and relative fatigue at different illumination levels by lamps of different spectral energy distributions, such as incandescent lamp, sodium lamp, and mercury vapour lamp, are shown in Fig. 5.90. While Figs 5.91, to 5.93 show colour rendering differences referring to hue, saturation, and lightness of an incandescent lamp and two kinds of strip lights.

To help visualizing the messages of the diagrams, respective Figs C54 to C56 show yellow, orange and blue surfaces appearing in the light of sunshine, incandescent, mercury vapour, and sodium lamps.

Primarily in the interest of environment colour design, all these phenomena prompted the description of light sources—in addition to correlated colour temperatures—by some colour rendering index.

Mainly based on Ouweltjes's (1960) work, CIE rejected as inadequate this temporary method, and agreed on a proposal to define colour rendering index of the light source and a special colour rendering index respectively, by using standard colour samples with definite spectrum reflection properties.

Determination of the CIE colour rendering index relies on the following principles: colour rendering of a given light source is defined as a function of its effect on colour impression by a standard solid colour, compared to the effect of a comparative light source on the same colour sample.

Below 5000 K correlated colour temperature, a black body of the same correlated colour temperature, and above 5000 K that phase of daylight colour distribution is considered, the colour of which differs the least from the light source being assessed are taken as comparative light sources.

Colour coordinates of standard colours at an illumination D65 are presented in Fig. 5.94. Colour rendering indices referring to single standard colours are the so-called special colour rendering indices, their average being the mean colour rendering index. Significance of the colour rendering index appears from Fig. 5.95, locating colour points in the CIE–UCS diagram for human face, blue sky, and green grass in daylight and in incandescent light, after HUNT (1977).

Nowadays, however, ever more problems emerge with the determination of colour rendering index. Such are e.g. to reckon with the colour adaptation of human eye, or the re-definition of standard colours. Recently at the 1976 CIE Conference the problem of preference for standard colours arose.

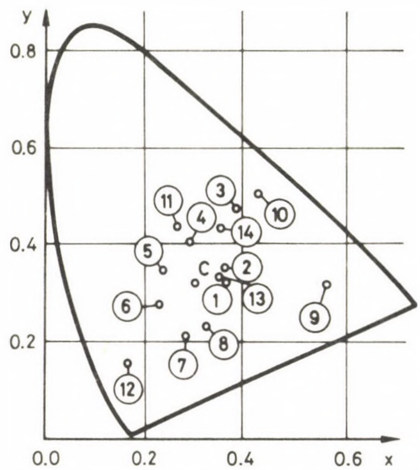


Fig. 5.94. Standard colours for computing the CIE colour rendering index at illumination D65

Further problems in applying colour rendering indices are as follows: To feel comfortably in an artificially illuminated environment, the illumination level and colour temperature of the light source must be proportional. The lower the illumination level, the lower colour temperature of the light source is preferred. This preference depends, of course, on age, but also on other parameters, first of all, on climatic conditions.

In spite of these problems practical use of colour rendering indices has begun. Colour rendering indices of artificial light sources range from 0 to 100. The higher the colour rendering index of a light source, the better it suits working processes where colour recognition is of prime importance. For rooms with different functions, light sources with the following colour rendering indices are suggested: minimum 90 for museums, studios, graphic workshops, surgeries, medical reception rooms, textile factories, and printing offices; min. 80 in department stores, food shops, auditoriums, and offices. For passages, staircases, and other traffic areas—contrary to earlier concepts—now an illumination with a colour rendering index of at least 60 is suggested.

Recently, prospectuses of major strip light factories such as General Electric, Osram, Philips, Sylvania, Ediswan, and Tungsram, suggest the fields of application for a given type of fluorescent strip light based on colour rendering indices.

Light sources, however, can be designed not only in respect of colour rendering indices, but also with the purpose of lending pleasant colours to some well-known

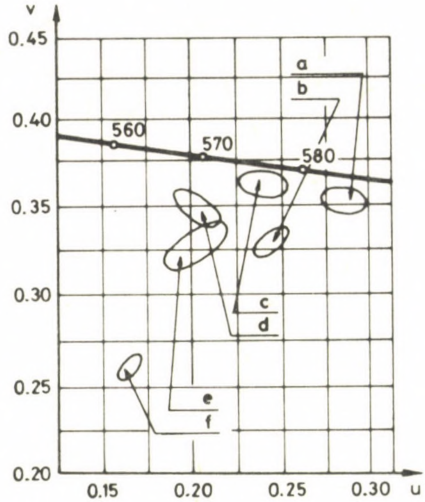


Fig. 5.95. Colour of the human face illuminated by incadescent lamp (a) and sunlight (b), of the sky illuminated by incandescent lamp (c), and sunlight (f), and of grass illuminated by incandescent lamp (c) and sunlight (d) after HUNT, in the CIE 1931 diagram

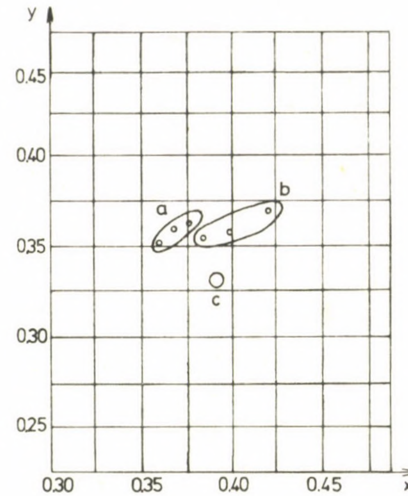


Fig. 5.96. Preferred colours of the human body in incandescent light plotted in the CIE 1931 diagram: a) highly preferred colour points after SCHANDA-NEMCSICS, b) preferred colour points after SCHANDA-NEMCSICS, c) medium preferred colour point after JUDD

objects. This aspect is expressed in terms of the light source colour preference index. There is, however, still much of controversy in selecting preferred colours. Colour preference values for the human skin were plotted in Fig. 5.96.

5.3.3. Role of Direction of Illumination in the Appearance of Colours

Visual appearance of our environment is affected by size, shape, and quality of radiant surfaces, but also by its spatial position. Under an overcast sky outdoors illumination is diffuse but it is technically possible to produce such an effect indoors, being the most favourable for evaluating environment colours.

Another type of illumination is that by a point-like or nearly point-like source. This is experienced outdoors in sunshine, or indoors under natural illumination, when windows are not too large, as well as for most of the conventional artificial light sources. The casting of shadows helps the recognition of spatialness of objects, and interpretation of space conditions, but impairs colour sensation, and the recognition of colour values.

Depending on its principal direction, illumination may be:

— back-light, where the coloured object is between the light source and the observer, its side facing the observer is in complete shadow;
— full light, where the light source is behind the observer, and the surface looked at is free of shadows, and illuminated nearly at 90°;
— shading light, where the light from the light source is incident on the object at an angle so that shadows are cast on the colour bearing surface, emphasizing its reliefs.

Principal directions of illumination are schematically shown by Fig. 5.97. In Figs 5.98 to 5.100 it has been plotted how light of the same quantity and quality but of different directions affects colour appreciation. Red of Coloroid saturation *T*40 and Coloroid lightness *V*50 has been chosen as reference. Evaluation was made for each colour parameter, such as hue, saturation, and lightness.

Colour sensation is best in diffuse light, especially, for violet, blue and bluish green, but least so for yellow. It is the most advantageous for unsaturated, dark colours.

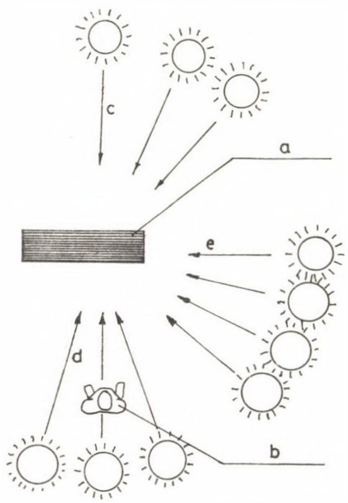


Fig. 5.97. Scheme of principal directions of illumination: a) environmental element, b) observer, c) back-light to the observer, d) full light to the observer, e) shading light to the observer

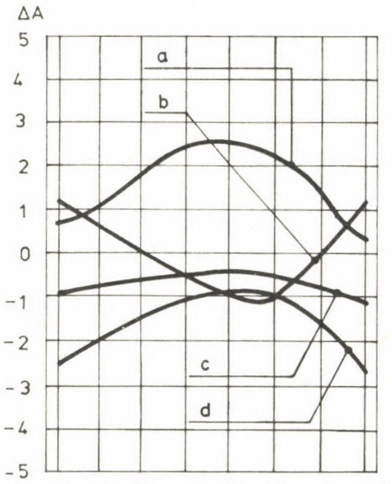


Fig. 5.98. Dependence of the correct hue sensation on the direction of illumination. Horizontal axis shows Coloroid hues, vertical axis deviations from the colour of the surface seen in light reflected from the north sky in Coloroid *A* units. Further symbols: a) diffuse light, b) full light, c) shading light, d) backlight

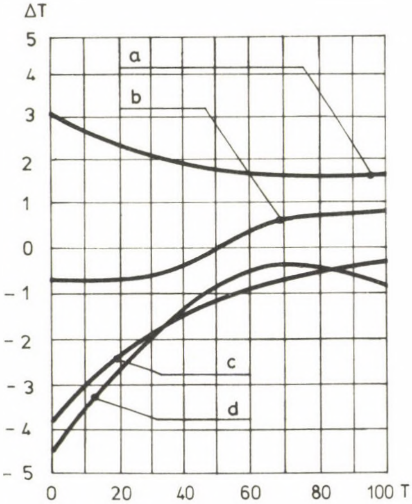
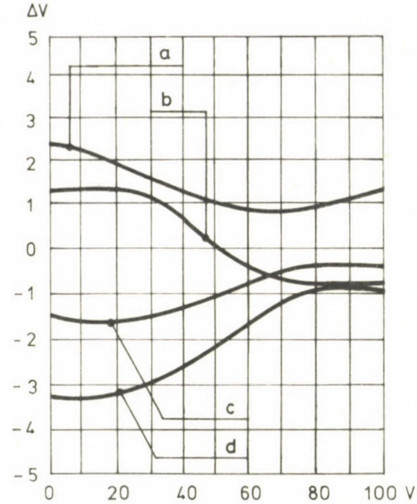


Fig. 5.99. Dependence of the correct saturation sensation on the direction of illumination. Horizontal axis shows Coloroid saturations, vertical axis deviations from the colour of the surface seen in light reflected from the north sky in Coloroid *T* units. Other symbols are as in Fig. 5.98

Fig. 5.100. Dependence of the correct lightness sensation on the direction of illumination. Horizontal axis shows Coloroid lightnesses, vertical axis deviations from the colour of the surface seen in light reflected from the north sky in Coloroid *V* units. Other symbols are as in Fig. 5.98



In full light, colour sensation is very different in each colour domain. While yellow, orange, red, and yellowish green are effective in full light, the same is not advantageous for violet, blue, and bluish green. It neatly renders the more saturated and darker varieties of any colour tone.

Colour sensation is poorest in back-light, where unsaturated, dark varieties of yellows and oranges are the least well perceived.

Shading light also hampers correct perception of colour relations. Because of contrasts between shaded spots and high luminances on coloured surfaces, correct perception mainly of unsaturated dark colours becomes difficult. In such a light, blues are somewhat better distinguished than are yellows and oranges.

An orange and a blue colour in diffuse light and illuminated from different directions are seen in Figs C57 and C58, respectively. The presented, almost incredible direction-dependent deviations in colour appearance look in reality not so serious, because of adaptation and colour constancy. The importance of deviations may be appreciated by looking at a sunlit façade on which a shadow is cast.

5.3.4. Light and Space Ambience

Being inside a built environment is felt to be pleasant or unpleasant depending on the homogeneity of the luminous intensity, the spectral composition of light sources, the direction and nature of the illumination—depending on the lighting fixture(s) position and type. This applies to any establishment in general, but specifically to a room.

For instance, in homes, no illumination level differences between rooms exceeding 300 to 400 lx are permissible (Fig. 5.101), while these differences may be as high as 1000 to 1500 lx in some major establishments or plants (Fig. 5.102), without perceiving the resulting important luminance differences between colour bearing surfaces. Large distances between rooms permit eyes to adapt to different luminances.

In not very large rooms with natural illumination, the relative illumination intensity is largely determined by the observer's distance from the window without feeling unpleasant (Fig. 5.103). Skylights produce much more uniform illumination, providing almost uniform relative intensity throughout the room. Because of missing shadow effects, however, this method of illumination is not unambiguously favourable for creating a pleasant ambience (Fig. 5.104).

Depending on whether artificial light sources produce a direct, a homogeneous diffuse, or an indirect illumination, they significantly affect the pleasantness of an interior, irrespective of illumination intensity (Fig. 5.105). Direct illumination is always hard and

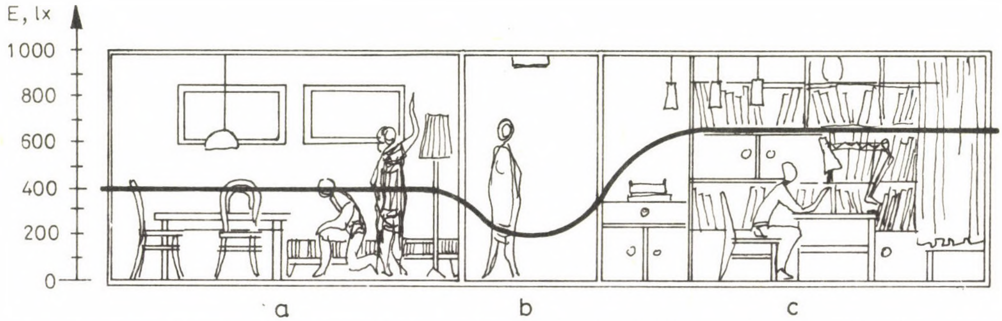


Fig. 5.101. Curve showing optimum differences between illumination levels in a home: a) bedroom, b) passage, c) study

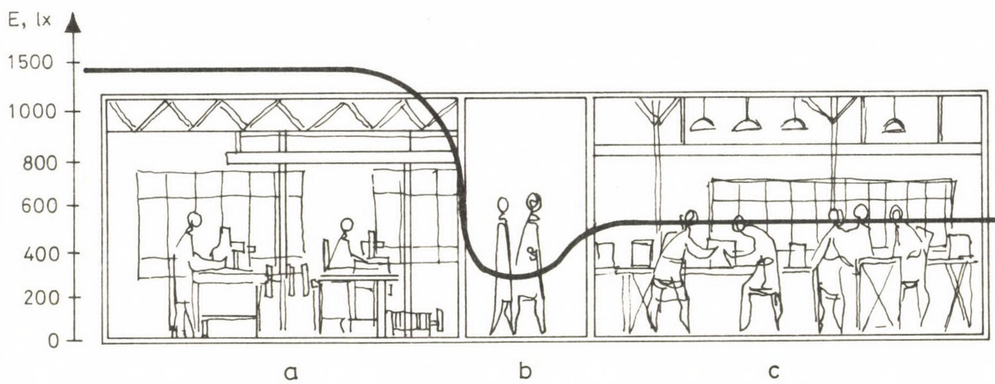


Fig. 5.102. Curve showing optimum differences between illumination levels in a machine tool factory: a) machining workshop, b) passage, c) packaging workshop

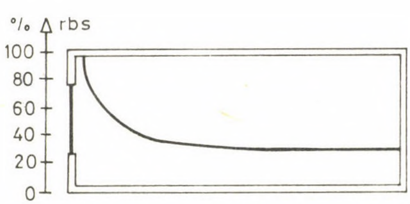


Fig. 5.103. Decrease of relative intensity of illumination in a room illuminated laterally, with the distance from the window

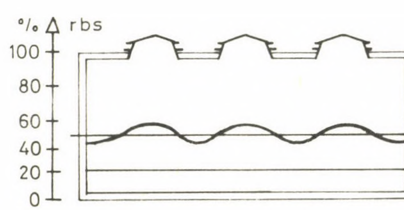


Fig. 5.104. Variation of relative illumination intensity in a room with skylight

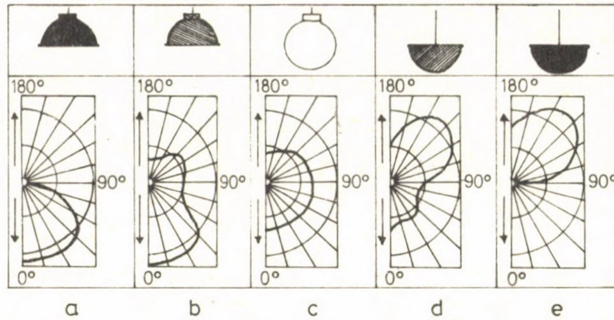


Fig. 5.105. Light sources, different illuminations and light distribution curves: a) direct light, b) dominant direct light, c) homogeneous diffuse light, d) dominating indirect light, e) indirect light

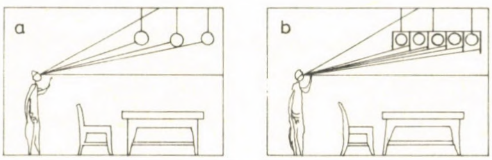


Fig. 5.106. Dazzling may be avoided by applying lamellae preventing direct light from the light source to reach the eye: a) incorrect, b) correct mode

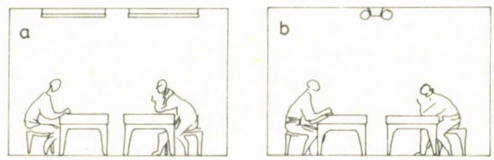


Fig. 5.107. Two ways of fitting strip lights: a) wrong, b) right arrangement

mostly unkind. A homogeneous diffuse illumination produces soft shadows giving rise to pleasant effect. Indirect light reflected from the ceiling is almost without any shadow effect. Colours prevail in light.

Also lighting fixtures have to be placed with care. Beams incident on eyes directly from the light source are unpleasant, because of dazzling. Properly constructed lighting fixtures eliminate this problem (Fig. 5.106). There is an increased risk of dazzling when strip lights are placed crosswise to the workplace (Fig. 5.107). Occupants of a room should not be directly exposed to the high luminance from light sources. Also a too low luminance on some surfaces is unpleasant.

No light sources of different types, with highly different colour temperatures should be used in the same room, or even in adjacent rooms, if it can be avoided.

5.4. Colour and Ergonomics

Ergonomics is the synthesis of knowledge acquired in different sciences concerning man under his actual living and working conditions. In ergonomics, "man–machine–environment" is considered as a complex functional entity, in which man has a doubtless primary part. Ergonomics and colour dynamics are strictly related. They started in the same period and initially colour dynamics was even considered as part of ergonomics.

Study of the man–machine system has been concerned with man, and with his aspects closely related to his work efficiency, summarized as the "human factor". This expression which was enunciated together with technical psychology and ergonomics, may be interpreted as follows: "Human factors" are integrated characteristics of relations between man, machine, and environment, manifest in the functioning, interactions, and under the actual conditions of the man–machine–environment production system. As to its goal, ergonomics may be considered partly as the science of developing optimum relations within the man–machine system, and partly, as a human approach to environmental design, which is a component part of colour dynamics. Colour is a tool for ergonomics to assist it to realize its objective, the development of an ideal complex of man–machine–environment. Conversely ergonomic knowledge has to belong to the armory of environment colour designers, both when designing a factory interior or a home.

In previous chapters, several man to colour relations have been discussed, which are considered in ergonomics as human factors of the environment. This chapter will only deal with some problems not yet discussed, mainly for workplaces, such as the function of colour in compensating harmful environmental effects, and in forming community relations. Some ideas will be outlined for the coloration of machines and for safety colours and for informational signals.

5.4.1. Compensation for Harmful Environmental Effects

In these days, society is much concerned about environmental pollution. The social movements against it primarily strive to eliminate the causes of pollution, that is, however, impossible at the present level of technical development. In the built environment, man is continually exposed to various disturbances. A home on a main street is too noisy; if it faces south, it is too hot. In, for example, textile factories, noise cannot be reduced below a given level; in a plastics factory or galvanization plant, unpleasant smells cannot be totally eliminated. In certain industries, technologies involve excessively high or low temperatures. Thus, the built environment also functions as a system of effects to which occupants are continually exposed. Often no other means are available to counteract them apart from the methods of colour dynamics. Psychophysical and psychosomatic effects of colours may help to increase or reduce perceptions elicited by stimuli acting on our different sensory organs.

In this respect, environment colour design may contribute to the compensation of harmful effects arising from our built environment, and particularly, from those of the

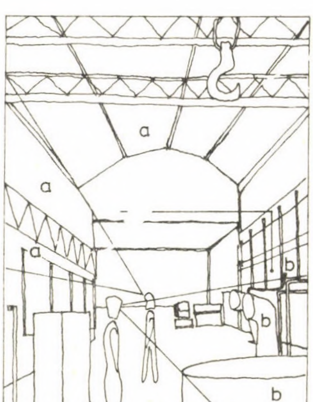
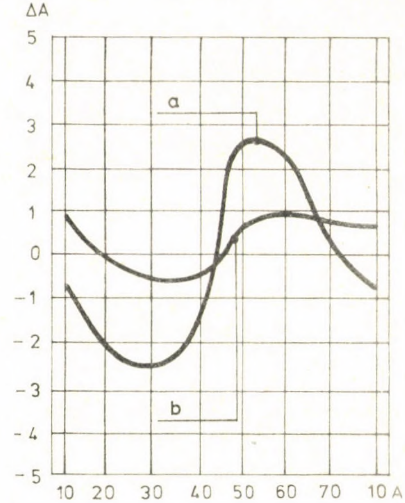


Fig. 5.108. Colour-bearing surfaces having important roles in the compensation of a) dry heat, and b) moist heat

Fig. 5.109. Hues compensating a) dry heat, and b) moist heat. Horizontal axis bears Colorid hues, vertical axis the degree of compensation as compared to that by medium gray



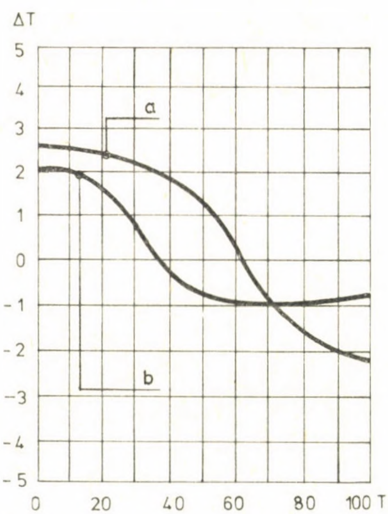


Fig. 5.110. Saturations compensating a) dry heat, and b) moist heat. Horizontal axis bears Coloroid saturations, vertical axis the degree of compensation as compared to that by medium gray

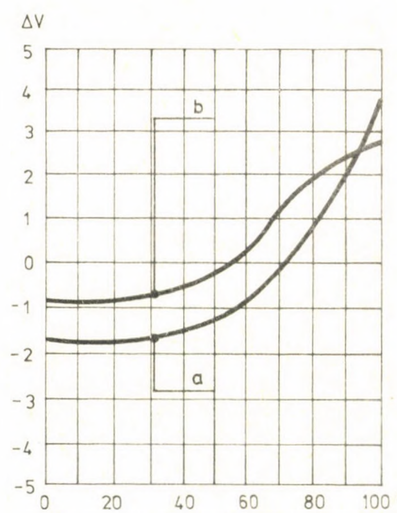


Fig. 5.111. Lightnesses compensating a) dry heat, b) moist heat. Horizontal axis bears Coloroid lightnesses, vertical axis the degree of compensation as compared to that by medium gray

rapidly growing industrial environment and thereby become an effective means of environment protection.

Specialists in colour dynamics have up to now been most intensively concerned with the effects of colour in modifying heat sensation. It has been observed that colour bearing surfaces in the room play different roles in compensating for dry or moist heat (Fig. 5.108). Dry heat is best offset by blue and bluish green. In such a surrounding, no orange or red should be applied, but in a moist heat, they can be applied in a subdued way. In a hot surrounding, saturated or dark colours are unpleasant, light and unsaturated ones are favourable (Figs 5.109 to 5.111).

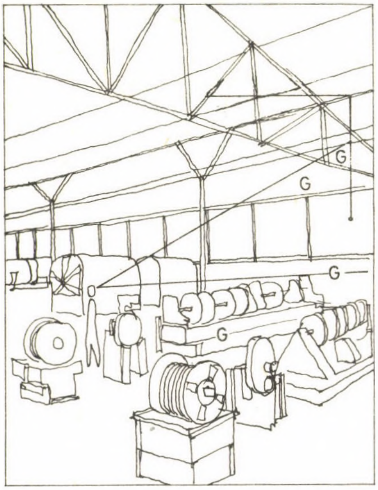


Fig. 5.112. Colour bearing surfaces (G) prominently serving the compensation of shrill and dull noises

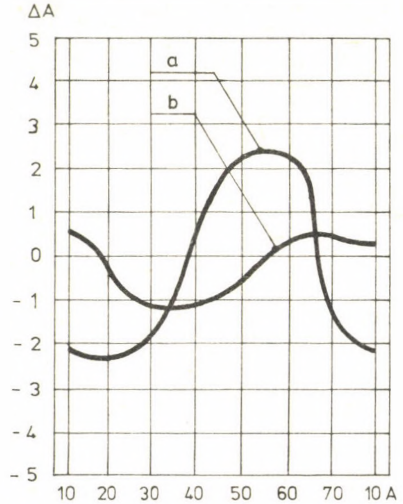


Fig. 5.113. Hues compensating shrill (high frequency) (a) and dull (low frequency) (b) noises. Axis notations are those in Fig. 5.109

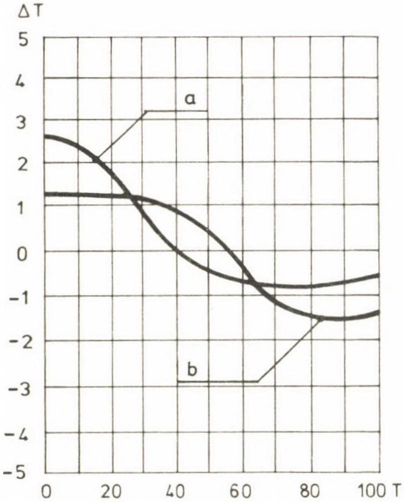


Fig. 5.114. Saturations compensating shrill (a) and dull (b) noises. Axis notations are those in Fig. 5.110.

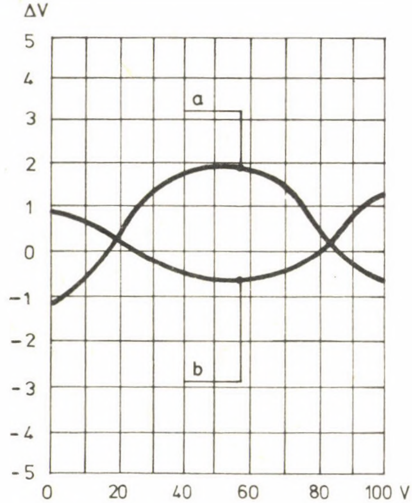


Fig. 5.115. Lightnesses compensating shrill (a) and dull (b) noises. Axis notations are those in Fig. 5.111

Colours may significantly compensate for noise sensation. Interior colour bearing surfaces are not equally effective in this respect (Fig. 5.112). Different hues, saturations and lightnesses suit to offset shrill (high frequency) or dull (low frequency) noises in a workshop. Shrill noises are best dampened by green and bluish green, while dull noises by yellowish green. In a noisy environment, saturated colours are poorly tolerated, less saturated colours better. Medium light colours tend to offset shrill noises, whereas light and dark colours rather compensate dull noises (Figs 5.113 to 5.115).

Colour bearing surfaces participate differently in compensating for smells (Fig. 5.116). The smell of formaldehyde is likely to be better compensated by blue, whereas those of ammonia and hydrogen sulfide by green. Any of these smells is better supported in either unsaturated or very saturated, possibly light colour surroundings (Figs 5.117 to 5.119).

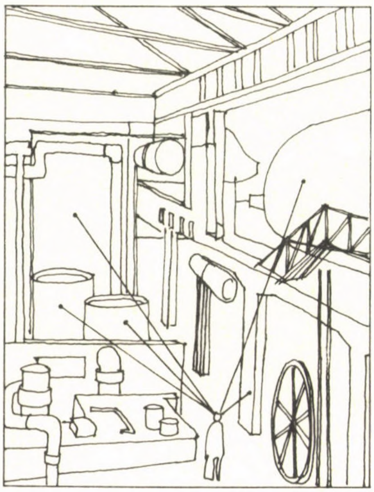


Fig. 5.116. Colour bearing surfaces primarily participating in smell compensation

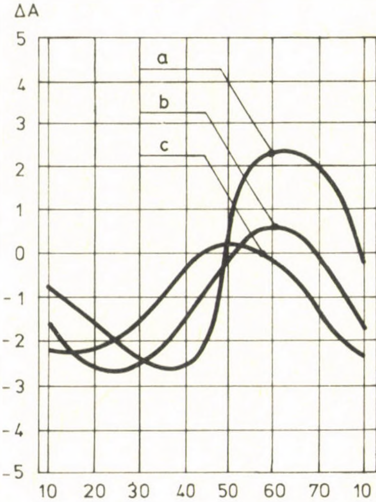


Fig. 5.117. Hues compensating smells of ammonia (a), hydrogen sulfide (b), formaldehyde (c). Axis notations are those in Fig. 5.109

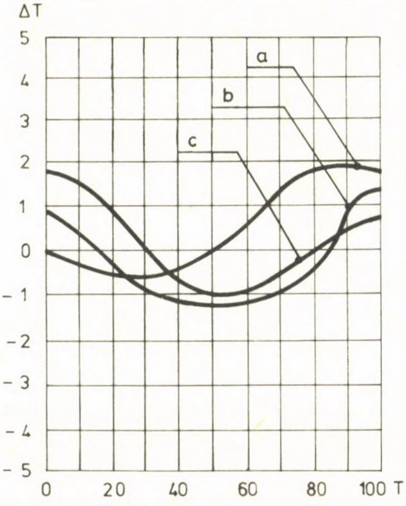


Fig. 5.118. Saturations compensating smells of ammonia (a), hydrogen sulfide (d), formaldehyde (c). Axis notations are those in Fig. 5.110

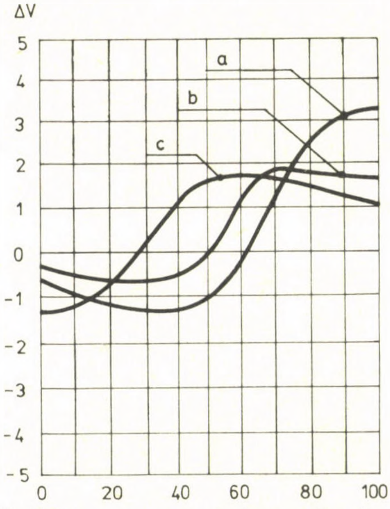


Fig. 5.119. Lightnesses compensating smells of ammonia (a), hydrogen sulfide (b), formaldehyde (c). Axis notations are those in Fig. 5.111

5.4.2. Community Relations and Colours

Creation of the built environment has been one of the most important social tasks. Since the very beginning of human society, the goal of this activity has been to offer a man-made space for different processes of life in order to protect from Nature's forces, not only man but also his tools. How well this goal could be realized has always depended on material–economical possibilities of society and on different aspects of social relations and other factors. As a result, mankind has developed a new, man-made, built environment for himself, being not only part of material reality but also a bearer of social features reflecting at the same time demands, mental–spiritual features, habits, and relationships of man as a social being. Thereby becomes environment design, inclusive colour dynamics, the special activity directing the complex material, mental and social process of space-forming by means of colours—which is an art.

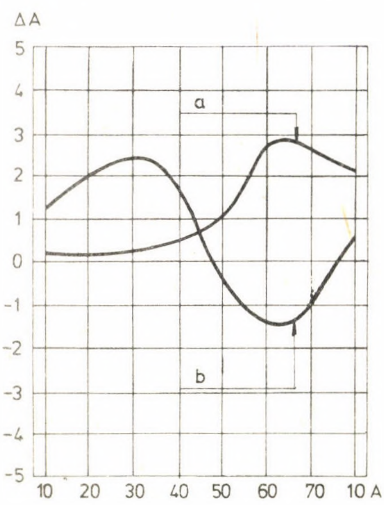


Fig. 5.120. Hues favourably and unfavourably affecting community (a) and casual (b) relations. Horizontal axis shows the Coloroid hue scale, vertical axis the intensity of the relation referred to an achromatic environment

Environment design is a multiple skill expressing the activity and creativity of man and his power over Nature. It includes not only design and organization of space, but also its colouration. It requires not only wide-range, top-level practical and theoretical knowledge, technical scientific experience, neither is it based alone on a knowledge of social conditions, and characteristics, but also on a thorough acquaintance with ways and modes of living, and still more: consideration of human totality, and human requirements.

This coloured built environment resulting from this complex activity reacts on man himself, causing him to change, develop, since humanness, human features, penetrate the world of objects, all the coloured environment.

Social activities, the world of small and large communities, family systems and the whole structure of the community and its variation in any society underlie the demand for coloured environment. Just as political activities and power, decisions based on economic and social factors, have always dominated architecture, they are also of undeniable importance in the present day conscious environment colour design. Just as various forms of activity interact, so do they penetrate our environment transforming activity from prehistory to now. Society with its aspirations features, presence, and overwhelming relationships, has always and everywhere been the most decisive factor in forming the environment.

The result of this activity—the created coloured environment—has repercussions on society; it creates a connection or otherwise, a division, between classes and individuals, communities, generations, and productive activities, i.e. between a wide range of social components. Built environment is a determinant for human life itself, in countless aspects of home, workplace, town and traffic. Thereby built environment becomes a factor forming society and inside it, society reacts on itself (Figs 5.120 to 5.122).

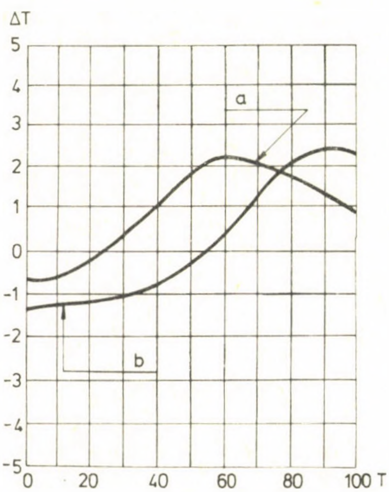


Fig. 5.121. Saturations favourably and unfavourably affecting community (a) and casual (b) relations. Horizontal axis shows the Coloroid saturation scale, vertical axis the intensity of the relation referred to an achromatic environment

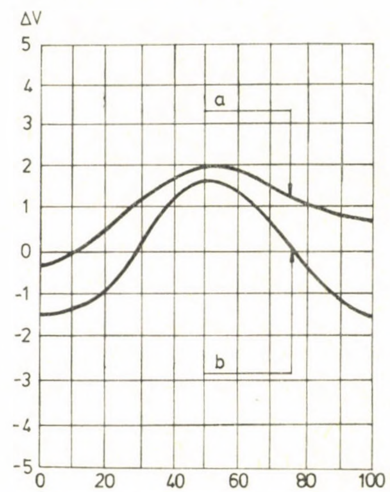


Fig. 5.122. Lightnesses favourably and unfavourably affecting community (a) and casual (b) relations. Horizontal axis shows the Coloroid lightness scale, vertical axis the intensity of the relation referred to an achromatic environment

Spiritual life and activities of a society are strictly related to financial–economical activities. Architecture, hence also environment colour design, are organic parts of this spiritual activity, almost inseparable from arts or science, or even, from the social aspects, moral and social habits, the educational level, ideas, and demands of the masses, groups, and individuals creating or utilizing the built environment. Therefore there can be no gulf between culture and built environment of a people, built environment being characteristic of the complex development of material and spiritual life.

Of course, built environment is also our coloured environment, the up-to-date creation of which is the objective of colour dynamics as a new science. This science has already done well to study and interpret interactions between colour, man and environment, but has still much to do to become acquainted with environment as a factor forming society, as a social system, and to assess the relevant functions of colours.

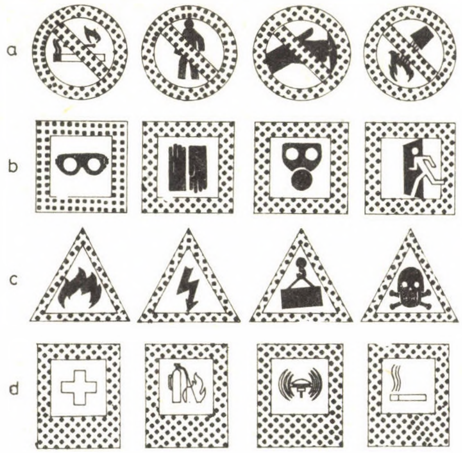


Fig. 5.123. Some safety colour signs: a) prohibition boards, b) information boards, c) warning boards, d) instruction boards

5.4.3. Colouration of Machinery

In working places, man is surrounded by machines of different size, mass, and form. Machine colours are of importance for a pleasant atmosphere at work. Colour selection is primarily determined both by the dimensions and functions of machines, and surrounding colours. In addition, an optimum colour contrast between colours of machine and workpiece has to be formed, mainly by hue and saturation. Lightness contrast is adverse, causing untimely fatigue of workers' eyes. The colour of machines should be definitely different from that of their surroundings. Coloration has to point out functional coherence between parts of equipment (Fig. C59). Moving, dangerous parts should be painted in saturated colours, preferably red. Also control units must be highlighted by colours.

5.4.4. Safety Colour and Information Signs

Safety colour and information signs call attention to danger and risk of accident, and also, in the event of an accident, help to find quickly safety or emergency implements. These signs should be applied in every factory and establishment where required by work safety aspects. Colour and information signs should be uniform throughout an establishment, lest trouble and misunderstanding result in an accident due to differences between factory units. To avert accidents, these signs should be displayed where there is a possibility of danger or accident, or where they can help fast recognition of safety equipment or means of protection (Fig. 5.123).

6. Colour Harmony Relations

The problem of colour harmony has long been regarded as an esoteric matter for the artist. But since the advent of interdisciplinary research on colours, colour harmony has become an object of scientific research giving rise to several theories on colour harmony. These theories emphasized different relations between the role of colour harmony in environment and man, his culture, his message, and considered these as the exclusive laws of harmony. Although these theories are often biassed, they point out several important features of harmony relations. That is why this chapter will be concerned first with the development of knowledge on colour harmony, followed by our own experiments and results on fundamental conditions of harmony sensation. Thereafter the concept of colour harmony will be defined from the aspect of environment theory. Lastly, basic types of colour harmony will be considered.

6.1. Development of Knowledge on Colour Harmony

A colour composition comprising harmonizing elements is considered as harmonic. The concept of colour harmony denotes thus an accordance of colours. But, in fact, what can colour harmony be attributed to? What is the relation between elements said to be harmonizing? The answer to this question would point to the meaning of harmony; attempts to define this have been made since the mid-18th century, resulting in several theories of colour harmony, relying on three, essentially different fundamental ideas.

6.1.1. Harmony; Balance between Psychophysical Forces

The first group of theories on harmony attempted to explain the origin of harmony from the mechanism of vision. Already in the second half of the 18th century, some earlier observations, e.g. that looking for a long time at a green surface produced a red after-image, and that this after-image was always the complementary of the observed colour, had been confirmed by experiments. This phenomenon, the so-called successive contrast, has been the starting point of several theories on harmony stating that the eye spontaneously tends to balance colour effects. The first definition of harmony based on this observation is due to RUMFORD who stated in 1804 that harmony is an equilibrium between psychophysical forces.

RUMFORD also contended that harmonizing colours are always complementary, adding up to an achromatic colour. This finding was later explained by HERING (1879) who wrote: "That condition of the optic substance corresponds to medium or neutral gray where dissimilation, that is, consumption by vision, and assimilation, that is, renewal, are equal, so that the mass of the agent (optic purple) is invariant. This means that medium gray creates a perfect equilibrium in the eye." Complementary colours establish this very equilibrium.

These findings were the basis of the much quoted theories of totality by GOETHE, and of duality by SCHOPENHAUER. According to GOETHE (1810), an arrangement which contains in some form the entire colour circle is harmonic (Fig. 6.1). SCHOPENHAUER (1830) studied relations between lightness and hue qualities of colours as a harmony sensation elicitor. In his colour circle, lightness differences between colours were compensated by hue differences (Fig. 6.2). These theories transmitted by HOELZEL (1910) subsisted in works on theory of art by KANDINSKY (1941), KLÉE (1961), ITTEN (1961), ALBERS (1963), MOHOLY-NAGY (1928b), and still influence theoretical and practical activities involving colours. These authors further developed concepts on relations between surface area and lightness of colour in a harmony complex. Their recognition that harmony was always a function of the message of the underlying work was a completely new idea. As KANDINSKY put it: "Contrast between two colours need not be a contrast by being complementary; for instance, a complex of red and blue—two colours in no psychophysical relation—is also harmonic, because they enable different messages to be expressed."

CHEVREUL, the French chemist (1879), arrived at similar conclusions, stressing the role of complementariness in creating harmony, supporting his theory by successive contrast phenomena. His message transmitted by DELACROIX was translated by SEURAT and SIGNAC into the practice of painting. SEURAT himself experimented with harmonies, recapitulating his results by stating that harmony is a unity of opposites and similarities, a principle serving as the theoretical basis of pointillism (Fig. C60).

These theories essentially stressed relations between hues of harmonizing colours. Development in psychophysical research questioned the scientific fundamentals of these relations. Tests by KRAWKOW (1955) among others, showed that the colours involved in complementary and in successive colour contrast are not the same and therefore fail to prove theories deduced from this phenomenon by RUMFORD, GOETHE, SCHOPENHAUER, CHEVREUL, and others.

Referring to his own, and to FEDOROV's investigations, KRAWKOW wrote: "According to our investigations, successive contrast of blue (453 nm) is an orange yellow (586 nm), while its complementary is a pure yellow (572 nm). Successive contrast of this yellow is purple rather than indigo (Fig. 6.3). At the same time, for green, the colour of successive contrast is its complementary. In general, the successive contrast colour is shifted from the complementary towards green within the colour circle. Eye adaptation to colour stimuli shows from the beginning of stimulation an uneven decrease of eye sensitivity to red, green and violet. Decrease is the fastest for violet. Thereby, after a longer or shorter colour perception, relation of the basic stimuli to the original stimulus changes so that

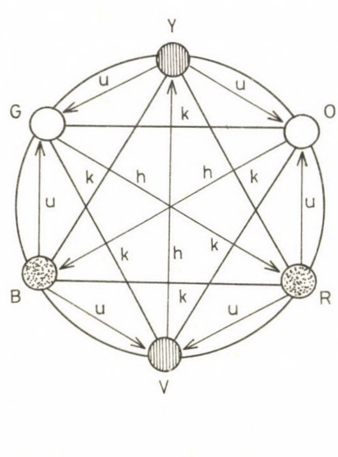


Fig. 6.1. Colour circle representation of GOETHE's theory of colour harmony based on the principle of totality. Y yellow, O orange, R red, V violet, B blue, G green, h harmonizing pairs of colours, k characteristic pairs of colours, u disharmonic pairs of colours

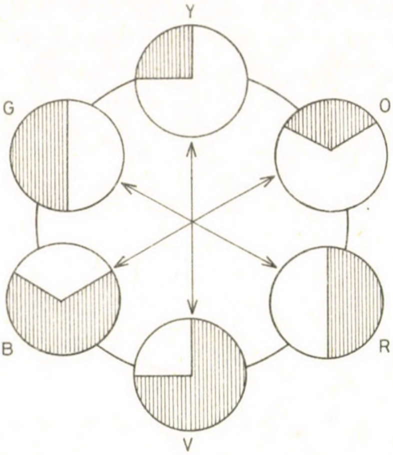


Fig. 6.2. Colour circle representation of the theory of colour harmony relying on the principle of duality by SCHOPENHAUER. Y yellow, O orange, R red, V violet, B blue, G green

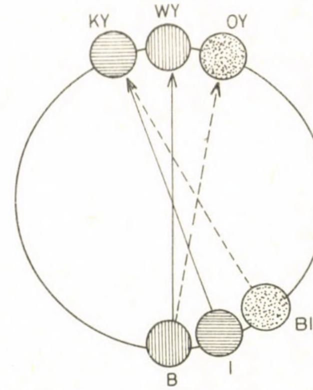


Fig. 6.3. Scheme of KRAWKOW's statements on deviations between successive and complementary effects. KY cold yellow, WY warm yellow, OY orange yellow, B blue, I indigo, BI purple

after some seconds of colour impact, the share of basic stimulus increases. Consequently, colour tone perception is shifted toward green. The colour of successive contrast is, however, complementary of the colour having altered the tone of the original colour."

It has become clear that relations between hues of harmonizing colours are of importance for the development of harmony but these relations cannot be deduced simply from the psychophysical laws of colour vision. These theories are erroneous not only because of their preference for hue relations but also by considering the role of lightness with bias, i.e. only in its relation to hue, and completely neglecting the role of saturation, let alone the problem of pleasing, and the role of harmony complex in the environment.

These recognitions prompted surveys by MOON and SPENCER (1944b, c) using Munsell colour samples, to define statistically the laws of harmony between hues. Based on their results and on several recent tests in Japan (MORI, 1967), it can be concluded that the harmony relation between colours of a colour complex also depends on the regular relation between hues of the colours, to be defined exclusively by statistical surveys.

By now, these theories of harmony have outlined the role of hue in a harmony complex, the importance of various hues in harmony creation, but failed to support scientifically such concepts as triadic and tetradic harmonies, although these are frequently used in the literature.

6.1.2. Harmony; Arrangement of Colours in Scales

It was observed by textile dyers and printers* that mixing a colour with white, gray or black in different proportions led to very attractive, harmonic colour complexes. It was one of the secrets of the trade of painters to make each of their colours dull by admixing

* Such observations were underlying the colour collection made by LE BLOND, engraver in Frankfurt, in 1730, and the atlas by GAUTIER, printer in Paris. In his 1766 book "The natural system of colours", HARRIS classified saturated colours and those mixed with white, gray and black.

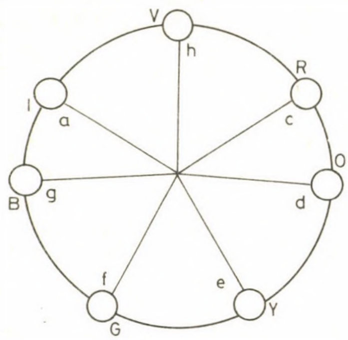


Fig. 6.4. Colour circle connected to the musical scale by NEWTON, underlying this theory of colour harmonies. R red, O orange, Y yellow, G green, B blue, I indigo, V violet. Small letters joining circles mean musical scale tones

a colour in different proportions, helping colours in the picture to form harmonic complexes. Both approaches arose from the recognition that colours with uniformly varying saturations or lightnesses i.e. those forming a scale appeared harmonic. This observation was the starting point of the second generation of theories on harmony.

The first scale of colour harmony was constructed by NEWTON, and published in his "Optica" in 1704. Dividing the spectrum discovered by him into seven colours, he paralleled it to the musical scale of that age (Fig. 6.4). His idea was further developed by HOFFMANN in his book published in 1786, explaining colour harmonies with the aid of acoustic analogies. In 1810, the painter RUNGE suggested and attempted to develop a unified system of musical and colour harmonies. These ideas misdirected research on colour harmonies for a long time since even their followers were concerned only with hue scales.

OSTWALD (1956) and PLOCHÈRE (1948) were the first to define the arrangement in scales by writing relationships between saturations and lightnesses. Scale members were described by OSTWALD as additive, and by PLOCHÈRE as subtractive colour mixing components. In his theory of harmonies, OSTWALD pointed out: "In order to find every possible harmony, possible orders in the colour solid have to be found. The simpler this order, the more clear and self-evident is the harmony. There are essentially two of these orders: those in the equivalent colour circle and in the isochrome triangle."*

This latter statement expresses the dependence of harmony on the uniform variation of saturation and lightness.

OSTWALD's theory was progressive in that it connected the laws of colour harmony with relations between exactly measurable components. For the achromatic scale, the laws of harmony are coincident with experience. In other respects, however, experience fails to support his findings. The essential deficiency of his laws of harmony resides in his colour system. Colour points of his colour system represent colour perceptions related only by mathematically definable quantitative variations of colour mixing components. Interrelation between them comprises no perceptionally equal or uniformly varying intervals.

PFEIFFER, a painter (1926) starting from the Bauhaus school, later a graduate from the University of Cologne who became professor at the Ecole d'Architecture in Paris,

* OSTWALD called *equivalent* the colour circle of equally light colours and *isochrome* the axial section of his colour solid.

considered the creation of a colour harmony system as his chef-d'œuvre. He started from the acoustic meaning of "harmony"—namely that the three main tones, do, mi, sol, of a vibrating chord are proportional in a way that the chord length for *mi* is the harmonic mean between chord lengths for *do* and *sol*. The algebraic generalization of this rule was applied for determining colour harmonies.

Referring to tests by ROSENTHIEL and FECHNER (1876), he established that lightness intervals of the logarithmic scale are in a harmonic relation, and called this scale a harmonic scale. Then he deduced correlations between the logarithmic scale and golden scale obtained by the golden section. In his book he described in detail his tests using Plateau and Maxwell discs to create harmonic scales. He classified his scales into two groups: isochromic or equal hue scales, and isophanic or equal lightness scales. First he defined each kind of harmony, and then presented its mode of construction by means of a revolving disc, followed by analysis of the psychic character of harmony. Charateristic of his work are his chromatologic tables, with the aid of which he defined harmonizing colour groups.

One of PFEIFFER's chromatology tables, the Pythagorean table is seen in Fig. 6.5. He advocated the construction of such tables as auxiliaries in creating various harmonies. Letters A, B, C, D etc. in the table signify colours, being not ordered members of various isochromic or isophanic scales. Colours in the table were obtained by mixing. Various harmonic structures can be delimited from this structure.

Schemes of two such harmonic substructures are seen in Fig. 6.6. PFEIFFER called the upper structure harmony of the latent chord, because the harmony relation between the mixed colours was defined by the chord of basic colours. The lower structure in the figure is a harmony of double structure. First, a harmony corresponding to a complete chord develops, then a secondary one, so that the first structure encloses another one.

PFEIFFER deserves credit first of all for having created his theory from the standpoint of practice. He defined primarily the mode of construction of harmony complexes

	A	B	C	D	E	F
A	AA	AB	AC	AD	AE	AF
B	AB	BB	BC	BD	BE	BF
C	AC	BC	CC	CD	CE	CF
D	AD	BD	CD	DD	DE	DF
E	AE	BE	CE	DE	EE	EF
F	AF	BF	CF	DF	EF	FF
G	AG	BG	CG	DG	EG	FG
H	AH	BH	CH	DH	EH	FH

Fig. 6.5. Pythagorean table of colours after PFEIFFER

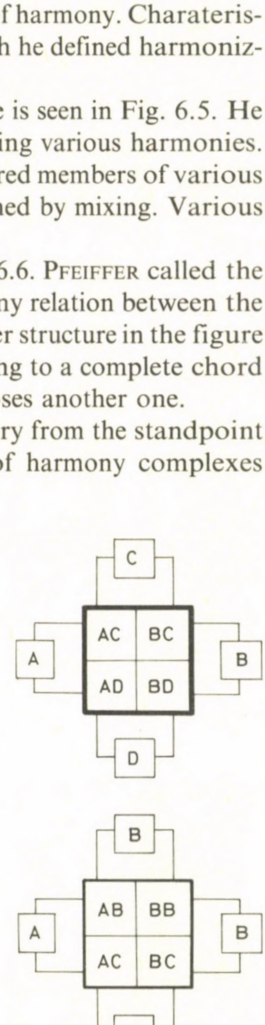


Fig. 6.6. Harmonic structures. Harmony of latent accord, harmony of double structure after PFEIFFER

current in architectural practice. It is also to his credit, that among his isochromic scales, the lightness scale was made with perceptionally uniform intervals. A deficiency of his system is not to have defined harmony relations between colours of equal saturation, and taking as the exclusive condition of harmony that it should be ordered to scale.

Harmonic scales can be developed not only according to laws of additive or subtractive colour mixing but also by taking perceptionally uniform intervals between colours. Colours of the MUNSELL's colour system constitute such perceptionally approximately uniform hue, saturation, and lightness scales. Several researchers used these scales to develop their theories of harmony. MUNSELL's perceptional intervals were the basis of JOHANSSON's (1949) system and harmony laws. He classified colour harmonies as identities, differences, and polarities. In developing theories of harmony, MOON and SPENCER (1944 a, b) as well as LE GRAND (1961) started from MUNSELL's perceptional intervals. LEBLANC (1946) intended to define harmony relations discovered by them in the international CIE diagram.

There has been an increasing interest in defining intervals between scale members. DIMMICK (1933) and BORING (1950) determined the smallest of such intervals. They

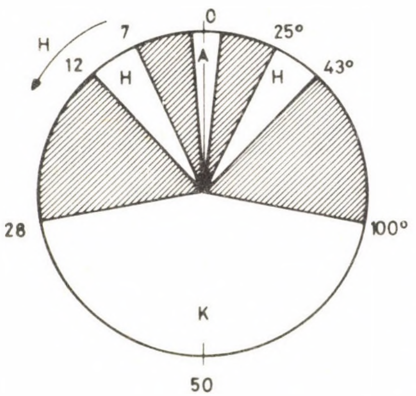


Fig. 6.7. Scheme visualizing the statements of MOON and SPENCER on the harmony relation between hues in the Munsell system. This Munsell colour circle may have zero point at any hue. Shaded areas refer to colours indifferent for the induction of colour harmony sensation. Other symbols: A identical colours, H similar colours, K contrasting colours

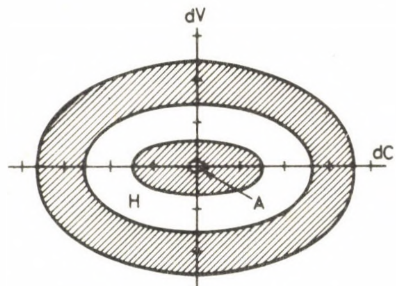


Fig. 6.8. Dependence of harmony sensation on intervals dC and dV according to MOON and SPENCER. Shaded areas refer to colours indifferent for colour harmony sensation. Other symbols are as in the preceding figure

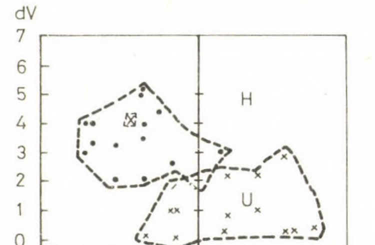


Fig. 6.9. Development of harmony sensation in different ranges of dC and dV, after MORI, NAYATANI, TSUJIMOTO, IKEDA and NAMBA. Colours in area H harmonize, those in area U do not

found that for an interval less than a certain value no harmony can any longer develop. MOON and SPENCER found that these intervals were different for different hues (Fig. 6.7 and 6.8). To examine and confirm this observation, the Japanese MORI and al. (1967) made experiments (Fig. 6.9) and their findings agreed with those of earlier tests on lightness intervals by KATZ (1935), further by GELB (1929) and GRANIT (1947). HESSELGREN (1954) called this hue-dependent interval between different lightnesses creating harmony the preferential interval. Previous experiments by CHANDLER (1928) were forerunners of this statement.

In fine arts, intervals between colours in a picture have always been important and characteristic of the given painter. MATISSE (1908) has always striven for uniform intervals in his colour compositions. As MONDRIAN wrote it in 1945: "For millennia, painting expressed proportionality in terms of colour relations and form relations, achieving but recently the finding of proportionality itself."

It has thus become clear that lightnesses of harmonizing colours form a scale but the question remained open as to saturation. Neither has it been decided whether hue relation, e.g. complementarity, or scalar lightness and saturation is the dominant factor of harmony. Another problem was to describe the order in scales by colour codes, simply because this problem could be solved only in an aesthetically uniform colour space.

6.1.3. Harmony; Preference for a Colour Complex

As early as in the 18th century, the idea was proposed that colour harmony was bound to era and nationality, based on the observation that in different ages colour complexes of different kinds were applied.

It was observed that different colour harmonies appeared on national costumes of different peoples, in pictures by different painters, other colour complexes were preferred at young age than when old and what was harmonic for one might not be so for the other. These observations have led to the conclusion that the problem of colour harmony can be settled only by statistical surveys, an idea adopted by researchers of the third group of colour harmony theories.

Statistical surveys of scientific value concerning colour relations felt to be harmonic were first conducted in the late 19th century. The best known of them are those by AARS (1899) and COHN (1894), starting from the assumption that colour harmony has to be rated as pleasing or displeasing alone. Similar premisses were applied in tests by DASHIELL (1917), with the restriction that he laid emphasis on selection between hues. ALLEN and GUILFORD (1936) were predominantly concerned with the role of lightness in selections said to be harmonic.

ALLESCH (1927) periodically repeated his tests with the same test persons. Results led him to conclude that there are no permanent rules of harmony; they are subject to variation with time, or even with the environment. Later he observed that some shade relations had more of aesthetic content than others, an observation guiding him from his original starting point to look for objective laws of harmony. Similar conclusions were drawn by JASTROW (1897) from his tests on visitors to the Columbia World Exhibition. He found some colour relations to be preferred to others. In the first category were combinations of polar colour accessible by mixing the principal colours which were found to be harmonizing. Later, GRANGER (1955), RABATÉ (1955), DUMAREST (1955) and

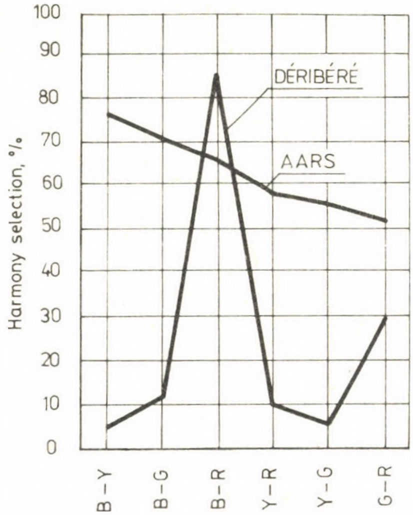


Fig. 6.10. Intensity of harmony sensation arising when looking at some pairs of colours after AARS and DÉRIBÉRÉ. B blue, Y yellow, G green, R red

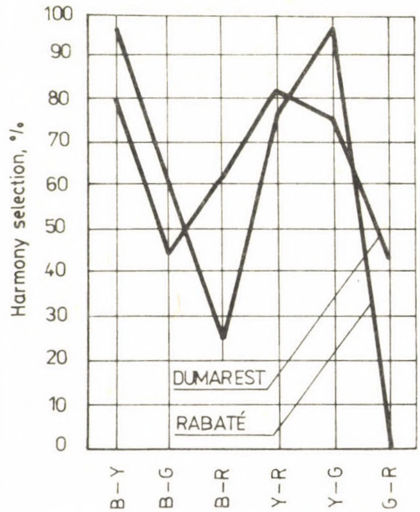


Fig. 6.11. Intensity of harmony sensation arising when looking at some pairs of colours after DUMAREST and RABATÉ. B blue, Y yellow, G green, R red

DÉRIBÉRÉ (1968) made experiments on preferences for harmony pairs and harmony triads—unfortunately, with results no more useful than those of their predecessors, leading to antagonistic publications. This trend of harmony research was doomed to failure since variations of the millions of distinguishable colours exceed the limits of assessment of preference whatever systematic test series is applied (Figs 6.10, 6.11).

Approaching colour harmony from several angles made it obvious that by "colour harmony" nothing is understood other than a complex value judgement—depending partly on colour perceptional conditions created by colour stimuli, partly on psychical, age, cultural, social, etc. features of the spectator, and partly, on the environment of the colour complex including illumination, structure, material, spatial position and function. BIRKHOFF (1933) and EYSENCK (1941) were the first to attempt to formulate the elements of complexity in colour harmony.

However, no theory on colour harmony with a unified approach to components giving rise to a colour harmony sensation has been developed up to this day. Even the latest works regard it from a single aspect granting it absolute priority, neglecting the significance of complexity, and within it, possibilities of harmony inducing relations between colour and built space.

6.2. Colour Harmony Experiments

Before proceeding with the planned formulation of the concept of colour harmony from the aspect of environmental theory, it seemed advisable to check experimentally the published statements on fundamentals of colour harmonies. At the same time, it was necessary to determine whether colour harmony relations could not be expressed in a simpler way by using colour codes of the Coloroid colour system based on colour harmony intervals. To this aim, a multistage test series has been performed, involving a large number of observers. Selection of the observers, illumination of test sheets, observation geometries, and other conditions were the same as for other tests outlined in previous chapters. Test results were used to develop our theory of colour harmony (NEMCSICS, 1982, 1987).

6.2.1. Significance of the Aesthetically Uniform Scale

Our systematic colour harmony research had to be preceded by fundamental research to show whether Coloroid colour codes having an aesthetically uniform colour space are superior to Munsell or DIN colour codes applied by others for describing colour harmony relations. It had to be examined whether complexes created from aesthetically uniform scales are more harmonious than are those using other scales. To solve this problem, five tests were carried out using scales of uniformly varying lightnesses and saturations each composed of six colours of the same dominant wavelength. The colours were selected a) from the Coloroid colour system having aesthetically uniform lightness and saturation scales, b) the Munsell colour system with perceptionally uniform lightness and saturation scales, and c) the DIN colour system with lightness and saturation scales following some other relationships. Scales composed of colours of each of the three colour systems represented the following dominant wavelengths:

1. $\lambda =$ 572 – 574 nm, yellows
2. $\lambda =$ 602 – 610 nm, reds
3. $\lambda = (-502)$–(-509) nm, purples
4. $\lambda =$ 468 – 475 nm, blues
5. $\lambda =$ 520 – 530 nm. greens

Colours of the individual six-membered scales were assembled in compositions involving every colour four times. Care was taken to put colours at the same position in the scales in the same place in every composition. Compositions, in turn, were exempt from any distinguishable configuration, not to allow voting to be affected by formal differences of the compositions (Fig. 6.12).

Colours of all the five wave bands in the three colour systems were each assembled in a composition of identically varying lightness and identically varying saturation. Out of the total of 30 compositions, observers were always shown simultaneously compositions belonging to the three colour systems, but otherwise, of colours of the same wavelength,

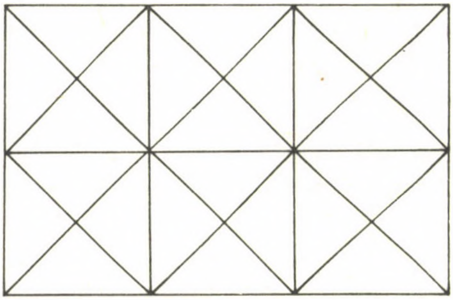


Fig. 6.12. Scheme of colour harmony compositions used in the tests containing 4 × 6 colours

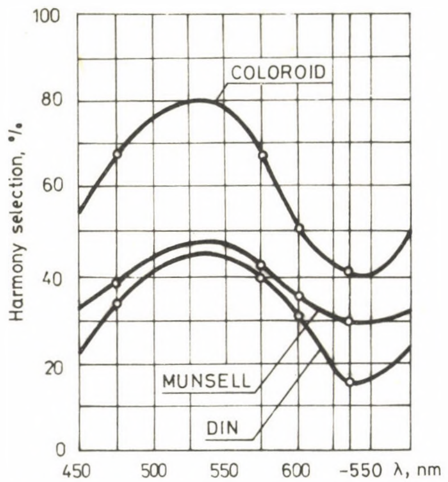


Fig. 6.13. Harmony content of lightness scales of different hues along the colour circle of Munsell, DIN and Coloroid colour systems. Horizontal axis shows dominant wavelengths for different hues, vertical axis the percentage of harmony selection

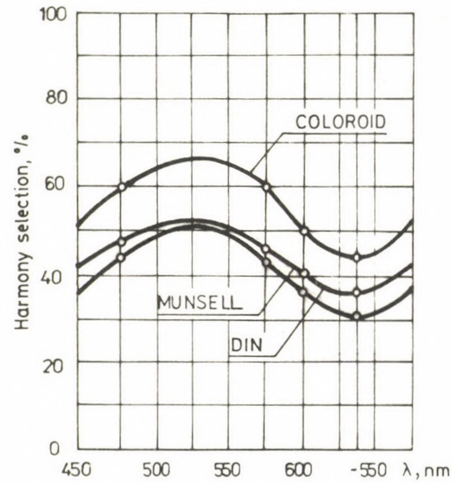


Fig. 6.14. Harmony contents of saturation scales of different hues of Munsell, DIN and Coloroid colour systems along the colour circle. Symbols on axes are the same as before

and varying according to the same colour perception parameters. Observers—university students of both sexes aged 20 to 23—were invited to arrange compositions according to the harmony sensation intensity elicited in them.

Test results obtained by processing 36 thousand data were plotted in Figs 6.13 and 6.14, showing respective harmony contents of lightness scales, and of saturation scales, of various hues of the three colour systems. Results have led to the following conclusions:

— Observers found aesthetically uniform Coloroid scales to be the most harmonious among both saturation and lightness scales.

— Test results supported our assumption that among possible colour systems, aesthetically uniform scales of the Coloroid colour system are best suited to form harmony complexes.

6.2.2. Significance of Ordering into Scales

Two test series have been made on the harmony creating potential of scalarness. Scalarness is that particular characteristic of a colour complex that makes it possible to arrange Coloroid saturation and lightness parameter values of its members into an arithmetic or geometric series.

The first test series examined, on the one hand, how much the degree of colour regularity affects the induction of harmony sensation, and on the other hand, the relative importance of scalarness and complementarity, the latter having been assumed in previous publications to be the most important harmony creating factor.

Just as in previous tests, observers were presented colour compositions of six colours each, of the same sizes and arrangements as before, and invited to arrange them in the order of intensities of the elicited harmony sensation. The twenty compositions were presented in sets of four. Composition comprised three colours each for every hue of the following pairs of hues:

Hue pair	Coloroid code	Dominant wavelength
1	$A52$–$A13$	$\lambda = 475.44$– 576.06 nm,
2	$A52$–$A30$	$\lambda = 475.44$– 602.72 nm,
3	$A52$–$A40$	$\lambda = 475.44$–(-502.69) nm,
4	$A52$–$A62$	$\lambda = 475.44$– 495.28 nm,
5	$A52$–$A72$	$\lambda = 475.44$– 555.96 nm.

Four compositions have been made for every pair of hues, differing only by colour arrangements in the Coloroid colour plane, as seen in Fig. 6.15. Horizontal lines represent equal lightnesses, vertical lines equal saturations. Expressing the degree of regularity in terms of the number of lines connecting colour loci in the Coloroid colour plane and let n be the number of colours in the complex, then members of the regularity scale below express the regularity within the colour plane of colours in a composition of six colours each for every pair of hues:

Composition no.:	1	2	3	4
Scale regularity:	1	n	$\frac{n^2}{4}+2$	$\frac{n(n-1)}{2}$.

Results are shown in Fig. 6.16. Clearly, the harmony level in compositions arranged of colours of pairs of different hue correlates with the regularity of the scales. Processing of results revealed the following relationships:

— The most regular scale proved to be the most harmonic one. With decreasing regularity, harmony diminished steeply.

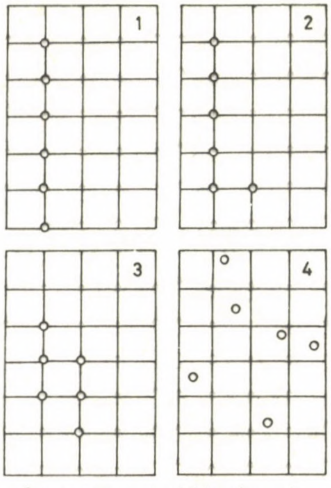


Fig. 6.15. Types of arrangement within the colour plane of colours of the same hue

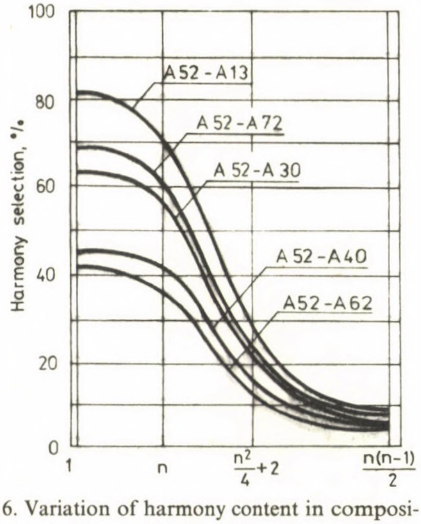


Fig. 6.16. Variation of harmony content in compositions made of colours of different hue pairs according to the regularity of scales

— Complementarity is not decisive in the induction of harmony sensation, but contributes to the intensification of the harmony sensation elicited by scalarness.
— Complementarity cannot elicit harmony sensation when lightness or saturation values of component colours are not ordered according to a scale.

In our second test series we wished to obtain information about the relative intensities of harmonic effects elicited by different scales of colours of different hues. Observers were presented compositions of six colours each, arranged as before. The hues were *A*11 ($\lambda = 572.64$ nm), *A*26 ($\lambda = 597.79$ nm), *A*40 ($\lambda = -502.69$ nm), *A*51 ($\lambda = 468.71$ nm), and *A*66 ($\lambda = 520.40$ nm). Four scales were selected from the colour planes of all five hues, such as:

type 1: colours of uniformly increasing saturations and equal lightnesses;
type 2: colours of uniformly increasing saturations and lightnesses;
type 3: colours of uniformly increasing lightnesses and equal saturations;
type 4: colours of uniformly decreasing saturations and uniformly increasing lightnesses.

In order to be of general application, scales were also described by the angle of rotation β from the horizontal saturation scale about the centre of gravity of Coloroid colour planes (Fig. 6.17). The twenty test compositions were presented to observers in groups of four, so that colours in a group had the same Coloroid hues. Compositions were ranked by 200 test persons aged 20 to 23. Results were plotted in Fig. 6.18, showing harmony content variation in different hue scales according to scale type. Processing the results has led to the following conclusions:

— Coloroid lightness is more important for harmony sensation than is Coloroid saturation.
— The most harmonic scales are those with concurrent Coloroid lightness and saturation variations.

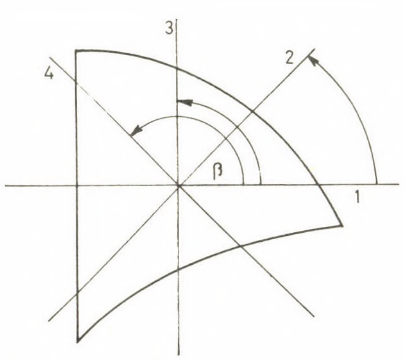


Fig. 6.17. Scale types (1 to 4) as a function of angle of rotation β from horizontal of straights bearing the scales in the colour plane

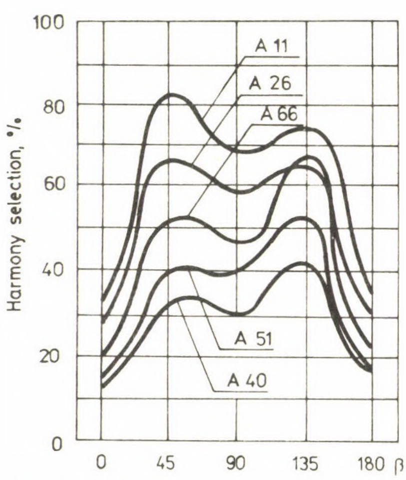


Fig. 6.18. Harmony content variation in scales of different hues with variation of the scale type. Horizontal axis shows angles enclosed by the straight line bearing the scale with the horizontal, vertical axis shows percentages of harmony content

— Scales with specifically light Coloroid hues and the same trend of variation for lightness and saturation are the more harmonic.
— Scales with specifically dark Coloroid hues and opposing lightness and saturation values are more harmonic.

A specifically light Coloroid hue is that with a dominant spectrum colour of tristimulus $Y=70$ to 100, while for a specifically dark Coloroid hue, $Y=3$ to 30.

6.2.3. Significance of Hue

To test the role of hue in harmony, observers were presented with compositions made of three colours each of different hue pairs in scalar relation, totaling six colours each. Formal arrangements of all the compositions were the same as before and identical for all compositions.

The test series included four tests, involving hue-pair compositions. One of the hues was kept constant and was *A*13, *A*35, *A*52, and *A*63, of dominant wavelengths $\lambda=576.06$ nm, $\lambda=-498.45$ nm, $\lambda=475.44$ nm, and $\lambda=498.45$ nm, respectively. In the first test, composition colours were used to make up scales of constant lightness and uniformly increasing saturations; in the second test, scales of uniformly increasing saturations and lightnesses; in the third test, equal saturations and uniformly increasing lightnesses; while in the fourth test, uniformly increasing lightnesses and decreasing saturations.

In each test, 24 compositions were presented in a definite set. Test process and the sets were the same in all the four tests, hence only one of them will be here described. The first step was to present observers three colour compositions of six colours of three hue pairs each. Hue pairs were: *A*13–*A*20, *A*13–*A*43, *A*13–*A*65. Observers were asked to rank compositions by the intensity of harmony sensation they felt. Harmony preference percentage for a composition was converted to a relative harmony preference value using Eq. (117), the maximum being 100. The result was considered as a reference harmony preference system.

Thereafter observers had to vote about members of three groups of compositions consisting of nine hue pairs each. Vote results were transformed to the reference system using Eqs. (119) and (120). The transformation axis was defined by the harmony preference for compositions sharing the reference system of the sets of compositions. In different steps of each test, 30 compositions were presented but only 24 of them were entirely different.

Results of the first test, harmony sensation intensities for compositions made with scales type 1 of hue pairs of Coloroid hue *A*13 with other hues, are shown in the circular diagram of Fig. 6.19. Results of the second, third and fourth tests are seen in Figs 6.20 to 6.22. Perimeters show Coloroid hues, radii preference percentages. Results have led to the following conclusions:

— Definitely, some hue pairs exhibit more harmony than others. A summary of test results established definitely harmonic and disharmonic hue relations (Fig. 6.23 where 0 is locus of the constant hue member of the reference harmony pair).
— Loci in the colour circle for colours in harmonic relation to the starting colour were found in or around fields containing similar and contrasting colours in Moon and Spencer's harmony scheme.

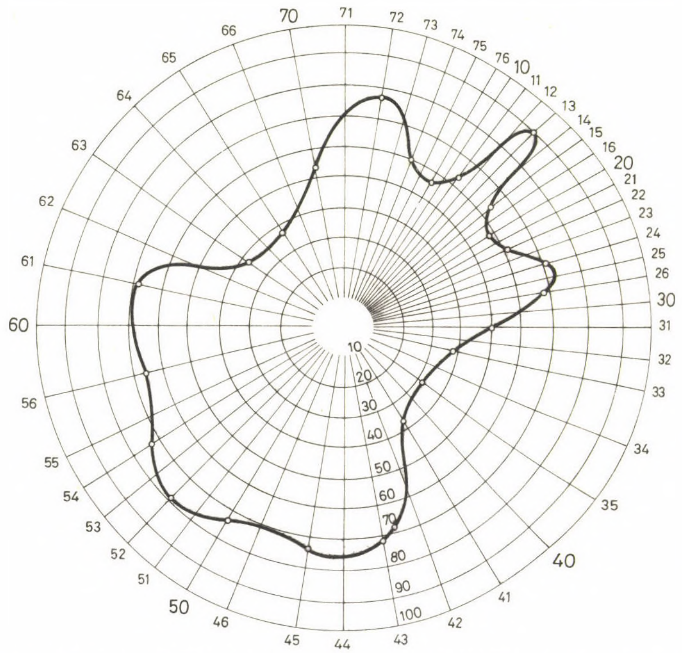


Fig. 6.19. Magnitude of harmony content in compositions made of scales type 1 of hue pairs of Coloroid hue *A*13 and other Coloroid hues. Hues are shown along the perimeter, frequency of harmony selection on the radius of the circular diagram

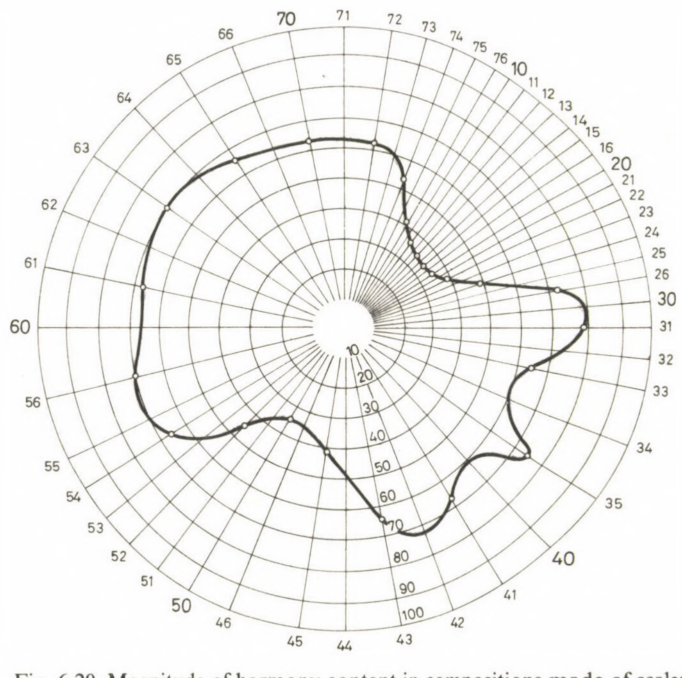


Fig. 6.20. Magnitude of harmony content in compositions made of scales type 2 of hue pairs of Coloroid hue *A*35 and other Coloroid hues

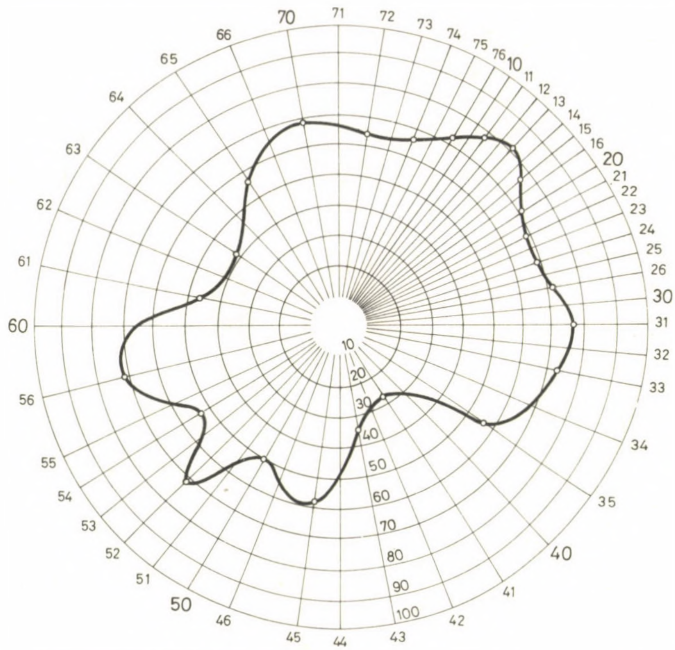


Fig. 6.21. Magnitude of harmony content in compositions made of scales type 3 of hue pairs of Coloroid hue *A*52 with other Coloroid hues

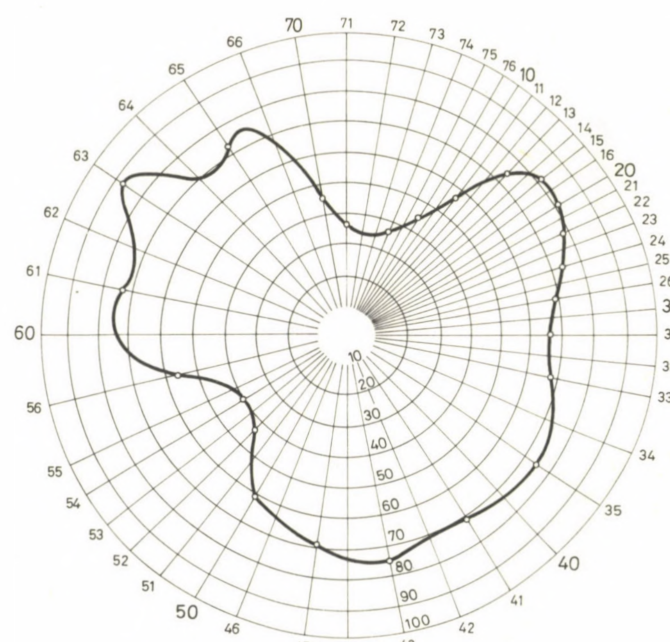


Fig. 6.22. Magnitude of harmony content in compositions made of scales type 4 of hue pairs of Coloroid hue *A*63 with other Coloroid hues

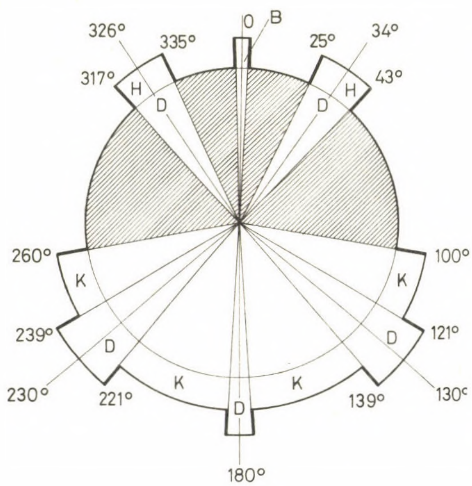


Fig. 6.23. Harmony conditions of the hue scale based on NEMCSICS's tests. The circle represents the hue scale of the Coloroid colour system. Zero can be set to any hue. Shaded areas refer to colours indifferent for the induction of colour harmony sensation. Other symbols: B identical colours, H similar colours, K contrasting colours, D colours most likely to affect harmony sensation

— In conformity with tetradic and triadic harmony relations, a higher preference was found for certain harmony relations of the colour circle. Colours forming a triad with a colour are each found in colour planes of the Coloroid colour solid deflected at 130°, 230° from the colour scale of the given colour as a mean. Colours forming a tetrad with a colour each are in or near the colour planes of the Coloroid colour solid deflected at 34°, 130°, 230° or 130°, 230°, 326° from the plane of the given colour as a mean (See Table 7 in Annex).

6.2.4. Significance of Preference

Compositions similar to those above were prepared from scales containing six colours of different hues each. Compositions met harmony requirements defined earlier and were presented to fifty observers in three age groups of 15, 25, and 50 years.

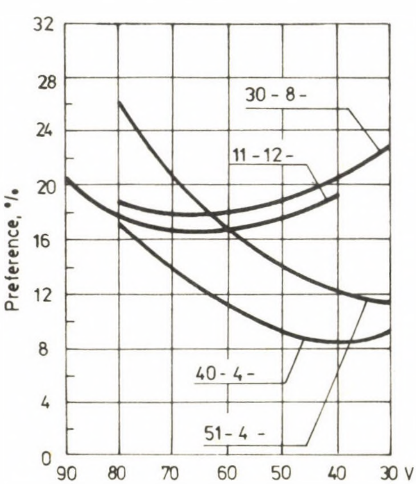
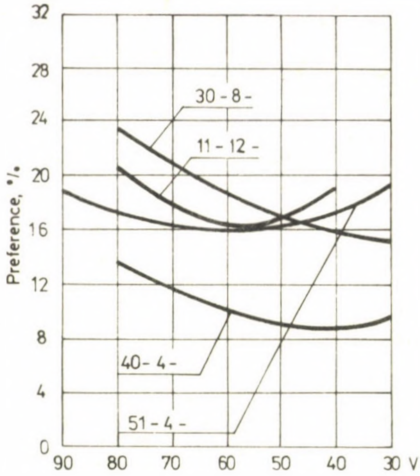


Fig. 6.24. Preference indices expressing colour preferences of boys aged 15 for members of scales of colours of equal hues and saturations but different lightnesses. Horizontal axis shows Coloroid lightnesses, vertical axis shows colour preference indices

Fig. 6.25. Preference indices expressing colour preferences of men aged 25 for members of scales of colours of equal hues and saturations but different lightnesses. Axis notations are the same as in Fig. 6.24



Test subjects were called upon to rank compositions by harmonies. After evaluating the results, we found that composition rankings in different age groups were closely related to preferences for the colours in the compositions. Boys aged 15 found the composition based on hue *A*30 the most harmonic. According to colour preference index number system defined earlier, for them, colours of this very composition received the highest rating, also as an average, compared to the other compositions. In contrast, men aged 25 had given the colours in the composition of hue *A*30 the highest mean average preference, nevertheless they found the composition containing colours of hue *A*11 to be the most harmonic, since colours in this composition—although preferred only by 17.45% as against the former 18.57% as an average—were more uniformly preferred than the others. According to men aged 50, composition of colours with a hue *A*11 was the most harmonic. Note, that these colours obtained the least differing colour preference indices (Figs 6.24 to 6.27).

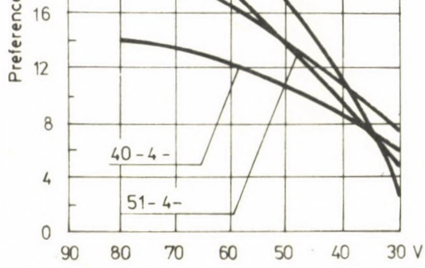


Fig. 6.26. Preference indices expressing colour preferences of men aged 50 for members of scales of colours of equal hues and saturations but different lightnesses. Axis notations are the same as in Fig. 6.24

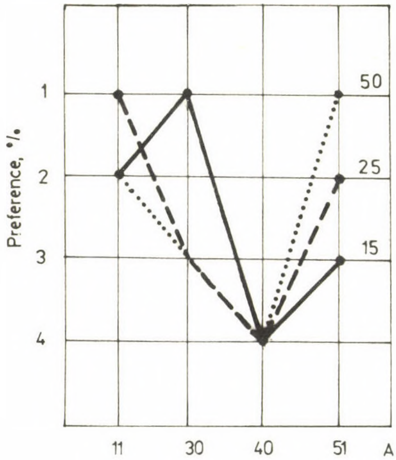


Fig. 6.27. Compositions of scales of different hues ranked according to harmoniousness by men aged 15, 25 and 50. Horizontal axis shows hues, vertical axis shows gradation. Points connected by lines mean harmony selections by people of the same age as indicated

Compositions were ranked by different age groups as:

	Aged		
Ranked	15	25	50
First	*A*30	*A*11	*A*51
Second	*A*11	*A*51	*A*11
Third	*A*51	*A*30	*A*30
Fourth	*A*40	*A*40	*A*40

Results have led to the following conclusions:

— Perception of harmony sensation requires an average level of preference.

— Perception of harmony sensation requires small differences between preference indices of colours in the complex.

— Preference index of every colour in the complex has to reach a certain level.

6.3. The Concept of Colour Harmony in Environment Theory

Colour-bearing surfaces of our built environment have colours of different hues, saturations and lightnesses. In other words, they are perceived, and act in shaping the space as a complex, in interaction, rather than by themselves. The role of various colour sensations in modifying distance perception or expressing function can be discussed independently only theoretically; in a real space, space sensations are always formed by colour harmony complexes. Therefore the regularities ordering our colour perceptions to a harmony complex i.e. the content of the concept of colour harmony are problems of prime importance.

Surface colours of built space are important factors in the development of space sensation. The content of space sensation can be deduced from two components: space perception and its relation to the function of the real space. Colour perceptions are present in both components as harmony complexes. Correlations ordering our colour perceptions to harmony complexes represent the content of the concept of harmony. Content of correlations affecting the harmony generates different levels of generalization. In this chapter three superimposed levels of the content of colour harmony will be discussed. The first level is closely related to colour perception. It involves relations valid for most people since they depend on the process of colour perception and can be explained by psychophysical relations. The second level involves the effect of the perceived colour complex on the observer's psyché. At this level, appreciation is affected by psychic, somatic, age, cultural, social features of the observer. The third level of the colour harmony purport is complex interaction between colour, man and environment. Thus, appreciation of harmony sensation depends on the environment of the colour complex, involving light, structure, material, but also spatial position and function. Colour harmony is always directly related to the aesthetic function of the environment.

6.3.1. Levels of the Formation of Colour Harmony Sensation

Content of the colour harmony sensation has several components such as colours of the complex, environment containing these colours, and man living in this environment and perceiving these colours. This relation is the more general, the more numerous are people for whom the same situation gives rise to the same harmony sensation. Depending on the general applicability of this harmony content, different levels of this content can be identified (Fig. 6.28).

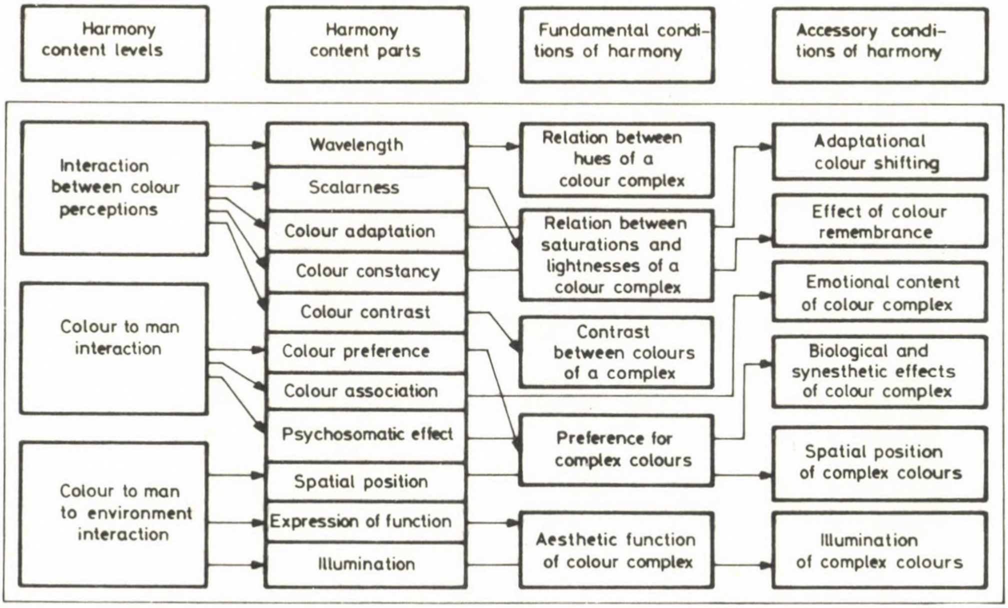


Fig. 6.28. Contents of the concept of colour harmony. Conditions of colour harmony sensation

Relations between colour perceptions
The content of colour harmony has three superimposed levels. One is perception, involving relations basically identical for everybody, since mainly resulting from the process of colour perception, and can be explained by fundamental psychophysical events. These relations express interactions between colour perceptions which can be described, in turn, in terms of relations between colour perception parameters: hues, saturations, and lightnesses of harmonizing colours. These relations lend names to the harmony types such as complementary harmony, triadic harmony, scale of equal saturations and others.

Relations between colour complexes and man
The second level of the colour harmony content involves the psychosomatic effects of the perceived colour complex on the perceiver. A proper relation between colour perception parameters in a certain colour complex does not elicit a harmony sensation in everybody. This sensation depends on the observer's age, sex, nationality, culture—and also on associations, and even, on psychosomatic effects elicited by the colours.

Relations between colour complexes, man, and environment
Perception of any colour complex, and harmony sensation resulting from it much depend on the spatial position of colours in the complex, their relative areas, illumination intensity, spectral power distribution of the light source, and direction of illumination, as well as on the environment function to be expressed by it, or simply, the function of the affected environment. These relations, the interaction between colour, man and environment, are the third level of the harmony content.

6.3.2. Components of the Content of Colour Harmony Sensations

Contents of colour harmony represent different levels, differently affecting the development of harmony sensations.

Wavelength
Colour formulations in everyday practice refer to harmony or disharmony of different hues, to statements such as: blue is seldom pleasant with green, but mostly it is so with yellow, forming a harmonic pair. Millennia of fine arts call our attention to the experience that certain hue combinations are more aesthetic than others. Harmony relations between hues can be primarily expressed by relations between dominant wavelengths of radiations eliciting colour perceptions. These relationships may be explained by the mechanism of colour perception, supported by recent countercolour theories.

Scalarness
In architecture it has been known for a long time that certain proportions between dimensions of space elements or their parts are more aesthetic than others. Such proportions have been deduced in Antiquity from the Pythagorean golden section. Similarly, the most essential factor of colour harmony is proportionality between colour parameters saturation and lightness, and a scalar relation between members of the colour

complex. Scalar is a relation where Coloroid saturation and lightness parameters of colours in the complex constitute a uniformly increasing or decreasing series. Scalarness expresses a regular relation between colour stimulus and colour perception. For instance, colour perceptions of a uniformly decreasing lightness scale are elicited by quadratically decreasing colour stimuli—approximating to the golden section.

Colour adaptation

It is known from experience that in a colour space which at the first sight looks pleasant after looking around for a few minutes, the harmony sensation raised often changes to the unpleasant. Or else, an impression not too pleasant at the first sight changes gradually to a harmonious experience. Eyes adapt themselves to the prevailing colour of the space; consequently, colour bearing surfaces seem to have changed their colours as compared with the first impression. This phenomenon follows from the mechanism of colour vision. It arises also in looking at the colour harmony of a planar surface, e.g. of a picture. Our sensing mechanism reacts on the same stimulus by a colour perception modified by the effect of the surroundings. This change has a different magnitude and tendency in every colour domain.

Colour constancy

Harmony sensation elicited by a planar composition or the complex of colour-bearing surfaces in the built space is not exclusively due to the harmony between colour qualities perceived. Colour appreciation cannot be dissociated from earlier memories imprinted by colour-bearing surfaces of particular forms. Perception elicited by a stimulus reaching the eyes from the surface is subjected to the modifying effect of remembrance. Since only some often encountered colour-bearing surfaces are remembered, this process sometimes markedly affects the development of harmony sensation, while on other occasions only negligibly.

Colour contrast

Only colour complexes with a contrast relation between at least one of hue, saturation or lightness parameters of its members are felt as harmonic. Magnitude and character of the contrast relation affect emotional message of the harmony. Lightness contrast has a rather dynamic and obvious message, while saturation and hue contrasts suit more subtle, emotional messages. There exists also a contrast relation between surface areas of harmonizing colours. Smaller areas are needed and sufficient from more intensive, more saturated colours to create harmonic units with adjacent duller surfaces.

Colour preference

Murals and fabrics of the early Middle Ages often exhibit colour complexes of English red, sienna and ultramarine colours generously applied also in plain colours. In contrast, Baroque buildings often displayed French gray, Sèvres green, Rosroside, palace yellow, and Medici blue. The early Middle Ages had colour harmonies different from those in Late Baroque. Preference for complexes of saturated, dark, warm shades were replaced for those of lighter, rather dull, cooler colours. Numerical values of colour parameters of complexes show regular relations in both periods, albeit quite different ones. Youth prefers colours different from those preferred by elderly people, and accepts different complexes as harmonic. Development of harmony sensation also depends on the preference for colours in the complex.

Colour association
Sight of some colour complexes raises emotional and conceptual messages. If an emotional message is unambiguously expressed by the colour complex then it is felt to be pleasant, expressive, harmonic. Otherwise, no harmony sensation is likely to be induced.

Psychosomatic effect
Red, orange raise blood pressure, yellow increases gastric juice secretion, blue and green attenuate the activity of the nervous system. Sensitivity to these colour effects and the like varies with the individual. Colour complexes with some people exert harmful biological effects, seem unpleasant in a room, raise antipathy, and the complex is felt to be unpleasant, disharmonic. In this case, aesthetic judgement is influenced by physiological factors.

Position in space
Some colours are not equally welcome on all colour-bearing surfaces of the environment. For instance, a light cobalt blue is less pleasant on the floor than on the wall, pink is unpleasant on the ceiling but acceptable as a pullover. Colour harmony sensation is affected or even impeded by ignoring experiences of this kind in deciding on surface colours.

Expression of function
Primrose yellow, cadmium red and Mitis green in a complex of uniformly decreasing lightness and saturation expresses exultant merriness. It is felt to be harmonic on the beach, in a circus or a bar, but in an office or medical consulting room we feel it to be disturbing, disharmonic. Emotional message of the colour complex in a room cannot be contrarious to its function. If the colour complex expresses the function of the space, the satisfaction of recognition adds to the aesthetic value of the colour complex.

Illumination
Intensity of a harmony sensation elicited by a colour complex also depends on its illumination. Depending on intensity, quality and direction of illumination, one and the same coloured surface may appear in different colours. Variable illumination may alter the individual colours in different ways changing thereby the aesthetic content of the complex.

6.3.3. Basic Conditions for the Development of Colour Harmony Sensations

Five among the factors contributing to harmony purports may be considered as fundamental and indispensable for the aesthetic content of a colour complex.

Relation between saturations and lightnesses in a colour complex
Based on tests outlined in the preceding subchapter we may state, that the fundamental condition of colour harmony is a scalar relation between saturations and lightnesses in the colour complex. The type of harmony depends on the character of these scales. A scale of lightnesses and decreasing saturations is a harmony complex with extremely fine,

almost decadent message, safe from emotional outbursts. Dark varieties of this scale suggest the thought of death, its light varieties were applied in Classicism. A scale of colours of equal saturation and decreasing lightnesses is somewhat coarse, but very dynamic, and is frequent in our age. Saturation and lightness scales varying in the same sense or in the opposite sense express richer, more definite and more vigorous messages than the former ones. Beyond these four fundamental scales, harmony relations are borne out by so-called boundary scales consisting of members containing white or black in varying proportions.

Relation between hues of the colour complex
One component of space perception is the visual appearance of material surfaces, in which hue is an essential factor. Relation between hues of the colour complex is determinant for the kind of colour harmony, distinguished as isochrome, group-wise, complementary, triadic and tetradic. The simplest and the most current ones are isochrome and group harmonies, preferred in this age, but also complementarity is known to be of importance for the harmony sensation. Its aesthetic significance makes it to excel among other hue relations, but it has no primary importance over other harmony contents as had been long believed. Triadic and tetradic relations are less important than is complementarity. Complementary harmonies are full of tension. Triadic and tetradic harmonies are less tense and richer than are complementary ones, and hold manifold messages.

Contrast relations between colours of a complex
Hue, saturation and lightness contrasts are fundamental conditions of harmony. Any form of the scalar relations above comprises one or more of these contrasts, but also quantity and quality contrast in the harmony complex are of importance. The message of the complex is affected by relative surface areas and surface appearances of the colours involved. Surface appearance includes texture and whether it is polished or lustreless.

Preference for colours in the complex
Essential determinants of preference for a colour complex are cultural and ethnic background, the surrounding landscape as well as sex and age of the subject. Beyond that, preference may also depend on physical and mental condition, or illness.

Aesthetic function of the colour complex
Harmony complex is a product with an aesthetic content, and as such, an elementary work of art. If it is present in the built space as the inducer of space sensation, it has to express utility and informative functions of space and its elements.

6.3.4. Accessory Conditions of the Development of Colour Harmony Sensations

The following conditions are not indispensable for harmony sensation, although when present, they help to generate it, and enhance the aesthetic value of the complex. Harmony sensation has six accessory conditions.

Colour shifting by adaptation
Adaptation permits the appreciation equally of a harmonic colour complex in spite of the slowly changing light conditions in different times of the day. Otherwise, since light intensity conditions are varying from minute to minute, this would prevent creation of harmony complexes for other than instantaneous light conditions and making the aesthetic content undefinable. Owing to adaptation, after a few minutes of looking at yellowish green, orange, red and purple, colour perceptions are shifted towards yellow, while green, bluish green and violet shift toward blue. Also the perception of saturation is much modified by adaptation.

Effect of colour remembrance
Colour remembrance elicits primarily the phenomenon of colour constancy. It modifies colours or well-known forms in space, and its effect can be eliminated only if the colour in the complex much differs from that remembered. Colour harmony sensation also affected by custom. The more habitual a complex, the more harmonic is it felt to be.

Emotional message of the colour complex
Under otherwise identical conditions, the complex with the more definite emotional message is felt to be more harmonic. Colour symbol systems in various ages consisted of harmony relations with emotional messages.

Biological and synesthetic effects of colour complexes
Under identical basic conditions, colour complexes with more favourable biological effects, and those suiting to elicit synthesis with another sensory organ, usually, with hearing, are felt to be more harmonious.

Spatial position of colours in the complex
Harmony sensation is also affected by which members of the complex are situated on a horizontal and which on a vertical surface, above or below the observer's horizon, nearer to, or farther from, the observer. Harmony development is also affected by articulation and shape of the colour-bearing surface.

Illumination of the colours of the complex
Variation of light intensity modifies saturation perception, that may reduce, in turn, the aesthetic content of the colour complex. If a harmony complex is devised under illumination by a light source of other than continuous spectral energy emission, spectral energy distribution of the light source to be used has to be reduced, since the aesthetic content of the complex unfolds only in a light of similar energy distribution. Oranges, yellows and reds are felt in back-light to be less saturated, and so are blues and greens in full light. Harmony sensation best arises in a built environment provided with diffuse illumination.

6.4. Kinds of Colour Harmony

Harmonic colour complexes may be classified according to relations between parameters of the composing colours. Depending on whether colours in the complex belong to one, two, three, four or more different hues, monochrome, dichrome, trichrome, tetrachrome, or polychrome harmonies are spoken of. If there is a preferential relation between hues sharing the harmony, there is a diadic harmony, involving complementary, triadic and tetradic harmonies. There is a preference for a relation, where in case of complementaries, the two hues are at 180° in the Coloroid colour circle, while for triadic harmonies, three hues are at 130° and 230°, for tetradic harmonies, four hues at 34°, 130° and 230°, or at 130°, 230° and 326° from zero.

Every kind of colour harmony comprises several harmony scales. Colour complexes where numerical values of saturation or lightness parameters or both of the component colours form arithmetic or geometric series are called scales. Consequently, harmonizing colours have spatial loci in the Coloroid colour solid on straights, regular curves, or in simple geometric figures. Emotional value of harmony complexes is defined primarily by the relation between hues of the component colours, i.e. by the kind of harmony, while its dynamism by the scale type. Magnitude of harmony content in colour complexes depends on the regularity of colours in the complex. More regular complexes are more harmonious.

6.4.1. Monochrome Harmonies

For the simplest type of colour harmony complexes, members have the same Coloroid hue. For these monochrome harmony complexes, colour points of all the colours lie in the same Coloroid section. Colours of the same hue harmonize if numerical values of saturations and of lightnesses are in a regular relation, mostly forming arithmetical or geometrical series. This requirement not only applies to monochrome harmonies but is also valid for any kind of harmony.

Monochrome harmonies mostly have a definite emotional message conveyed by associations linked to the common hue of members of the harmony complex. This message is nuanced, and is given more dynamism or restraint by correlations between colour saturations and lightnesses, i.e. by the scale type formed by members of the colour complex. Let us consider the most typical scales.

Figures C61 to C63 show the same spot-like still life. Each of them was painted using five tones of Coloroid orange hue *A*20. Colour points for colours in Fig. C61 are equidistant on the straight line for saturation *T*12 parallel to the achromatic axis. Thus, colours in the still life have two parameters in common, those for hue and saturation; lightness parameters follow an arithmetic series. Since the scale is near the achromatic axis, it hardly shares the emotional effect of orange, but still makes a warm, sunny impression. Lightness scales are simple but always dynamic, and used often in our age.

Colours of the still life in Fig. C62 are of the same lightness but of different saturations. Colours are equidistant on the normal to the achromatic axis for lightness *V*70 in the Coloroid section. Every colour of the still life has the same hue and lightness, while saturations increase according to an arithmetic series. Such compositions are extremely fine, almost decadent. Even so, the subdued fire and light of orange transpires in this composition. Colour complexes of such a composition are called saturation scales.

Colours of the next still life (Fig. C63) have only the hue parameter in common, both saturations and lightnesses increase according to an arithmetic series. Colour points are equidistant along a skew line of the Coloroid section. Colour complexes comprising such scales are able to transmit rich, definite messages.

Beyond those detailed above, still many other scales are conceivable, differing slightly by their messages. Loci of members of Coloroid hue *A*66 of a scale of decreasing lightnesses and increasing saturations in the colour plane are seen in Fig. 6.29. If the numerical value of one parameter of scale colours varies according to arithmetic series, and that of the other according to geometric series, then colour points for scale members will lie on curves rather than on straights. Such are scales in Figs 6.30 to 6.33. Scales for Figs 6.30 and 6.31 are called boundary scales since their members lie on the boundary of the half-plane section of the colour solid containing surface colours. Scales in Fig. 6.30 are always fresh, give a clean impression, while scales in Fig. 6.31 have only colour and black content. Composing of colour scales has already been discussed in Chapter 3. Parameters of any member of a scale forming an arithmetical series is obtained from the

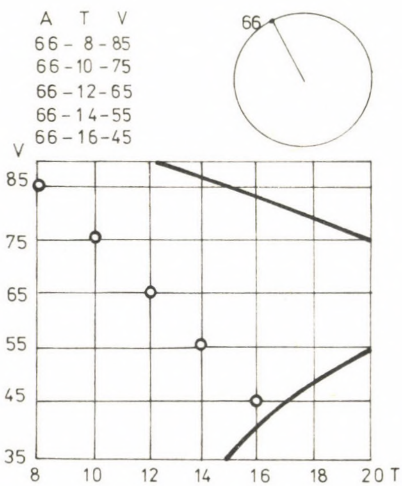


Fig. 6.29. Monochrome harmony

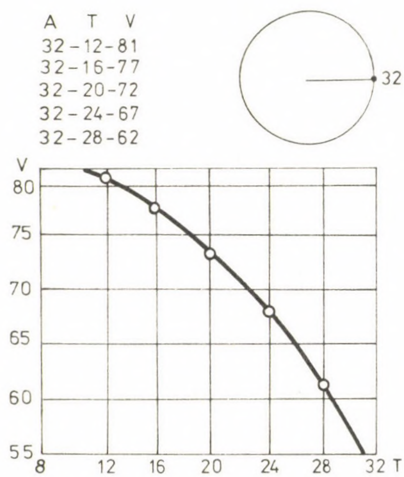


Fig. 6.30. Monochrome harmony

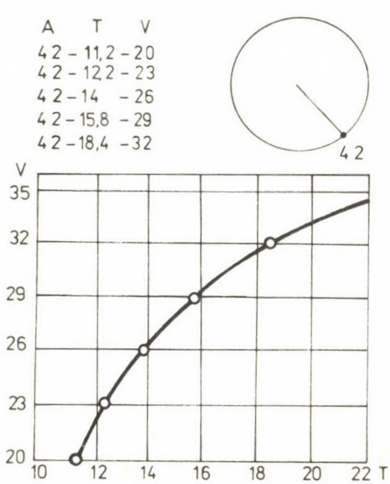


Fig. 6.31. Monochrome harmony

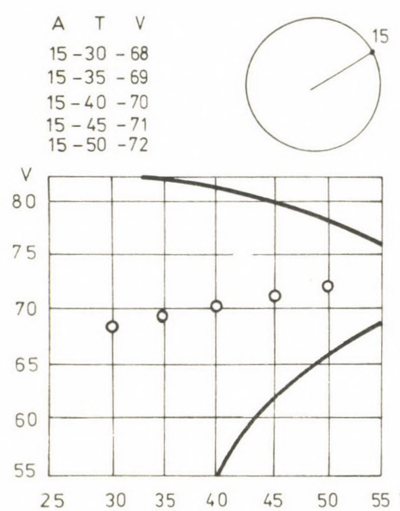
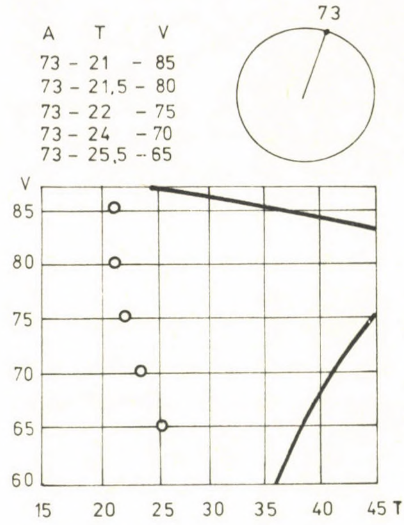


Fig. 6.32. Monochrome harmony

Fig. 6.33. Monochrome harmony



first term and the interval as:

$$a_n = a_1 + (n-1)d. \tag{123}$$

Any member of a geometric series is obtained from the first term and the quotient q as:

$$a_n = a_1 q^{n-1}. \tag{124}$$

In everyday practice, mostly duplicates or other variations of the described scales are encountered (Figs 6.32, 6.33). In this case colour points for scale members are on simple geometric figures in the given Coloroid colour plane. Colours for Figs C64 to C67 have been selected from the colour plane for Coloroid red *A*31. Four colours of the composition in Fig. C64 are colours common between two lightness scales and two boundary scales. This composition is light, fresh and vigorous. The composition in Fig. C65 comprises eight colours taken from two lightness scales; one of them has colours near the achromatic axis, the other has more saturated ones. This composition is richer, and somewhat more intensive but less fresh than the former.

Figure C66 has been composed of seven colours. Colours are those of a saturation scale and of a scale with members having saturation and lightness codes increasing according to arithmetical series. One colour of the composition is present in both scales. It gives a refined, delicate impression. Composition in Fig. C67 makes a much more vigorous but still rich effect. Eight colours of the composition are members of a dark boundary scale and of a scale parallel to it. Saturation values of the composition colours vary according to arithmetical series, and lightness values according to geometrical series.

6.4.2. Dichrome Harmonies

Harmony complexes where colours belong to two different hues are dichrome harmonies. Among them complementary harmonies have an outstanding importance by being harmony groups most saturated with tension. They always have a definite emotional message, pointed out be referring to the opposite of this message. They are dynamic and manifold.

Figures C68 to C71 show spotlike still lifes like those before. Colours of composition in Fig. C68 are complementaries *A*20 and *A*54, of uniformly increasing lightnesses and saturations. This composition is built up on a tense balance between cold and warm colours. Composition in Fig. C69 is definitely cold due to greenish blue varieties of hue *A*56 enlivened by brown arabesques, low-saturant varieties of orange red of hue *A*25. Composition colours belong to two lightness scales near the achromatic axis. Lightness scales are not continuous but are divided into dark and light parts. The duller scale exhibits a wider, the less dull, a smaller gap. A peculiar, unbalanced group of harmony complexes is that of deficient scales such as that for the still life in Fig. C70. Composition hues are at 130° in the Coloroid colour circle. This hue relation always excels as aesthetic. Colours in this composition form a deficient saturation scale belonging to two lightnesses.

Composition in Fig. C71 is rather balanced, of somewhat concealed dynamism. Its colours form two scales of oppositely varying saturations and lightnesses. Colours in Figs C72 and C73 have complementary hues *A*11–*A*51. This complementary hue pair combines the most intensive lightness contrast to the highest dynamism. Composition in Fig. C72 is clean, intense, and dynamic. Colours belong to a lightness scale and to a scale of colours of uniformly increasing saturations and lightnesses. Intervals of this latter scale vary according to the rules of golden section. The more colours that are present in a complex, the more of scalar relations have to exist between its members. An example is the composition of twelve colours in Fig. C73. These complexes are always emotionally nuanced and manifold. Also composition in Fig. C74 comprises colours of complementary hues, belonging to two lightness scales. Multiple relations are illustrated in the explanatory drawing to this figure.

6.4.3. Trichrome Harmonies

Trichrome harmonies are more varied than are dichrome ones but less unambiguous in mood. Colours are selected from three different hues. Among them, triadic compositions are most noteworthy. In these compositions, hues are at about 34°–130°, at 130°–230°, or at 230°–326° in the Coloroid colour circle. The complex in Fig. C75 is a regular triadic composition, with colours arranged in a scale of uniformly increasing saturations and lightnesses, but differs from the previous ones by involving two or even three colours at some of its colour points, indicated by small concentric circles in the explanatory drawing. Hues in the complex of the next figure (C76) are no longer in triadic relation. Numerical values of both saturations and lightnesses form an arithmetical series. This composition is harmonically regular but not too exciting. Composition in Fig. C77 has more emotional content. Its hues are in a semilateral triadic relation and colours belong to two lightness scales.

Compositions in Figs C78 to C80 comprise colours of hues *A*35, *A*53, *A*72 in a regular triadic relation. Compositions differ by different regularity degrees of colour scales. Colours in Fig. C78 follow three lightness scales with gaps. This composition is felt to be somewhat gaudy. This feeling disappears when looking at the composition in Fig. C79, in spite of its more intensive, more contrasting colours compared to those in the previous composition. Composition scales are again lightness scales but they are uniform, and equidistant within each scale. Composition in Fig. C80 is enigmatically ambiguous. Its colours may be arranged both in lightness scales and in scales of uniformly varying saturations and lightnesses. They are of low saturation and in a perfectly ordered relation.

A special type of trichrome harmonies is seen in Fig. C81. Two of the hues are rather close in the Coloroid colour circle, while the third one is at 34°, preferential for its harmony content. Such a complex is usually called group harmony. Its nine composing colours belong to two lightness scales with different intervals. This composition has a definite emotional message.

6.4.4. Tetrachrome Harmonies

Tetrachrome harmonies include, so to say, the entire the colour circle, hence they are rather variegated. Among them, tetradic harmonies are of special importance, with hues at 34°, 130°, 230°, or at 130°, 230°, 326°. They are sophisticated and require the utmost care to produce if every hue in the composition is represented by a single colour, such as those in Figs C82 to C84. Composition hues in Figs C82 and C83 are in a regular tetrachrome, and those in Fig. C84, in a special tetradic relation. Saturation parameters of colours in the first two figures are definitely scalar, and so are lightness parameters of colours in the third figure.

Again, Figs C85 and C86 show still lifes. The former is balanced, dynamized only by lightness contrast. Saturations of colours in the picture are within a rather narrow range and also hues balance each other. Still life in Fig. C85 is less balanced without being more dynamic. Hues are not integrated within the colour system of the picture, essentially due to unfavourable relative deflections within the colour circle, since all four hues are in the same half of the colour circle. Although the lightness scale of the composition has five intervals, the saturation scale has only three members. The most exciting and most dynamic composition is that in Fig. C86, with tetradic hue relations. Its scales are almost parallel, with increasing saturation and lightness. There is not only a lightness contrast but also an intensive saturation contrast.

Colours of every composition in the concluding series, Figs C88 to C91 belong to two hues of two complementary pairs each. Colours in all the four figures have hues of complementary pairs *A*11–*A*51 and *A*33–*A*61. Essential differences between compositions are due to scale differences. Composition in Fig. C88 is the most balanced one; its colours are arranged in two parallel scales. Composition in Fig. C89 is more turbulent, with less emotional message. Its scales are of different kinds and less ordered. There is little order among scale members in Fig. C90. In spite of its strong colours, the composition is without a definite message and looks gaudy. Scales of the last composition (Fig. C91) are again more orderly. The composition itself makes a sombre effect, still enhanced by yellow flashes.

6.4.5. Polychrome Harmonies

In everyday practice, polychrome is called a colour complex when colours from more than one hue domain, but in the theory of colour harmony mostly compositions with more than four hues are called polychrome. Here the latter interpretation will be used.

Polychrome complexes in this meaning are infrequent in environment design but current in painting. But even this polychromy may mostly be reduced to the basic situations discussed above. That is to say, polychrome complexes are only felt to be beautiful and harmonic if hues in the complex form groups. Now, extreme members of a hue group may be deflected by max. 6° to 8° within the colour circle. Polychrome complexes generally comprise a maximum of four hue groups each. A complex of more than four hues about equidistant on the colour circle will result in a gaudy composition.

In this chapter only the fundamental trends of colour harmony relations could be touched on. They are to be expounded in more detail in a monograph on colour harmonies, now being written.

7. The Practice of Colour Dynamic Design

This last chapter has been devoted to methods and stages of colour dynamic design, the ways and means of applying previously discussed relations between colour–man–environment in different phases of design. A general method of colour dynamic design will first be described, then stages of colour dynamic design for two different complexes—a residential district and a plant—will be considered; the chapter concludes with some ideas on the design of establishments of different functions.

7.1. General Methods of Design

As in any design activity, environment colour design is a conflict between possibilities, complex requirements, and artistic endeavours. This conflict may take different courses depending on the designer's abilities and personality. That is why in the following no design recipes will be given but a method outlined, which permits both the given possibilities and demands to be taken into account. For the sake of clarity, the design process has been divided into steps.

7.1.1. Data Recording

The first step is to collect data of importance for designing the complex. There are four groups of data to be gathered, such as i) architectural features of the building and its surroundings, ii) functional data on activities inside the building, iii) human data on users of the building, and iv) illumination features including orientation and the illumination system of the building. Every group of features has several subgroups (Fig. 7.1).

Among architectural features, first the surrounding landscape has to be mentioned. Colour demands differ between buildings in a plain, a mountainous landscape, in one with rich vegetation, or in a barren landscape, but colour demand also depends on climatic features, daily average temperature, yearly average hours of sunshine, and dry or rainy climate. It is important to know the siting of the building complex to be colour designed, the surrounding development density and rise, functions of neighbouring buildings; whether it is in a residential area, in an industrial surrounding, or finally, in a recreation area. The surrounding system of development has to be known, since colour selection for a stricter system requires a stricter harmony structure (Fig. 7.2).

Structural features, formal and style marks of the building have to be defined. Hard lines require definite colour combinations; mild forms allow more shaded saturation combinations. Colour selection is also affected by the relation between units in the complex, whether there is a sequence of spaces of similar dimensions or with important volume differences. If, in a space, the volume density of objects is high, duller colours are needed, otherwise more saturated colours are advisable. The relation between spaces subject to colour design and their nearer or farther environment must be examined. This relation may be only functional, only visual, or both. Colour assortments of possible building materials, claddings, wallpapers, rugs, upholstery materials, inherent colours of some building technology should be collected.

The second category of design data comprises functional features, among them, activities inside the building; for instance, education, medical treatment, amusement, handicraft, whether the activity involves objects or only persons, directions of activity, flow of people, and other pertinent factors.

First of all, the exact function of the building must be defined together with sequence of rooms according to activities, within each room the pathways of technology must be established. Distinction should be made between units and rooms primarily determinant for the function of the establishment, auxiliary rooms directly helping functions, and parts having little to do with the essential function of the establishment (Fig. 7.3).

The likely functionally determined environmental effects on occupants of the establishment, should be examined. The temperature conditions, level and kind of noise, relative humidity, and perhaps odours should be established. Colour associations expressing function of the establishment and compensating environmental effects have to be determined. Colour combinations have to be found so as to express the utility function. Informative colours of the establishment, labour safety colour requirements, assortment of the necessary colour signals, domains of surrounding colours depending on the colour of workpieces have to be defined.

The third group of design data—that of the so-called human aspects—relates to the occupants of the building. Those working in each room have to be counted according to sex, age, qualification, skill, health condition, psychical constitution. Allotment of sq.m per capita and cu.m per capita have to be determined for every room submitted to colour design. Average colour demands of the occupants have to be determined mainly

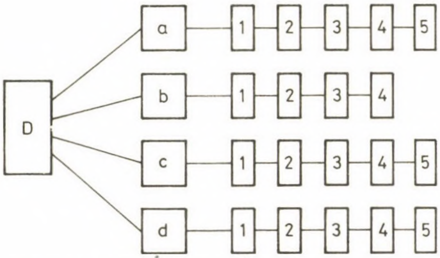


Fig. 7.1. Scheme of steps in the phase of data recording. a) Architectural features: 1. landscape, 2. developed surrounding, 3. architecture, 4. relation to the environment, 5. building materials; b) functional features: 1. activities, 2. environmental effects, 3. colour associations expressing function, 4. colour features; c) human aspects: 1. sex, 2. age, 3. number of persons, 4. characteristics, 5. colour preferences; d) illumination: 1. kind, 2. nature, 3. type, 4. luminance, 5. spectral energy distribution

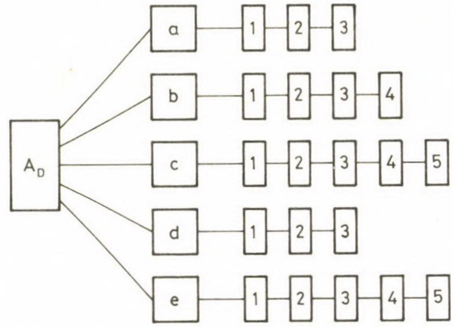


Fig. 7.2. Comprehensive scheme of architectural features. a) Landscape: 1. relief, 2. vegetation, 3. climate; b) developed environment: 1. development density, 2. rise, 3. function, 4. structure of development; c) architecture: 1. structure, 2. form and style, 3. space connections, 4. dimensions, 5. volume density of equipment; d) relation to the environment: 1. visual relation, 2. functional relation, 3. both; e) building materials: 1. silicate products, 2. textiles, 3. timber, 4. plastics, 5. other

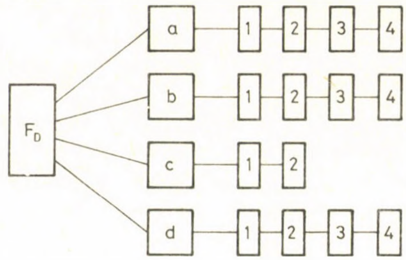


Fig. 7.3. Comprehensive scheme of functional features. a) Activities in the building: 1. kind of activity, 2. type of activity, 3. relations between activity processes, 4. human flow directions; b) environmental effects: 1. temperature, 2. noise, 3. smell, 4. relative humidity; c) colour associations expressing function: 1. expressive associations, 2. compensating associations; d) colour features: 1. information colours, 2. labour safety colours, 3. signal colours, 4. workpiece colours

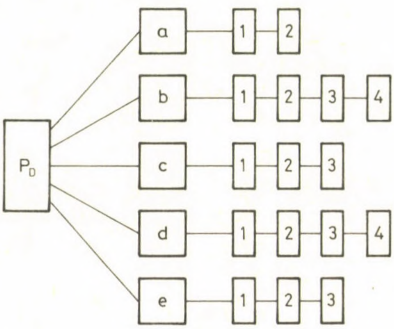


Fig. 7.4. Comprehensive scheme of human features. a) Sex: 1. man, 2. women; b) number: 1. total, 2. per room, 3. capita/sq.m; c) age: 1. young, 2. middle-aged, 3. old; d) properties: 1. qualification, 2. profession, 3. health condition, 4. psyché; e) colour preference: 1. principal colours, 2. colour groups, 3. relation to the colour preference index number system

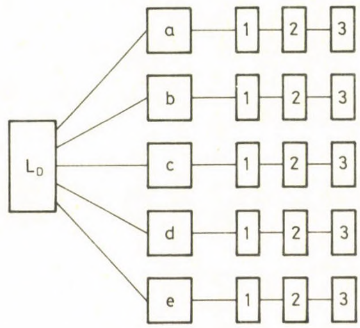


Fig. 7.5. Comprehensive scheme of illumination features. a) Kind of illumination: 1. natural, 2. artificial, 3. mixed; b) character of illumination: 1. directed, 2. diffuse, 3. mixed; c) type of illumination: 1. overall, 2. local, 3. mixed; d) luminance on 1. floor, 2. side walls, 3. bench; e) spectral energy distribution: 1. continuous, 2. sectional, 3. mixed

for the principal colours and colour groups, then compared to data and curves of the colour preference index number system, to find the trend and nature of possible deviations (Fig. 7.4).

Finally, illumination data in the office or workshop have to be recorded, first of all, the system of illumination—only natural, only artificial, or both. Natural illumination data should include not only window surface areas, but also ratios of window to floor areas and light transmission rate of glazing. Glasses modifying the spectral energy distribution of incident sunshine are increasingly applied. Also orientation of windows is of importance. Before beginning colour design, it has to be known whether artificial illumination is directed, diffuse, or mixed; where is overall or local lighting, or both. Optimum luminances on floors, side walls and active surfaces have to be known, and compared to the illumination offered by the actual design. Also types of artificial light sources and their spectral energy distributions have to be known, because all this is decisive for the appearance of applied colours. Luminance on different colour bearing surfaces best coping with the function has to be coordinated with illumination intensity (Fig. 7.5).

7.1.2. Survey of Demands

In possession of these data, colour demands for the building have to be determined, again in four categories, with several groups of demands in each (Fig. 7.6).

Demands to modify the architectural appearance by coloration have to be assembled first. Colour may modify space effect, causing it to appear closed, open, properly or confusingly arranged. Colour may enhance or diminish the articulation of a room, modify its perceived volume, its height, width or depth. Colours may help in changing the volume effects of objects in the room. Colours may serve, according to our artistic concept, to highlight, or on the contrary, to conceal the structure of the building. By colours it may be attempted to connect—or else, separate visually the building to/from its environment. Colours may emphasize the style of the building—or else, make it appear to be built in another style (Fig. 7.7).

Functional demands belong to three groups. Colours may contribute to the utility function of the building, in a way so that its psychosomatic effects meet biological

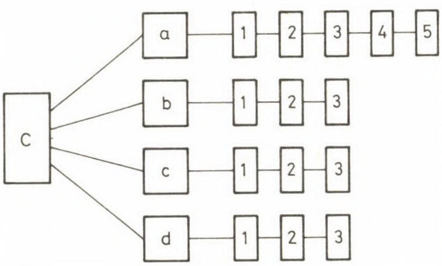


Fig. 7.6. Scheme of steps in the design phase survey of demands. a) demands for architectural appearance: 1. space effect, 2. volume effect, 3. structure, 4. environment, 5. style; b) demands for function: 1. utility function, 2. aesthetic function, 3. informative function; c) human demands: 1. colour preference, 2. psychosomatic demands, 3. aesthetic demands; d) demands dependent on illumination: 1. illumination intensity, 2. spectral energy distribution, 3. direction of light

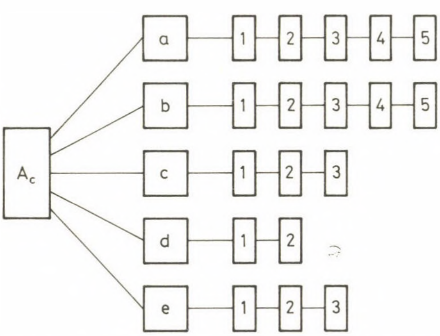


Fig. 7.7. Overall scheme of demands for architectural appearance. a) space effect: 1. closed space, 2. open space, 3. well-arranged space, 4. divided space, 5. undivided space; b) volume effect: 1. mass to be increased, 2. mass to be reduced, 3. height to be modified, 4. width to be modified, 5. depth to be modified; c) structure: 1. expressive, 2. antagonistic, 3. neutral; d) environment: 1. to be connected, 2. to be disconnected; e) style: 1. expressive, 2. antagonistic, 3. neutral

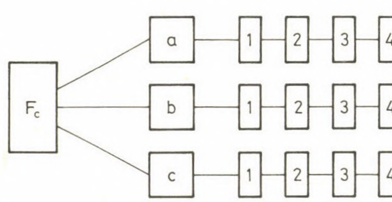


Fig. 7.8. Comprehensive scheme of functional demands. a) demands for utility function: 1. biological requirements, 2. calling attention, 3. avoidance of monotony, 4. arousing of comfort feeling; b) demands for aesthetic function: 1. use of expressive colour associations, 3. use of other relevant colour associations; c) demands for informative function: 1. information colours, 2. labour safety colours, 3. signal colours, 4. pictograms

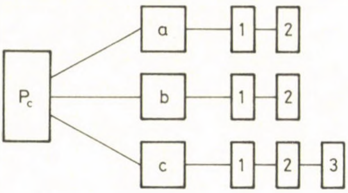


Fig. 7.9. Demands of occupants of the building, comprehensive scheme of human demands. a) colour preference demands: 1. use of preferred colours, 2. use also of other than preferred colours; b) psychosomatic demands: creation of 1. soothing, 2. dynamic atmosphere; c) aesthetic demands of occupants: 1. environment of harmonic appearance, 2. environment of contrasting appearance, 3. environment of expressive appearance

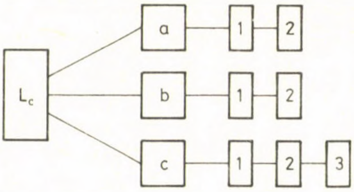


Fig. 7.10. Comprehensive scheme of illumination-dependent demands. a) demands depending on illumination intensity: 1. optimum light density difference between inner and environmental visual fields, 2. optimum light density difference between environmental and peripheral visual fields; b) demands depending on the spectral energy distribution of light: 1. selection of hue, 2. selection of saturation; c) demands depending on light direction: 1. selection of hue, 2. selection of saturation, 3. selection of lightness

requirements, increase attention, help avoiding monotony, and increase a feeling of comfort. Demands for the aesthetic function of colours inside the building are fulfilled by reckoning with colour associations expressing function and compensating environmental effects. Another important domain of requirements is the informative function of colours. Colour domains expected to have essential informative functions in the establishment, as well as labour safety colours, signal colours and pictograms to be applied, have to be fixed (Fig. 7.8).

Colour demands of the users and psychosomatic effects have also to be established, as well as the aesthetic requirements regarding the appearance of the building (Fig. 7.9).

Also demands for illumination belong to three groups, i.e. requirements for quality, direction and intensity, optimum luminance difference between inner and environmental visual fields, or between environmental and peripheral visual fields may be stipulated. Demands for the illumination quality have to do with the spectral energy distribution of light sources, affecting hue and saturation selection. Direction of light is of importance, because of its role in the determination of intervals to be preferred of all three colour sensation parameters (Fig. 7.10).

7.1.3. Analysis

The third step in colour design is to analyse previously collected data and requirements. Obviously, not all the data are of the same importance and there may also be conflicting demands. The function of the building, artistic ideas, or other aspects may justify preferences for certain demands. Colour design involves a parallel analysis of architectural, functional, human, and illumination data and requirements. First of all, environment analysis, space ratio analysis, form analysis and emphasis analysis should be given priority. For instance, emphasis analysis decides which part of the building has to be enhanced by coloration, or even, to be disemphasized to diminish its obtrusiveness due to its real dimensions. Analysis of functional features and demands points out essential activities inside the building, the best information system, and colours likely to express

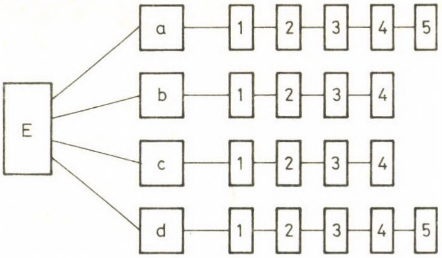


Fig. 7.11. Scheme of steps in the design phase analysis. a) analysis of architectural features and demands; 1. environment analysis, 2. space proportion analysis, 3. form analysis, 4. emphasis analysis, 5. analysis of other features and demands; b) analysis of functional features and demands: 1. activity organization, 2. compensation of environmental effects, 3. information system, 4. expression of function; c) analysis of human features and demands: 1. ergonomic demands, 2. social demands, 3. aesthetic demands, 4. colour preference demands; d) analysis of illumination features and demands: 1. orientation, 2. analysis of light directions, 3. intensity of illumination, 4. quality of illumination, 5. analysis of the directions of illumination

these functions. Analysis of human factors and demands contributes to the establishment of essential ergonomic, social and aesthetic demands. These investigations also help decision on the weight of preference data in colour design. Analysis of illumination data and requirements clears the role of orientation in colour selection, the importance of the type, intensity and direction of illumination, and enables decisions to be made about priorities in colour selection (Fig. 7.11).

7.1.4. Colour Delimitation

Hue, saturation and lightness intervals generally meeting previously determined colour demands require to be delimited (Fig. 7.12). The first step is to define colour demands numerically, and plot them for the sake of clarity. All this is helped by figures in previous chapters. Figures 7.13, 7.14, and 7.15 illustrate delimitation of hues, saturations, and lightnesses for colours of a building. Separate curves refer to demands for hue, saturation and lightness ranges from architectural, functional, human, and illumination aspects. Parts over the demand line *i* of the curve obtained by superposing these curves,—shaded in the figures—, indicate the ranges of hue, saturation and lightness of colours to be chosen from. The number of eligible colours thus defined is still very high. Colour delimitation simply permits an easy survey of appropriate colours and colour ranges.

Colour delimitation has three phases, referring first to the entire building, then to rooms, and finally, each of the colour bearing surfaces has to be considered.

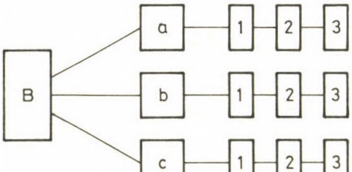
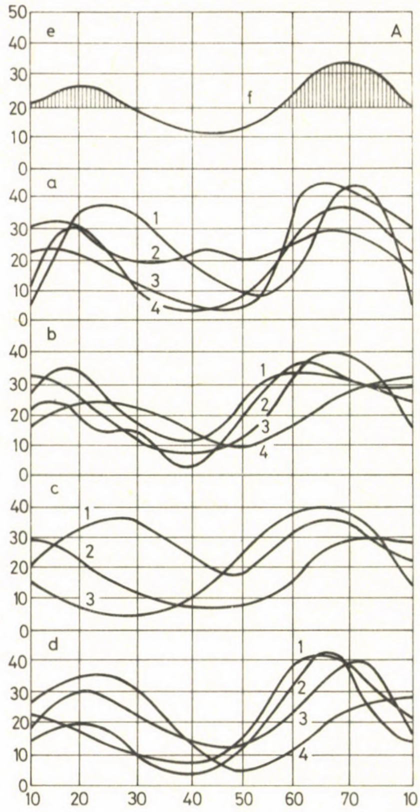


Fig. 7.12. Scheme of steps of the design phase colour delimitation. a) colour delimitation for the entire building: 1. hue, 2. saturation, 3. lightness; b) room-wise colour delimitation: 1. hue, 2. saturation, 3. lightness; c) colour delimitation for each colour-bearing surface: 1. hue, 2. saturation, 3. lightness

Fig. 7.13. Delimiting diagram for hues of colours for a building based on the analysis. a) delimiting curve for architectural possibilities and demands, b) delimiting curve for functional features and demands, c) delimiting curve for human features and demands, d) delimiting curve for lighting features and demands, e) overall delimiting curve, f) line of demands



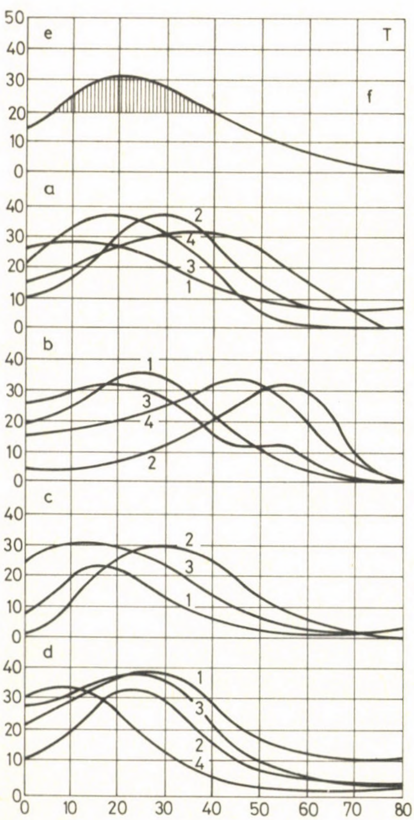


Fig. 7.14. Delimiting diagram of saturations of colours to be used for the design of building, based on data and demand analyses. Legend is as for Fig. 7.13

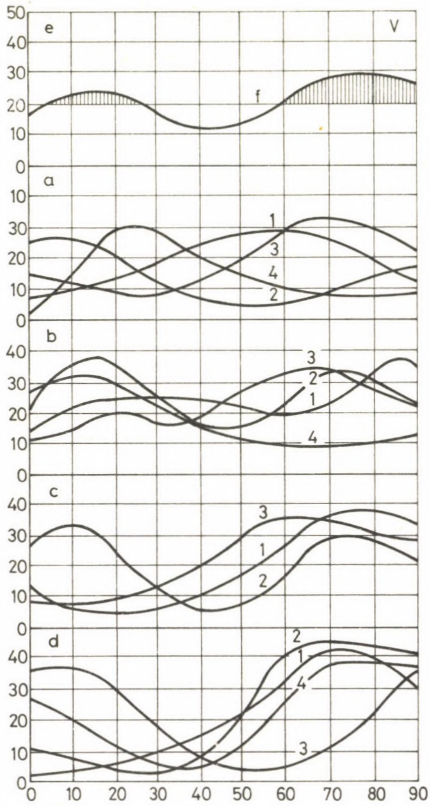


Fig. 7.15. Delimiting diagram of lightnesses of colours to be used for the design of a construction, based on data and demand analyses. Legend is as for Fig. 7.13

7.1.5. Colour Selection

The most fascinating step in design is to select colours for each of the colour-bearing surfaces from the delimited colour ranges. First a visual concept for the colour appearance of the establishment has to be set up. There may be many ways to do this. E.g. it can be based on a rhythmical dialogue between walls and roofs, on form effects, or on contrasts. It may emphasize structural or functional features of the building; perhaps its emotional message (Fig. 7.16).

The second phase of colour selection is decision about the kinds of harmony expressing the actual visual concept. It has to be decided whether to apply monochrome or polychrome complexes, complementary or triadic relations, saturation or lightness scales, or some composite harmony group to express the original intention. Such a decision still permits an infinity of harmony series, so that possibilities have to be restricted, taking fundamental conditions of colour harmony into consideration.

The last step in colour selection is to choose colours for each room and each colour-bearing surface, taking note of accessory conditions so as to arouse colour harmony sensation in the actual cases.

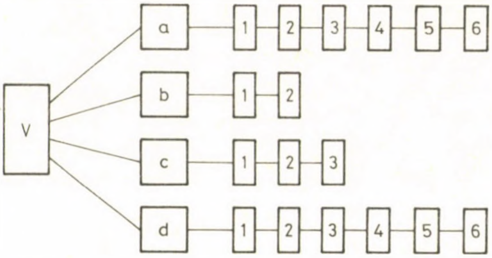


Fig. 7.16. Scheme of steps in the design phase of colour selection. a) elaboration of a visual concept: 1. based on surface effects, 2. based on form effects, 3. based on contrasts, 4. based on structures, 5. based on function management, 6. based on emotional content; b) selection of harmony type: 1. hue relations, 2. scalar relations; c) restriction of harmony possibilities: 1. contrast, 2. preference, 3. aesthetic function; d) selection of harmony complexes for each room and each colour-bearing surface: 1. adaptation, 2. colour remembrance, 3. emotional message, 4. synesthetic effect, 5. spatial position, 6. illumination

7.1.6. Documentation

Colour dynamic design documentation has five parts (Fig. 7.17) comprising colour consignation sheets, floor plans, sections and room-wise tables with notations of colour codes and colour names for every colour-bearing surface. The most spectacular parts of the documentation are painted design sheets, views, sections and perspectives.

Colours are defined by means of colour samples, and by CIE *XYZ* and Coloroid colour codes. Also technological specifications have to be given, indicating paints to be applied, and mixing formulations. Finally, a list of material consumption for each colour, technology, and room has to be compiled.

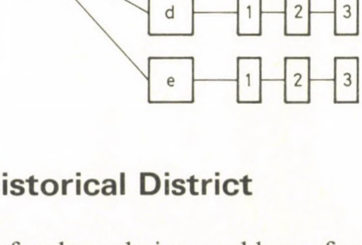


Fig. 7.17. Scheme of steps in the design phase documentation. a) colour assignment: 1. floor plan, 2. sectional views, 3. room-wise tables; b) painted design sheets: 1. views, 2. sectional views, 3. perspectives; c) colour definition: 1. colour samples, 2. CIE *XYZ* codes, 3. Coloroid codes; d) technology specifications: 1. applicable paints, 2. formulations, 3. technology instructions; e) material consumption: 1. colour-wise, 2. technology-wise, 3. room-wise

7.2. Colour Design for the Exterior of a Historical District

There are many kinds of built environments and so of colour design problems for different establishments. Colour designs for a city or a plant, a dwelling or a hospital are ruled by different aspects. So are interior or façade designs. Let us now consider some aspects of colour design specific for townscape complexes.

7.2.1. Townscapes

Any building in an unbroken street front is an organic part of the townscape. Visual appearance of its façade affects our visual impression of the whole town or district. In this impression, colours have an important part. In designing façade coloration, role of the topology, dimensions, and order of forms of the building within the townscape have to be considered.

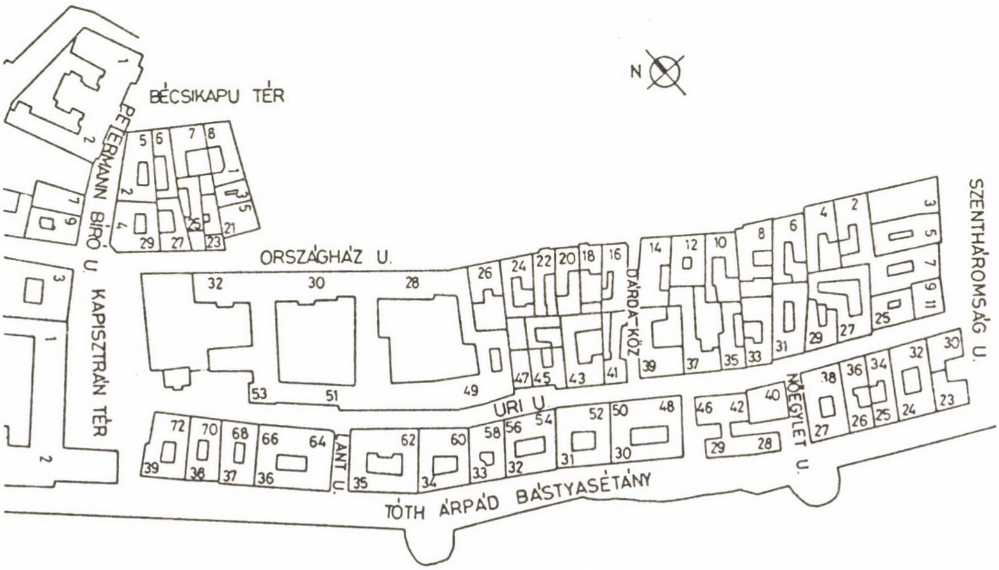


Fig. 7.18. Layout plan for a part of the Buda Castle district

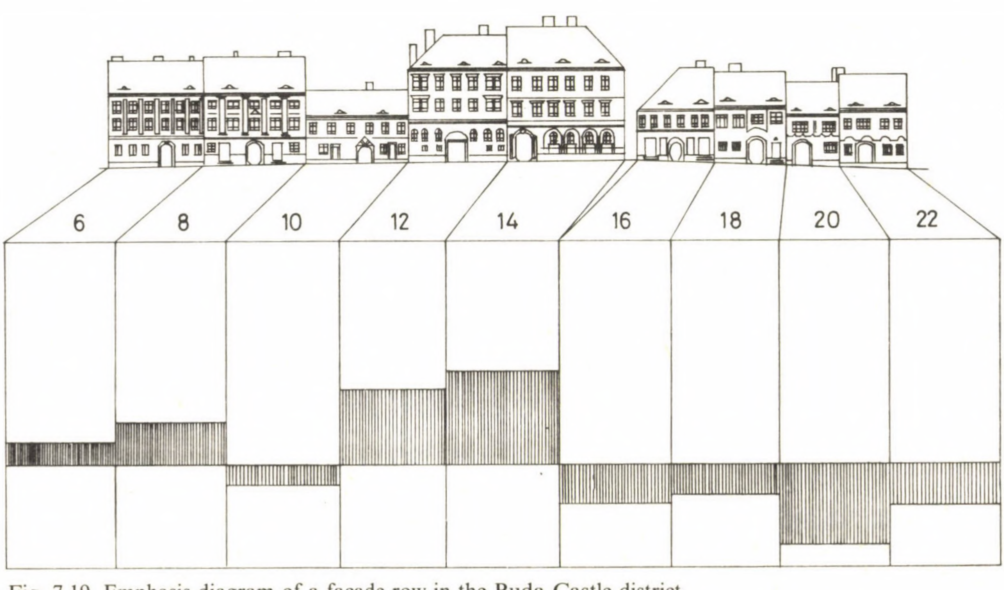


Fig. 7.19. Emphasis diagram of a façade row in the Buda Castle district

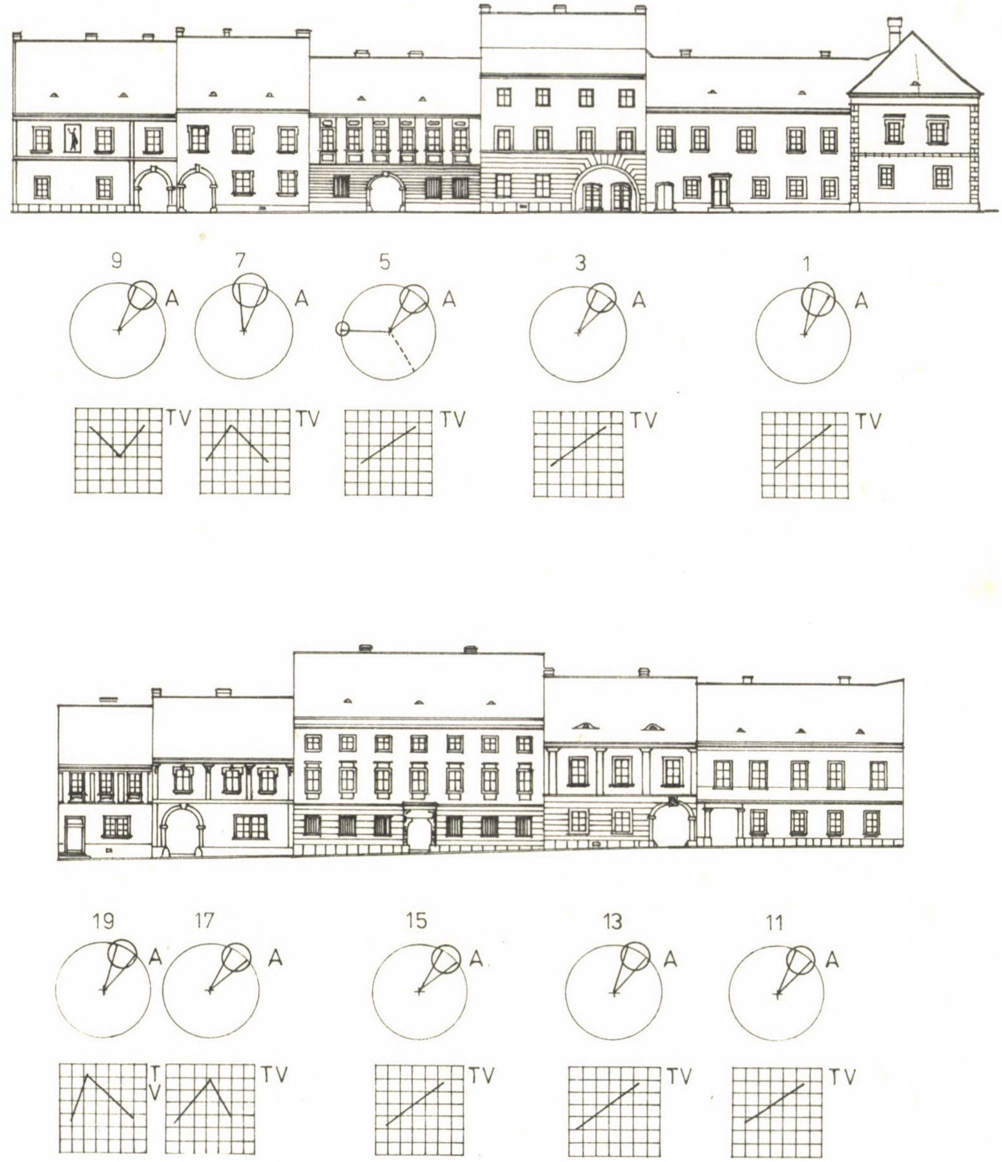


Fig. 7.20. A façade row in the Buda Castle district with harmony notations. Symbols under each façade show location in the colour space of colours proposed for the façades. Symbol relations show the colour harmony system of the façade row

A building is more decisive for the townscape if it is situated at a corner, a street bend, or in a square. Such buildings are expected to command our visual sensation. Colour selection should usually underline their importance, provided that the situation or other aspects are not against it (Fig. 7.18).

Façades may gain visual importance merely by their size. High-rise buildings are always more dominating by taking more of the skyline. Unfortunately, often the significance by dimensions of a building and its townscape value do not coincide. In such cases, the obtrusiveness of oversized buildings and the modesty of small ones should be offset by proper colour selection. Size differences can be analyzed by means of an emphasis diagram (Fig. 7.19).

It is of outstanding importance for the appeal of a townscape to enhance by colouration the visual appearance of buildings excelling in their harmonic proportions of their system of forms. Colour is a rather dynamic element in the street. Even the best form system may be 'slain' by unfit colouration. Visual importance of buildings with poor forms may be, in turn, minimized by proper colouration (Fig. C92).

It is also important for a townscape in what a rhythm a tone reappears on façades, whether there is only emotional or also systematic integrity of colouration between consecutive buildings. Balanced visual appearance is forwarded by approximately equal saturation and lightness differences between walls and courses (Fig. 7.20).

7.2.2. Historical Aspects

In cities, often modern buildings are adjacent to houses from past periods many centuries old. The problem is simple if a city can be considered as essentially mediaeval, baroque, or classicist. Unfortunately, this is exceptional; mostly buildings of different styles, from different ages are in juxtaposition. Historical aspects are met by applying strong, warm colours for mediaeval complexes, while cold, dull shades for classicist buildings. When buildings of various styles are side by side, topology, and relation between buildings have to be carefully recorded. Buildings have to be examined individually from such aspects as townscape importance and value. Thereafter a uniform colour tone has to be decided that may be pertinent to one of the historical ages. In any case, previous colours of the buildings in different historical periods should be ascertained, because this helps to recognize individual features. In summary, monumental aspects involve colourations, conform partly to the style of the given building, and partly, to its appearance in earlier, historical periods. This colouration must, however, not be antagonistic to the idea of visual unity, an essential aspect of colour dynamics (Fig. 7.21).

7.2.3. Architectural Aspects

A rich architecture is less in need of coloration based on saturated, marked contrasts. With façades with marked courses slight contrasts are sufficient to give an intensive colour appearance. Smooth, undivided façades in turn require rather contrasting colours. A street line is given better visual unity by a constant type of harmony of hue relations and saturation contrasts, than by equal lightness differences between walls and courses of every house (Figs C93, C94). Important factors, often protagonists in the visual appearance of a façade are shopwindows, gateways, sign-boards and advertisements. For them form and colour have to be chosen so as to become an integral part of the façade. Colour design for the street line has also to include suggestions covering such elements.

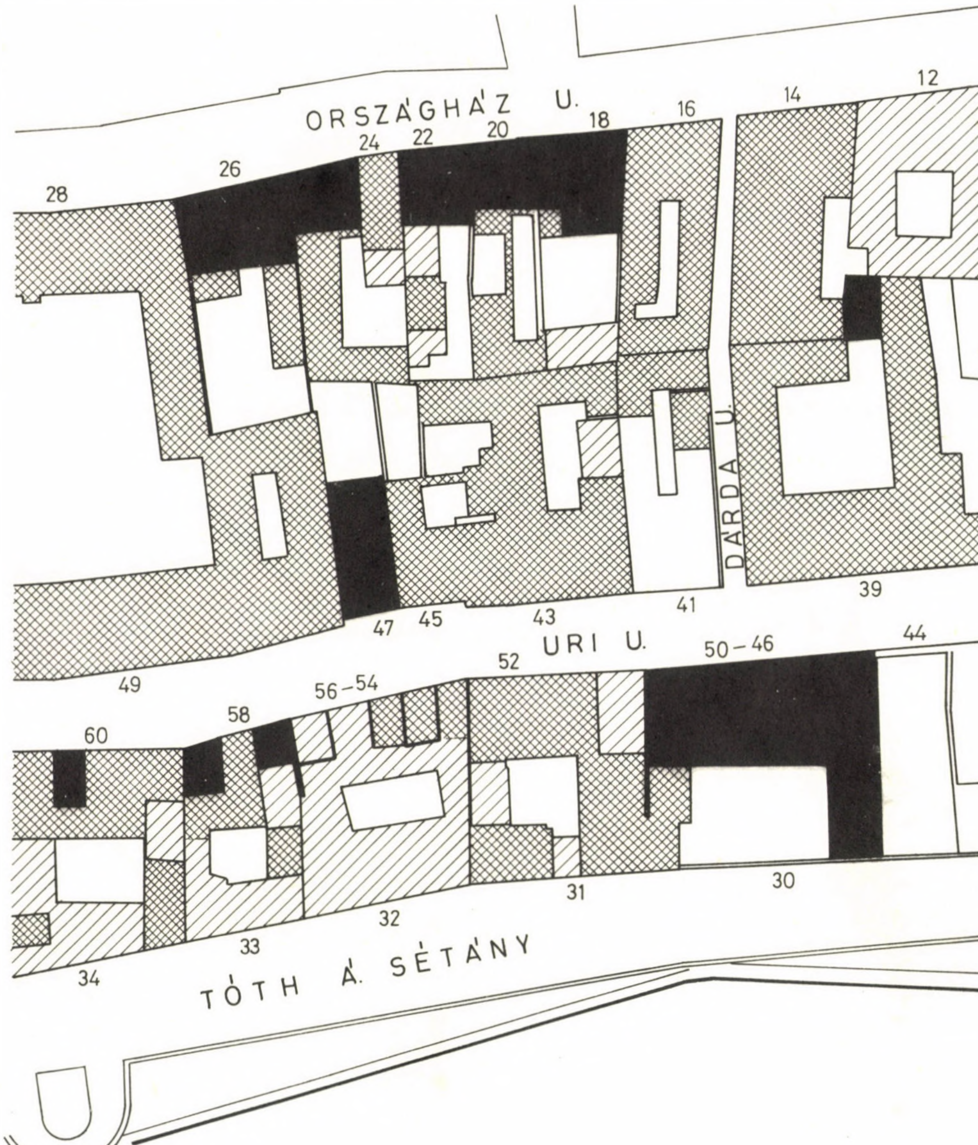


Fig. 7.21. Dating layout plan of a part of the Buda Castle district. Hatched buildings are mediaeval, shaded ones are baroque, empty ones are classicist

7.2.4. Orientation

From the aspect of colour design, a street may be either north–south or east–west oriented, requiring two different solutions of coloration. In the former case, there are about equal numbers of sunlit and shaded hours for both façade rows, so that orientation is almost irrelevant for colouration. On the contrary, in case of east–west orientation, one façade row is almost constantly insolated in the sunny hours, while the other never is. This markedly affects colouration, concerning the selection of all three colour parameters.

7.3. Interior Design (Industrial)

Colour design of building interiors is controlled by aspects different from those for façades. In industrial plants, function is the main determinant for colouration, but architectural, human and illumination aspects are also of importance.

7.3.1. Functional Aspects

Primarily, directions of material and personnel flow in the plant have to be studied and some kind of colour information system developed, either as cladding colours, or as continuous colour signals over all the rooms, perhaps as pictograms. Pictograms in Fig. C95 indicate plant units of a pharmaceutical factory at passage bifurcations. It is useful if coloration of walls and doors differentiates between premises which are different from an organizational or technological point of view. For instance, in a pharmaceutical factory, zones are separated according to the required degree of sterility. The second floor plan of the tabletting plant of Gedeon Richter Pharmaceutical Factory, Budapest, is seen in Fig. 7.22, indicating units different by the degree of sterility. Access to non-sterile units is through brown passages and brown doors. Access to the sterile unit is by the green staircase, while to the hypersterile one by the blue staircase. In addition to the colour information system, the aspect of function also involves considering the biological, expressive, and compensating effects of colour associations.

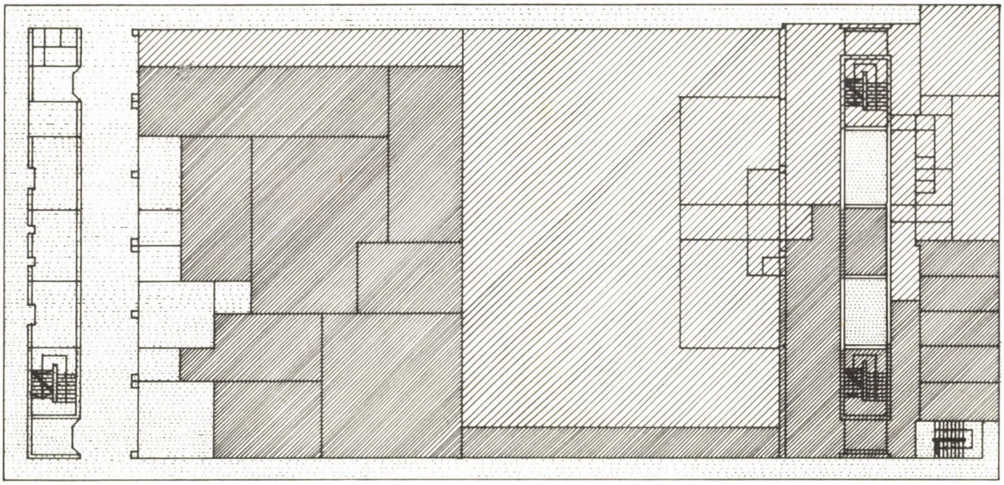


Fig. 7.22. Floor plan sketch of the second floor of the tabletting plant of the Gedeon Richter Pharmaceutical Plant, indicating functionally separate parts. a) non-sterile, b) sterile, c) strictly sterile areas

7.3.2. Architectural Aspects

Architectural aspects involve the creation of adequate room proportions and promotion of a vivid perception of the space structure; in other words, arousing a visual space sensation. In this phase of the design, conception designs illustrating and visualizing interiors in proportional patch systems rather than by real perspectives, are indispensable. Figures C96 to C99 belong to the colour dynamic design of a chemical manufacturing workshop hall of Gedeon Richter Pharmaceutical Factory in Dorog, Hungary. The lower horizontal colour strips represent the colour of the floor, the middle and upper ones that of the walls and the ceiling, respectively. Vertical and horizontal colour strips represent steel structures, pipelines; spots are for autoclaves, tanks and other equipment. Spot sizes are proportional to the actual sizes of spatial elements inside the hall.

7.3.3. Human aspects

Human aspects of colour design have to be taken into account in colour design; first of all, of interiors, with a special emphasis on colour preferences characteristic of the age and sex of those working there. For this purpose tables of the colour preference index number system, or circular diagrams of colour preference in this book may be of use.

7.3.4. Illumination

In the colour design of an industrial establishment, it has first to be established whether it operates under artificial or natural illumination, or both. Thereafter luminances desirable on walls, workpieces, equipment, and in their direct surrounding have to be determined. Colour selection is directly affected by the spectral energy distribution of light sources, and direction of light incident on the surfaces.

7.4. Colour Design of Buildings with Different Functions

Aspects to be emphasized, or more or less negligible in the colour design of a given building largely depend on its function. Here aspects to be absolutely respected for some types of buildings will be considered, and alternatives of colour selection for certain cases will be illustrated by figures.

7.4.1. Homes

Primarily, colour preferences of the inhabitants have to be respected, but also orientation, spectral energy distribution and position of artificial light sources, dimensions, furniture forms, sizes, styles and colours are determinant. In living rooms, marked colours with emotional messages may be applied. A wide range of colours may be used if not gaudy (Figs 7.23, 7.24).

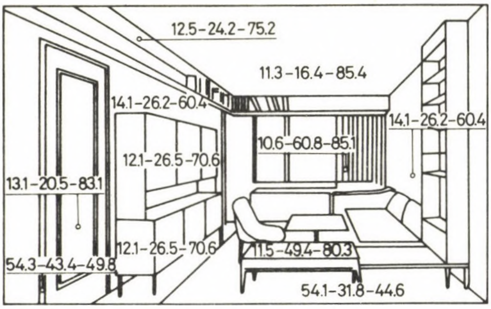


Fig. 7.23. Colour design for a living room

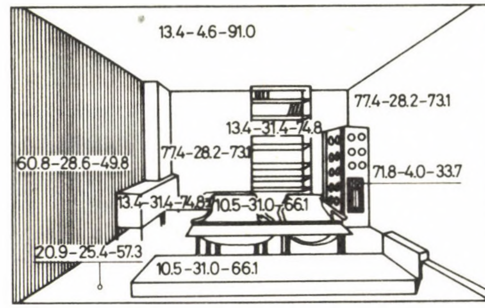


Fig. 7.24. Colour design for a living room

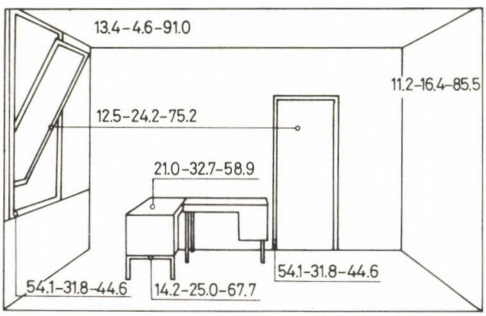


Fig. 7.25. Colour design for a medical consulting room

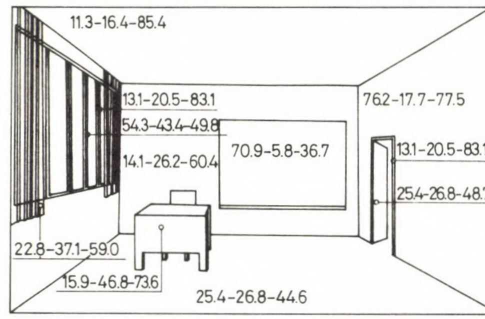


Fig. 7.26. Colour design for a primary school classroom

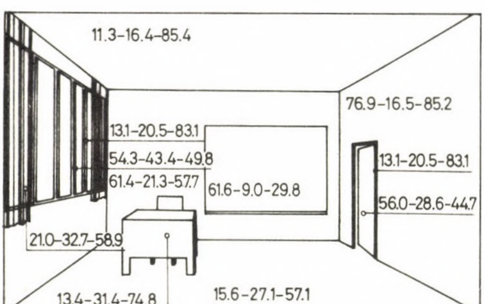


Fig. 7.27. Colour design for a primary school classroom

7.4.2. Medical Consulting Rooms, Hospitals

In medical consulting rooms and hospitals, mainly soothing colours have to be applied, in particular, varieties of green. In examining rooms marked contrasts have to be avoided. In wards, an intensive colour may have a pleasant effect. Colour selection has to take psychosomatic effects of colours into consideration. Primarily in children's divisions, it is imperative to reckon with colour preferences. No warm colours should be applied in lavatories or at any place where the patient can look at himself in a mirror, since in such an environment, complexions seem pallid, or sickly, which is disquieting for the patient. In a surgery, red, and in a urology, yellow, should be avoided (Fig. 7.25).

7.4.3. Schools

Walls containing windows should be lighter than the opposite ones. Hue of the colour of the wall surrounding the blackboard has to be similar to that of the blackboard, without much differentation by lightness. Blackboards may be deep brown, dark dull green or blue. Desks should be somewhat lighter than medium. Floors may be dark. Colour selection should be primarily controlled by colour preference and psychosomatic effects of colours (Figs 7.26, 7.27).

7.4.4. Offices

Colour selection for offices has to create a calm atmosphere without being monotonous. More intensive colours are advisable only on door and window casings. Adjacent offices should differ by colours. Essential aspects of colour selection are a pleasant space sensation and associative factors (Figs 7.28 to 7.30).

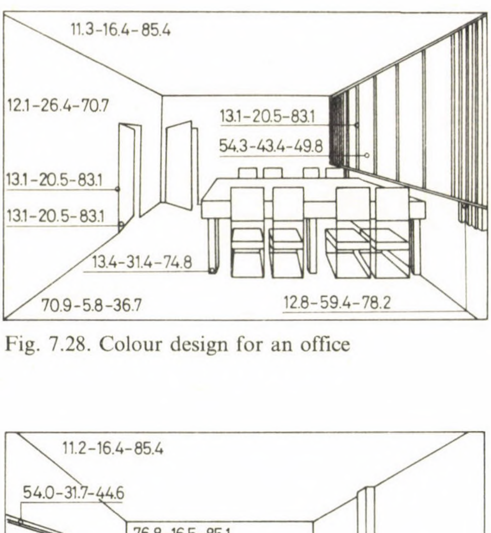


Fig. 7.28. Colour design for an office

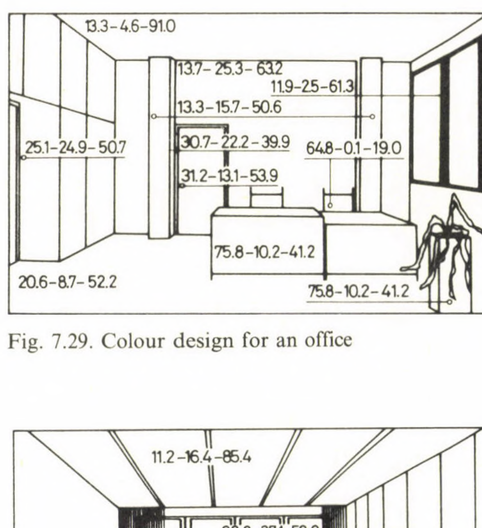


Fig. 7.29. Colour design for an office

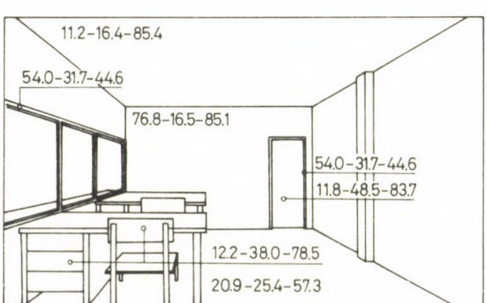


Fig. 7.30. Colour design for an office

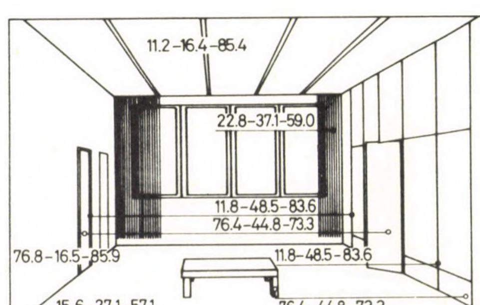


Fig. 7.31. Colour design for a nursery

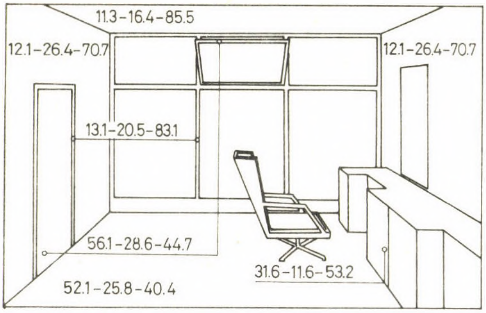


Fig. 7.32. Colour design for a ladies' hairdresser saloon

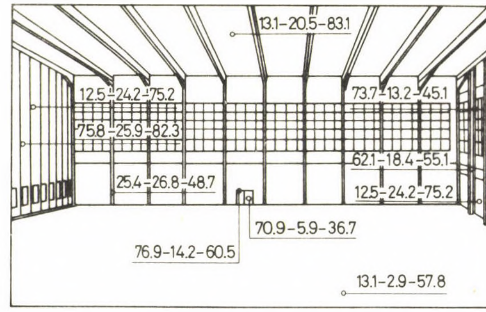


Fig. 7.33. Colour design for a hangar interior

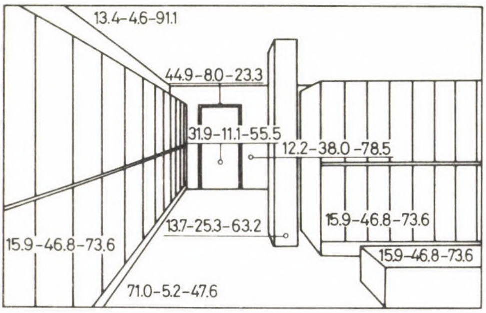


Fig. 7.34. Colour design for a locker room for men (in a machine tool factory)

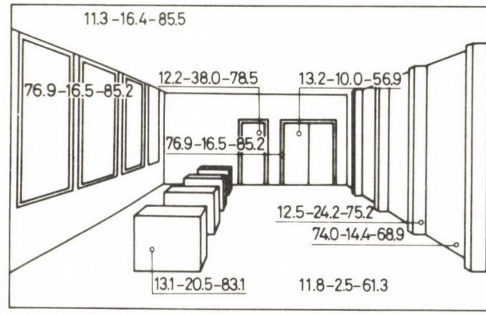


Fig. 7.35. Colour design for a moulding workshop

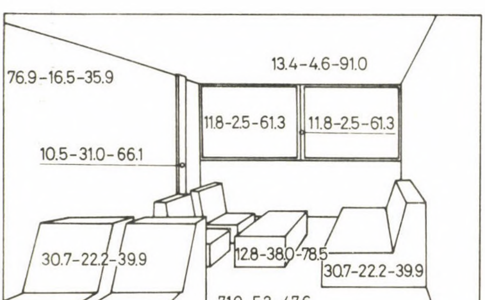


Fig. 7.36. Colour design for smoking and rest room (in a machine tool factory)

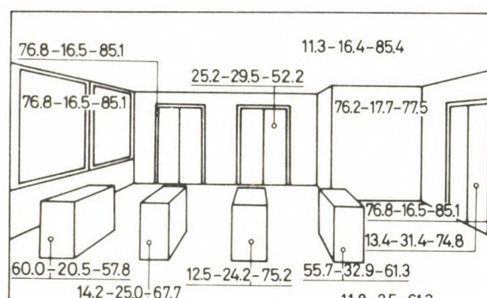


Fig. 7.37. Colour design for a machining workshop

7.4.5. Museums, Libraries, Theatres, Churches

Their functions require delicate colour designs based mainly on rather narrow saturations contrasts. Because of slight lightness differences, colour adaptation has an important role in the colour appearance of interiors. Colour selection is expected to create a relaxed atmosphere and a pleasant space sensation.

7.4.6. Amusement Places, Restaurants

Intensive, contrasting colours are advantageous. Warm colours should prevail over cold ones. Though, never let table boards be red or of other, very warm colour. Essential aspect of colour selection is to express the atmosphere, possible by taking associative properties of colours into consideration. Also synesthetic effects are of importance.

Lastly, without any comment let us present some examples of possible alternatives for colours in rooms not yet discussed (Figs 7.31 to 7.37). These examples have been developed following recommendations in this book, taking actual architectural, human, functional and illumination features and requirements into consideration. They illustrate possible solutions but are not intended as actual formulations. In colour designs of the past decades, relations disclosed in our research work and presented in this book have been applied in a wide range of establishments. Practical applications favoured one or the other aspect depending on the function of the given establishment. All these will be described in a study still to be elaborated.

Epilogue

To humanize this built world of ours is subject to several conditions, first of all, personal conditions, commitment, responsibility, visual culture and professional knowledge of those responsible for built environment. This book is intended to help in acquiring the latter by offering comprehensive information about the kingdom of colours and its laws, on their effects on man living in a built environment as well as scientific explanations for the most essential relations. The tables and diagrams that are included can be used as practical aids for actual colour designs.

This body of knowledge is needed for creative work with colours but insufficient for art composition, which requires—beyond that—invention and visual culture. To one lacking visual culture and failing to do his best to comprehend visually the wealth of colours, who avoids museums and exhibitions, let alone beautiful environments old and new, the subject matter provided is of no use.

In addition to personal conditions, dissemination of professional colour design is bound to material conditions, for instance, access to a Coloroid colour sample collection consisting of hundreds or even thousands of shades permitting one visually to assess his design.

Colour design still awaits legal regulation. It is helpful for the customer rather than for the designer to have specifications for the contents, quality, coordination, approval, and application of colour designs put down in regulations. There is not yet an established procedure, let alone, a system of conditions, to pass judgement on colour designs. An adequate system of conditions would forward generalization of expert colour design.

As to realization, a proper colour design embraces the possibilities of implementation, colour assortments of various materials, and surface appearances. An atmosphere of visual culture is conditioned by an adequate assortment of paints and of various other products of the building materials industry. The adequacy of a colour assortment is not absolutely proportional to the available range of colours of coloured materials or paints. Coloroid coding of colour assortment, by its general acceptance, offers increasing possibilities for the colour designer to develop harmonizing spaces, being at the same time economical by eliminating too close, or unfitting shades.

This book is recommended for those who wish to be—or to make their students—acquainted with the kingdom of colours, or to utilize statements herein to make our built world more attractive, more human.

Lastly, let me express my thanks to those who have helped me in compiling and publishing this book. First of all, I am indebted to my wife who has been a constant support in my work. Most of the figures are the work of her hands. Thanks are due to Dr. Lajos Gádoros and Sándor Szepessy for having encouraged me at the beginning of this work; to subsequent co-workers, first of all, to Dr. Elek Béres, Dr. Tihamér Gedeon and Zoltán Pálffy; to former pupils, among them, Csaba Klausz, who assisted me in tests, or called my attention to some new problems by their questions. Thanks are due to Dr. Lajos Gádoros, Dr. János Schanda, Dr. Gyula Hajnóczi and Dr. Zsolt Tánczos for helpful discussions, to the Section of Technical Sciences of the Hungarian Academy of Sciences and the Publishing House of the Hungarian Academy of Sciences for having supported the publication of this book.

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Appendix

A. 1

Tristimuli X_λ, Y_λ, Z_λ of Coloroid primary colours, angles φ for primary colours under standard illuminations C and D65

A	X_λ	Y_λ	Z_λ	φ_C	φ_{D65}
10	77.5745	94.6572	0.2032	59.00	58.05
11	80.5130	93.3804	0.1910	55.30	54.17
12	83.2782	92.0395	0.1808	51.70	50.38
13	85.8841	90.6482	0.1764	48.20	46.70
14	88.0488	89.3741	0.1724	44.80	43.58
15	90.6652	87.6749	0.1672	41.50	39.61
16	92.9124	86.0368	0.1612	38.20	36.30
20	95.0909	84.2291	0.1531	34.90	32.88
21	97.2454	82.4779	0.1431	31.50	29.39
22	99.3753	79.9758	0.1308	28.00	25.82
23	101.4350	77.4090	0.1170	24.40	22.17
24	103.4402	74.4014	0.1067	20.60	18.35
25	105.2466	70.7496	0.1021	16.60	14.32
26	106.2544	66.0001	0.0898	12.30	10.08
30	105.6125	59.6070	0.0696	7.70	5.53
31	100.1027	50.1245	0.0335	2.80	0.74
32	75.1400	32.1000	0.0100	−2.50	−4.38
33	72.6603	30.4093	10.5941	−8.40	−10.66
34	68.9620	27.8886	26.3780	−19.80	−24.35
35	65.9523	25.8373	39.2224	−31.60	−34.65
40	63.3815	24.0851	50.1944	−43.20	−46.21
41	60.9810	22.4490	60.4392	−54.60	−57.28
42	58.5492	20.7915	70.8175	−65.80	−67.95
43	55.8865	18.9767	82.1815	−76.80	−78.29
44	52.9811	16.9965	94.5807	−86.80	−87.66
45	49.6364	14.7168	108.8551	−95.80	−96.11
46	42.5346	9.8764	139.1643	−108.40	−108.10
50	33.6200	3.8000	177.2110	−117.20	−116.63
51	21.0174	8.6198	135.3567	−124.70	−123.81
52	13.7834	11.4770	102.0911	−131.80	−130.59
53	10.1787	13.5067	84.3955	−138.50	−136.98
54	7.9004	15.0709	72.7863	−145.10	−143.30
55	6.2658	16.4626	64.1692	−152.00	−149.91
56	4.4691	18.5949	54.1091	−163.40	−160.96

A	X_λ	Y_λ	Z_λ	φ_C	φ_{D65}
60	3.0372	21.1659	45.5077	−177.20	−174.64
61	2.1665	23.4022	40.0126	171.60	174.30
62	1.3989	26.1483	34.8136	160.20	162.65
63	0.7215	30.1137	28.7658	148.40	150.45
64	0.2586	36.6425	23.8402	136.80	138.37
65	0.7260	48.5346	16.7317	125.40	126.59
66	6.6010	71.7274	7.6233	114.20	114.70
70	24.2272	92.6325	2.7086	103.20	103.88
71	40.6663	99.0587	1.0284	03.20	93.75
72	52.7646	99.9862	0.5321	84.20	84.43
73	60.6873	99.3224	0.3695	77.30	77.25
74	66.4599	98.1981	0.2868	71.60	71.29
75	70.8358	97.0252	0.2470	66.90	66.35
76	74.4182	95.8592	0.2205	62.80	62.05

A. 2

Characteristics of Coloroid primary colours, Coloroid boundary colours, and Coloroid hues

Legend:

A	Coloroid primary colours and Coloroid primary hues;
λ	dominant wavelengths of Coloroid hues for Coloroid primary colours and Coloroid boudary colours;
x_λ, y_λ	colour coordinates for Coloroid primary colours and Coloroid boundary colours;
Y_λ	tristimuli Y for Coloroid primary colours and Coloroid boundary colours;
ε_λ	one percent of the sum of tristimuli for Coloroid primary colours and Coloroid boundary colours;
tg φ_C ctg φ_C	asymptotes of Coloroid hues for Coloroid primary colours and Coloroid boundary colours at standard illumination C;
tg φ_{D65} ctg φ_{D65}	asymptotes of Coloroid hues for Coloroid primary colours and Coloroid boundary colours at standard illumination D65.

Comments:

1. In this table boundary colours are entered with 1 nm intervals.
2. No tg φ and ctg φ values higher than 1.0 were included in the table, since exact computation requires trigonometric functions less than 1. ctg φ has to be applied if column for tg φ contains no value.
3. Purples have no dominant wavelength. For them, dominant wavelength of the complementary colour is given, with negative sign.
4. Dominant wavelengths of primary colours are given at a two-decimals accuracy.

A	λ, nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
10	570.83	0.44987	0.54895	94.6572	1.724349	0.6009	—	0.6236	—
	571	0.45106	0.54777	94.5450	1.726011	0.6087	—	0.6324	—
	572	0.45804	0.54084	93.8499	1.735273	0.6586	—	0.6860	—
11	572.64	0.46248	0.53641	93.3804	1.740845	0.6924	—	0.7220	—
	573	0.46499	0.53393	93.1162	1.743979	0.7114	—	0.7432	—
	574	0.47190	0.52705	92.3457	1.752123	0.7673	—	0.8037	—
12	574.38	0.47451	0.52444	92.0395	1.754986	0.7898	—	0.8278	—
	575	0.47878	0.52020	91.5400	1.759700	0.8270	—	0.8687	—
	576	0.48561	0.51339	90.7006	1.766705	0.8900	—	0.9377	1.0664
13	576.06	0.48601	0.51298	90.6482	1.767088	0.8941	—	0.9423	1.0612
	577	0.49241	0.50661	89.8277	1.773096	0.9573	1.0446	1.0119	0.9882
14	577.50	0.49578	0.50325	89.3741	1.775953	1.0070	0.9930	—	0.9516
	578	0.49915	0.49989	88.9204	1.778810	—	0.9718	—	0.9166
	579	0.50585	0.49321	87.9781	1.783782	—	0.9042	—	0.8502
15	579.31	0.50790	0.49052	87.6749	1.785074	—	0.8847	—	0.8276
	580	0.51249	0.48659	87.0000	1.787950	—	0.8421	—	0.7889
16	580.95	0.51874	0.48035	86.0368	1.791104	—	0.7869	—	0.7346
	581	0.51907	0.48005	85.9861	1.791270	—	0.7841	—	0.7319
	582	0.52560	0.47353	84.9392	1.793754	—	0.7300	—	0.6788
20	582.65	0.52980	0.46934	84.2291	1.794831	—	0.6976	—	0.6464
	583	0.53207	0.46709	83.8622	1.795413	—	0.6798	—	0.6295
	584	0.53846	0.46073	82.7581	1.796257	—	0.6329	—	0.5834
21	584.46	0.54137	0.45783	82.4779	1.798665	—	0.6128	—	0.5632
	585	0.54479	0.45443	81.6300	1.796300	—	0.5890	—	0.5405
	586	0.55103	0.44823	80.4794	1.795516	—	0.5479	—	0.5001

A	λ, nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
22	586.43	0.55367	0.44559	79.9758	1.794822	—	0.5317	—	0.4838
	587	0.55719	0.44210	79.3082	1.793900	—	0.5095	—	0.4625
	588	0.56327	0.43606	78.1192	1.791486	—	0.4735	—	0.4272
23	588.59	0.56680	0.43253	77.4090	1.789610	—	0.4536	—	0.4047
	589	0.56926	0.43010	76.9154	1.788307	—	0.4396	—	0.3941
	590	0.57515	0.42423	75.7000	1.784400	—	0.4077	—	0.3628
	591	0.58094	0.41846	74.4754	1.779805	—	0.3777	—	0.3334
24	591.06	0.58128	0.41811	74.4014	1.779484	—	0.3759	—	0.3316
	592	0.58665	0.41276	73.2422	1.774457	—	0.3492	—	0.3057
	593	0.59222	0.40719	72.0003	1.768226	—	0.3226	—	0.2798
	594	0.59766	0.40176	70.7496	1.760984	—	0.2977	—	0.2553
25	594.00	0.59766	0.40176	70.7496	1.760984	—	0.2974	—	0.2552
	595	0.60293	0.39650	69.4900	1.752600	—	0.2743	—	0.2325
	596	0.60803	0.39141	68.2219	1.742982	—	0.2525	—	0.2113
	597	0.61298	0.38648	66.9471	1.732200	—	0.2322	—	0.1915
26	597.74	0.616553	0.38300	66.0001	1.723444	—	0.2180	—	0.1777
	598	0.61778	0.38171	65.6674	1.720368	—	0.2129	—	0.1727
	599	0.62246	0.37705	64.3844	1.707596	—	0.1949	—	0.1550
	600	0.62704	0.37249	63.1000	1.694000	—	0.1778	—	0.1382
	601	0.63152	0.36803	61.8155	1.679651	—	0.1614	—	0.1224
	602	0.63590	0.36367	60.5314	1.664481	—	0.1457	—	0.1072
30	602.72	0.63896	0.36061	59.6070	1.652892	—	0.1352	—	0.0968
	603	0.64016	0.35943	59.2475	1.648385	—	0.1311	—	0.0929
	604	0.64427	0.35533	57.9637	1.631260	—	0.1173	—	0.0794
	605	0.64823	0.35140	56.6800	1.613000	—	0.1042	—	0.0668
	606	0.65203	0.34763	55.3961	1.593545	—	0.0921	—	0.0549
	607	0.65567	0.34402	54.1137	1.572989	—	0.0806	—	0.0437
	608	0.65917	0.34055	52.8352	1.551454	—	0.0699	—	0.0333

A	λ, nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
	609	0.66253	0.33722	51.5632	1.529063	—	0.0598	—	0.0234
	610	0.66576	0.33401	50.3000	1.505940	—	0.0501	—	0.0141
31	610.14	0.66619	0.33358	50.1245	1.502608	—	0.0489	—	0.0129
	611	0.66887	0.33092	49.0468	1.482143	—	0.0412	—	0.0054
	612	0.67186	0.32795	47.8030	1.457644	—	0.0326	—	−0.0030
	613	0.67472	0.32509	46.5677	1.432434	—	0.0244	—	−0.0108
	614	0.67746	0.32236	45.3403	1.406502	—	0.0155	—	−0.0197
	615	0.68008	0.31975	44.1200	1.379840	—	0.0098	—	−0.0253
	616	0.68258	0.31725	42.9080	1.352503	—	0.0030	—	−0.0318
	617	0.68497	0.31486	41.7036	1.324480	—	−0.0035	—	−0.0381
	618	0.68725	0.31259	40.5032	1.295745	—	−0.0094	—	−0.0438
	619	0.68943	0.31041	39.3032	1.266154	—	−0.0152	—	−0.0494
	620	0.69151	0.30834	38.1000	1.235639	—	−0.0204	—	−0.0545
	621	0.69349	0.30637	36.8918	1.204176	—	−0.0255	—	−0.0594
	622	0.69539	0.30448	35.6827	1.171928	—	−0.0304	—	−0.0641
	623	0.69721	0.30267	34.4776	1.139098	—	−0.0347	—	−0.0685
	624	0.69894	0.30095	33.2817	1.105888	—	−0.0391	—	−0.0727
32	625	0.70061	0.29930	32.1000	1.072500	—	−0.0431	—	−0.0765
	−491.09	0.70061	0.29930	32.1000	1.072500	—	−0.0431	—	−0.0766
	−492	0.67236	0.28467	31.3458	1.101105	—	−0.0869	—	−0.1233
33	−492.79	0.63925	0.26753	30.4093	1.136638	—	−0.1477	—	−0.1882
	−493	0.62830	0.26186	30.0861	1.148904	—	−0.1706	—	−0.2127
	−494	0.59401	0.24411	29.0275	1.189070	—	−0.2538	—	−0.3017
	−495	0.56652	0.22988	28.1236	1.223371	—	−0.3363	—	−0.3905
34	−495.28	0.53962	0.22631	27.8886	1.232286	—	−0.3600	—	−0.4525
	−496	0.54403	0.21824	27.3444	1.252935	—	−0.4185	—	−0.4789
	−497	0.52544	0.20862	26.6714	1.278471	—	−0.4992	—	−0.5660
	−498	0.50973	0.20048	26.0810	1.300874	—	−0.5792	—	−0.6499

A	λ. nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
35	−498.45	0.50340	0.19721	25.8373	1.310122	—	−0.6152	—	−0.6911
	−499	0.49638	0.19357	25.5627	1.320541	—	−0.6579	—	−0.7375
	−500	0.48481	0.18759	25.1008	1.338066	—	−0.7356	—	−0.8217
	−501	0.47486	0.18243	24.6934	1.353526	—	−0.8115	—	−0.9039
	−502	0.46607	0.17788	24.3256	1.367481	—	−0.8863	−1.0148	−0.9854
40	−502.69	0.46041	0.17495	24.0851	1.376610	—	−0.9391	−0.9585	−1.0431
	−503	0.45828	0.17385	23.9933	1.380091	−1.0415	−0.9601	−0.9381	—
	−504	0.45131	0.17024	23.6909	1.391567	−0.9681	−1.0330	−0.8730	—
	−505	0.44500	0.16698	23.4128	1.402118	−0.9045	—	−0.8165	—
	−506	0.43924	0.16399	23.1550	1.411900	−0.8490	—	−0.7668	—
	−507	0.43399	0.16128	22.9170	1.420933	−0.8002	—	−0.7231	—
	−508	0.42915	0.15877	22.6948	1.429365	−0.7567	—	−0.6621	—
	−509	0.42468	0.15646	22.4875	1.437229	−0.7178	—	−0.6490	—
41	−509.12	0.42386	0.15603	22.4490	1.438692	−0.7107	—	−0.6424	—
	−510	0.42053	0.15431	22.2926	1.444624	−0.6827	—	−0.6171	—
	−511	0.41667	0.15231	22.1096	1.451596	−0.6506	—	−0.5883	—
	−512	0.41306	0.15044	21.9370	1.458116	−0.6217	—	−0.5621	—
	−513	0.40965	0.14868	21.7726	1.464357	−0.5940	—	−0.5735	—
	−514	0.40645	0.14702	21.6165	1.470279	−0.5699	—	−0.5150	—
	−515	0.40344	0.14546	21.4691	1.475871	−0.5470	—	−0.4942	—
	−516	0.40065	0.14402	21.3313	1.481101	−0.5263	—	−0.4755	—
	−517	0.39805	0.14267	21.2017	1.486016	−0.5071	—	−0.4582	—
	−518	0.39553	0.14137	21.0756	1.490803	−0.4890	—	−0.4413	—
	−519	0.39311	0.14012	20.9539	1.495423	−0.4718	—	−0.4257	—
	−520	0.39082	0.13893	20.8376	1.499833	−0.4557	—	−0.4110	—
42	−520.40	0.38991	0.13846	20.7915	1.501583	−0.4494	—	−0.4050	—
	−521	0.38859	0.13778	20.7243	1.504134	−0.4402	—	−0.3967	—
	−522	0.38648	0.13668	20.6156	1.508257	−0.4257	—	−0.3865	—
	−523	0.38439	0.13560	20.5081	1.512337	−0.4117	—	−0.3707	—

A	λ. nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
	−524	0.38232	0.13453	20.4010	1.516400	−0.3979	—	−0.3581	—
	−525	0.38025	0.13346	20.2929	1.520504	−0.3842	—	−0.3453	—
	−526	0.37819	0.13239	20.1852	1.524587	−0.3708	—	−0.3330	—
	−527	0.37608	0.13130	20.0741	1.528803	−0.3572	—	−0.3205	—
	−528	0.37400	0.13022	19.9636	1.532997	−0.3439	—	−0.3084	—
	−529	0.37189	0.12913	19.8511	1.537265	−0.3306	—	−0.2960	—
	−530	0.36977	0.12803	19.7376	1.541574	−0.3174	—	−0.2839	—
	−531	0.36764	0.12693	19.6229	1.545925	−0.3043	—	−0.2719	—
	−532	0.36550	0.12582	19.5071	1.550318	−0.2913	—	−0.2597	—
	−533	0.36332	0.12469	19.3884	1.544824	−0.2782	—	−0.2477	—
	−534	0.36110	0.12354	19.2666	1.559445	−0.2650	—	−0.2355	—
	−535	0.35887	0.12239	19.1436	1.564114	−0.2519	—	−0.2233	—
	−536	0.35657	0.12120	19.0163	1.568941	−0.2386	—	−0.2111	—
43	−536.31	0.35586	0.12083	18.9767	1.570447	−0.2345	—	−0.2072	—
	−537	0.35423	0.11999	18.8858	1.573895	−0.2252	—	−0.1987	—
	−538	0.35179	0.11873	18.7487	1.579096	−0.2114	—	−0.1857	—
	−539	0.34934	0.11746	18.6100	1.584360	−0.1977	—	−0.1731	—
	−540	0.34682	0.11615	18.4664	1.589808	−0.1838	—	−0.1602	—
	−541	0.34417	0.11478	18.3146	1.595568	−0.1694	—	−0.1468	—
	−542	0.34145	0.11337	18.1574	1.601532	−0.1548	—	−0.1332	—
	−543	0.33859	0.11189	17.9912	1.607838	−0.1397	—	−0.1192	—
	−544	0.33564	0.11036	17.8179	1.614417	−0.1243	—	−0.1049	—
	−545	0.33258	0.10878	17.6369	1.621283	−0.1086	—	−0.0901	—
	−546	0.32941	0.10714	17.4480	1.628452	−0.0926	—	−0.0752	—
	−547	0.32605	0.10540	17.2457	1.636125	−0.0759	—	−0.0596	—
	−548	0.32251	0.10357	17.0306	1.644289	−0.0585	—	−0.0435	—
44	−548.11	0.32195	0.10328	16.9965	1.645584	−0.0559	—	−0.0408	—
	−549	0.31885	0.10167	16.8056	1.652828	−0.0410	—	−0.0271	—
	−550	0.31495	0.09965	16.5634	1.662018	−0.0225	—	−0.0098	—
	−551	0.31082	0.09752	16.3042	1.671853	−0.0035	—	−0.0082	—

A	λ. nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
44	−552	0.30652	0.09529	16.0309	1.682222	0.0160	—	0.0265	—
	−553	0.30191	0.09290	15.7338	1.693496	0.0365	—	0.0457	—
	−554	0.29707	0.09040	15.4184	1.705464	0.0575	—	0.0655	—
	−555	0.29192	0.08773	15.0769	1.718422	0.0794	—	0.0861	—
45	−555.96	0.28657	0.08496	14.7168	1.732085	0.1016	—	0.1070	—
	−556	0.28635	0.08485	14.7019	1.732450	0.1025	—	0.1079	—
	−557	0.28041	0.08177	14.2953	1.748080	0.1265	—	0.1306	—
	−558	0.27412	0.07852	13.8574	1.746695	0.1512	—	0.1541	—
	−559	0.26727	0.07497	13.3698	1.783195	0.1774	—	0.1788	—
	−560	0.25999	0.07120	12.8406	1.803277	0.2044	—	0.2045	—
	−561	0.25211	0.06712	12.2542	1.825527	0.2327	—	0.2314	—
	−562	0.24346	0.06265	11.5940	1.850577	0.2627	—	0.2599	—
	−563	0.23416	0.05783	10.8636	1.878294	0.2938	—	0.2896	—
	−564	0.22403	0.05259	10.0422	1.909461	0.3265	—	0.3209	—
46	−564.18	0.22202	0.05155	9.8764	1.915754	0.3327	—	0.3268	—
	−565	0.21288	0.04682	9.1064	1.944969	0.3608	—	0.3537	—
	−566	0.20064	0.04048	8.0384	1.985495	0.3969	—	0.3885	—
	−567	0.18708	0.03346	6.8021	2.032405	0.4350	—	0.4251	—
	−568	0.17201	0.02366	5.3572	2.087233	0.4753	—	0.4637	—
	−568.92	0.15664	0.01771	3.8000	2.146310	0.5141	—	0.5014	—
50	450	0.15664	0.01771	3.8000	2.146310	0.5141	—	0.5017	—
	451	0.15560	0.01861	3.9846	2.141304	0.5190	—	0.5062	—
	452	0.15452	0.01956	4.1768	2.135848	0.5244	—	0.5111	—
	453	0.15340	0.02055	4.3766	2.129346	0.5297	—	0.5166	—
	454	0.15222	0.02161	4.5842	2.121196	0.5358	—	0.5221	—
	455	0.15099	0.02274	4.8000	2.110800	0.5420	—	0.5281	—
	456	0.14969	0.02395	5.0243	2.097828	0.5486	—	0.5344	—
	457	0.14834	0.02525	5.2573	2.082315	0.5555	—	0.5411	—
	458	0.14693	0.02663	5.4980	2.064208	0.5633	—	0.5482	—
	459	0.14547	0.02812	5.7458	2.043454	0.5711	—	0.5559	—

A	λ. nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
	460	0.14396	0.02970	6.0000	2.020000	0.5799	—	0.5637	—
	461	0.14241	0.03139	6.2601	1.994100	0.5888	—	0.5722	—
	462	0.14080	0.03321	6.5277	1.965411	0.5983	—	0.5811	—
	463	0.13912	0.03520	6.8042	1.932982	0.6085	—	0.5909	—
	464	0.13737	0.03740	7.0911	1.895861	0.6195	—	0.6013	—
	465	0.13550	0.03988	7.3900	1.853100	0.6319	—	0.6128	—
	466	0.13351	0.04269	7.7016	1.803974	0.6457	—	0.6259	—
	467	0.13137	0.04588	8.0266	1.749639	0.6611	—	0.6405	—
	468	0.12909	0.04945	8.3666	1.691953	0.6786	—	0.6569	—
51	468.71	0.12736	0.05227	8.6198	1.649940	0.6924	—	0.6696	—
	469	0.12666	0.05343	8.7232	1.632780	0.6981	—	0.6750	—
	470	0.12412	0.05780	9.0980	1.573980	0.7196	—	0.6953	—
	471	0.12147	0.06259	9.4917	1.516553	0.7438	—	0.7178	—
	472	0.11870	0.06783	9.9045	1.460197	0.7707	—	0.7429	—
	473	0.11581	0.07358	10.3367	1.404816	0.8009	—	0.7709	—
	474	0.11278	0.07989	10.7884	1.350315	0.8349	—	0.8026	—
	475	0.10960	0.08684	11.2600	1.296600	0.8742	—	0.8388	—
52	475.44	0.10813	0.09020	11.4770	1.273415	0.8941	—	0.8568	—
	476	0.10626	0.09449	11.7532	1.243908	0.9193	—	0.8804	—
	477	0.10278	0.10286	12.2674	1.192591	0.9718	1.0290	0.9282	—
	478	0.09913	0.11201	12.7992	1.142721	1.0334	0.9677	0.9841	1.0162
	479	0.09531	0.12194	13.3452	1.094370	—	0.9042	1.0501	0.9523
53	479.29	0.09414	0.12506	13.5067	1.080809	—	0.8847	—	0.9331
	480	0.09129	0.13270	13.9020	1.047610	—	0.8385	—	0.8866
	481	0.08708	0.14432	14.4676	1.002493	—	0.7706	—	0.8185
	482	0.08268	0.15687	15.0469	0.959222	—	0.7005	—	0.7484
54	482.04	0.08249	0.15741	15.0709	0.957577	—	0.6976	—	0.7453
	483	0.07812	0.17042	15.6461	0.918093	—	0.6283	—	0.6760
	484	0.07344	0.18503	16.2717	0.879403	—	0.5541	—	0.6018

A	λ. nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
55	484.29	0.07206	0.18958	16.4626	0.868977	—	0.5317	—	0.5794
	485	0.06871	0.20072	16.9300	0.843450	—	0.4783	—	0.5257
	486	0.06399	0.21747	17.6243	0.810433	—	0.4010	—	0.4486
	487	0.05932	0.23525	18.3558	0.780255	—	0.3226	—	0.3701
56	487.31	0.05787	0.24109	18.5949	0.771732	—	0.2981	—	0.3451
	488	0.05467	0.25409	19.1273	0.752761	—	0.2430	—	0.2903
	489	0.05003	0.27400	19.9418	0.727798	—	0.1621	—	0.2095
	490	0.04539	0.29498	20.8020	0.705210	—	0.0801	—	0.1274
60	490.40	0.04353	0.30378	21.1659	0.697110	—	0.0489	—	0.0938
	491	0.04076	0.31698	21.7119	0.684961	—	−0.0030	—	0.0442
	492	0.03620	0.33990	22.6734	0.667062	—	−0.0866	—	−0.0393
61	492.72	0.03291	0.35696	23.4022	0.655804	—	−0.1477	—	−0.0998
	493	0.03176	0.36360	23.6857	0.651426	—	−0.1704	—	−0.1231
	494	0.02749	0.38792	24.7481	0.637967	—	−0.2540	—	−0.2065
	495	0.02346	0.41270	25.8600	0.626600	—	−0.3369	—	−0.2894
62	495.28	0.02240	0.41971	26.1483	0.623969	—	−0.3600	—	−0.3124
	496	0.01970	0.43776	27.0184	0.617204	—	−0.4187	—	−0.3711
	497	0.01627	0.46295	28.2293	0.609765	—	−0.4997	—	−0.4517
	498	0.01318	0.48821	29.5050	0.604355	—	−0.5794	—	−0.5315
63	498.45	0.01196	0.49954	30.1137	0.596037	—	−0.6152	—	−0.5669
	499	0.01048	0.51340	30.8578	0.601042	—	−0.6584	—	−0.6102
	500	0.00817	0.53842	32.3000	0.599900	—	−0.7362	—	−0.6875
	501	0.00628	0.56307	33.8402	0.600996	—	−0.8127	—	−0.7637
	502	0.00487	0.58712	35.4685	0.604111	—	−0.8878	—	−0.8385
64	502.69	0.00425	0.60321	36.6425	0.607414	—	−0.9391	—	−0.8887
	503	0.00398	0.61045	37.1698	0.608895	−1.0403	−0.9613	—	−0.9115
	504	0.00364	0.63301	38.9287	0.614977	−0.9670	−1.0341	−1.0166	−0.9837
	505	0.00386	0.65482	40.7300	0.622000	−0.9042	—	−0.9479	−1.0549

A	λ. nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
	506	0.00464	0.67590	42.5629	0.629724	−0.8490	—	−0.8882	—
	507	0.00601	0.69612	44.4309	0.638265	−0.8003	—	−0.8356	—
	508	0.00799	0.71534	46.3394	0.7889	−0.7568	—	−0.7889	—
	509	0.01060	0.73341	48.2939	0.658481	−0.7178	—	−0.7474	—
65	509.12	0.01099	0.73542	48.5346	0.659924	−0.7107	—	−0.7423	—
	510	0.01387	0.75019	50.3000	0.670500	−0.6824	—	−0.7092	—
	511	0.01777	0.76561	52.3569	0.683857	−0.6504	—	−0.6755	—
	512	0.02224	0.77963	54.4512	0.698423	−0.6210	—	−0.6447	—
	513	0.02727	0.79211	56.5690	0.714161	−0.5942	—	−0.6164	—
	514	0.03282	0.80293	58.6965	0.731033	−0.5695	—	−0.5907	—
	515	0.03885	0.81202	60.8200	0.749000	−0.5470	—	−0.5669	—
	516	0.04533	0.81939	62.9345	0.768065	−0.5261	—	−0.5452	—
	517	0.05218	0.82516	65.0306	0.788094	−0.5067	—	−0.5250	—
	518	0.05932	0.82943	67.0875	0.808842	−0.4890	—	−0.5065	—
	519	0.06672	0.83227	69.0842	0.830066	−0.4714	—	−0.4888	—
	520	0.07430	0.83380	71.0000	0.851519	−0.4555	—	−0.4623	—
66	520.40	0.08050	0.83391	71.7274	0.859523	−0.4404	—	−0.4599	—
	521	0.08205	0.84309	72.8185	0.873029	−0.4402	—	−0.4568	—
	522	0.08994	0.83329	74.5463	0.894604	−0.4257	—	−0.4417	—
	523	0.09794	0.83159	76.1969	0.916277	−0.4116	—	−0.4274	—
	524	0.10602	0.82918	77.7836	0.938081	−0.3977	—	−0.4132	—
	525	0.11416	0.82621	79.3200	0.960050	−0.3841	—	−0.3994	—
	526	0.12235	0.82277	80.8110	0.982182	−0.3705	—	−0.3855	—
	527	0.13005	0.81893	82.2496	1.004357	−0.3571	—	−0.3719	—
	528	0.13870	0.81478	83.6306	1.026427	−0.3437	—	−0.3582	—
	529	0.14677	0.81040	84.9491	1.048244	−0.3303	—	−0.3447	—
	530	0.15472	0.80586	86.2000	1.069660	−0.3172	—	−0.3313	—
	531	0.16253	0.80124	87.3810	1.090575	−0.3042	—	−0.3180	—
	532	0.17024	0.79652	88.4962	1.111038	−0.2911	—	−0.3048	—
	533	0.17785	0.79169	89.5493	1.131121	−0.2781	—	−0.2915	—

A	λ, nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
66	534	0.18539	0.78673	90.5443	1.150897	−0.2650	—	−0.2783	—
	535	0.19288	0.78163	91.4850	1.170440	−0.2517	—	−0.2648	—
	536	0.20031	0.77640	92.3734	1.189767	−0.2384	—	−0.2512	—
70	536.31	0.20259	0.77474	92.6325	1.195684	−0.2345	—	−0.2471	—
	537	0.20769	0.77105	93.2092	1.208853	−0.2250	—	−0.2377	—
	538	0.21503	0.76559	93.9922	1.227701	−0.2115	—	−0.2237	—
	539	0.22234	0.76002	94.7225	1.246316	−0.1976	—	−0.2096	—
	540	0.22962	0.75433	95.4000	1.264700	−0.1835	—	−0.1953	—
	541	0.23689	0.74852	96.0256	1.282865	−0.1693	—	−0.1808	—
	542	0.24413	0.74262	96.6007	1.300820	−0.1546	—	−0.1657	—
	543	0.25136	0.73661	97.1260	1.313562	−0.1397	—	−0.1505	—
	544	0.25858	0.73051	97.6022	1.336089	−0.1242	—	−0.1349	—
	545	0.26578	0.72432	98.0300	1.353400	−0.1085	—	−0.1187	—
	546	0.27296	0.71806	98.4092	1.370483	−0.0922	—	−0.1021	—
	547	0.28013	0.71172	98.7481	1.387422	−0.0757	—	−0.0852	—
	548	0.28729	0.70532	99.0312	1.404069	−0.0585	—	−0.0655	—
71	548.11	0.28807	0.70460	99.0587	1.410097	−0.0559	—	−0.0655	—
	549	0.29445	0.69884	99.2811	1.420652	−0.0410	—	−0.0494	—
	550	0.30160	0.69231	99.4950	1.437149	−0.0225	—	−0.0305	—
	551	0.30876	0.68571	99.6710	1.453541	−0.0035	—	−0.0110	—
	552	0.31592	0.67906	99.8098	1.462434	0.0161	—	0.0091	—
	553	0.32306	0.67237	99.9112	1.485961	0.0365	—	0.0302	—
	554	0.33021	0.66563	99.9748	1.501998	0.0576	—	0.0521	—
	555	0.33736	0.65885	100.0000	1.517800	0.0797	—	0.0747	—
72	555.96	0.34422	0.65230	99.9862	1.532830	0.1016	—	0.0975	—
	556	0.34451	0.65203	99.9856	1.533456	0.1026	—	0.0984	—
	557	0.35167	0.64517	99.9304	1.548896	0.1265	—	0.1231	—
	558	0.35881	0.63829	99.8325	1.564069	0.1514	—	0.1491	—
	559	0.36596	0.63138	99.6898	1.578922	0.1774	—	0.1761	—
	560	0.37310	0.62445	99.5000	1.593400	0.2045	—	0.2044	—

A	λ, nm	x_λ	y_λ	Y_λ	ε_λ	cot φ_C	tan φ_C	cot φ_{D65}	tan φ_{D65}
73	560.74	0.37838	0.61930	99.3224	1.603793	0.2254	—	0.2262	—
	561	0.38024	0.61750	99.2600	1.607444	0.2329	—	0.2340	—
	562	0.38738	0.61054	98.9742	1.621089	0.2627	—	0.2651	—
	563	0.39451	0.60357	98.6444	1.634346	0.2937	—	0.2979	—
	564	0.40163	0.59659	98.2724	1.647255	0.3265	—	0.3323	—
74	564.18	0.40290	0.59533	98.1981	1.649449	0.3327	—	0.3386	—
	565	0.40873	0.58961	97.8600	1.659749	0.3608	—	0.3685	—
	566	0.41583	0.58262	97.4083	1.669322	0.3969	—	0.4067	—
75	566.78	0.42141	0.57716	97.0252	1.681081	0.4265	—	0.4380	—
	567	0.42292	0.57563	96.9171	1.683668	0.4350	—	0.4469	—
	568	0.42999	0.56865	96.3856	1.694994	0.4751	—	0.4895	—
76	568.92	0.43647	0.56222	95.8592	1.704981	0.5140	—	0.5305	—
	569	0.43704	0.56167	95.8123	1.705850	0.5173	—	0.5344	—
	570	0.44406	0.55472	95.2000	1.176200	0.5616	—	0.5820	—

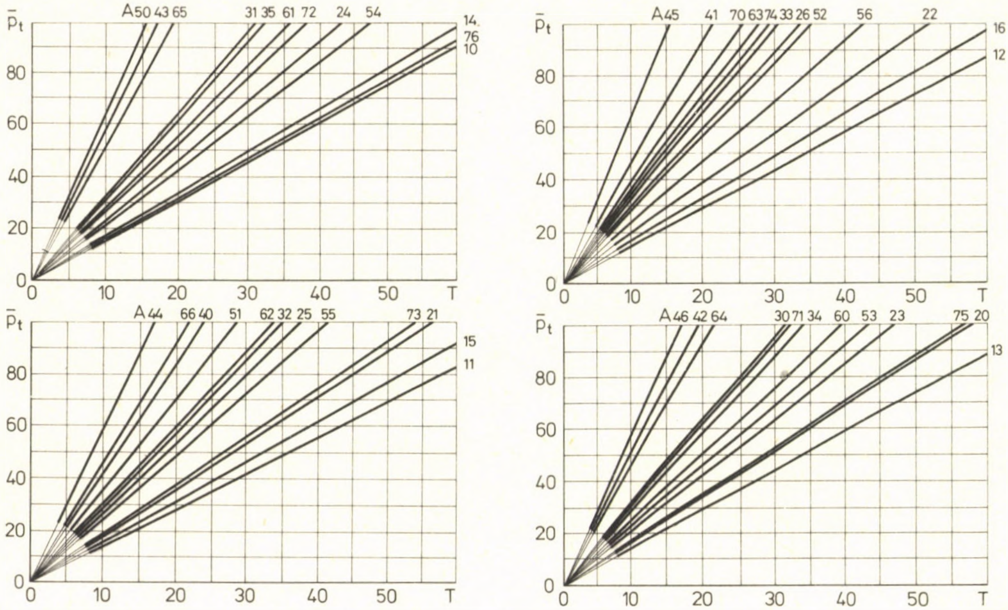
A. 3

Names of Coloroid primary colours and symbols of Coloroid primary hues corresponding to primary colours

Symbol of Coloroid primary hue (A)	Name of the colour domain	Name of the Coloroid primary colour
10	yellow	yellow 1
11		yellow 2
12		yellow 3
13		warm yellow 1
14		warm yellow 2
15		orange yellow 1
16		orange yellow 2
20	orange	yellowish orange 1
21		yellowish orange 2
22		orange 1
23		orange 2
24		orange 3
25		reddish orange 1
26		reddish orange 2
30	red	red 1
31		red 2
32		red 3
33		purple red 1
34		purple red 2
35		purple red 3
40	violet	purple 1
41		purple 2
42		violet 1
43		violet 2
44		violet 3
45		bluish violet 1
46		bluish violet 2
50	blue	violet blue 1
51		violet blue 2
52		blue 1
53		blue 2
54		blue 3
55		cold blue 1
56		cold blue 2
60	green 1	bluish green
61		cold green 1
62		cold green 2
63		cold green 3
64		green 1
65		green 2
66		green 3
70	green 2	warm green 1
71		warm green 2
72		warm green 3
73		yellowish green 1
74		yellowish green 2
75		yellowish green 3
76		yellowish green 4

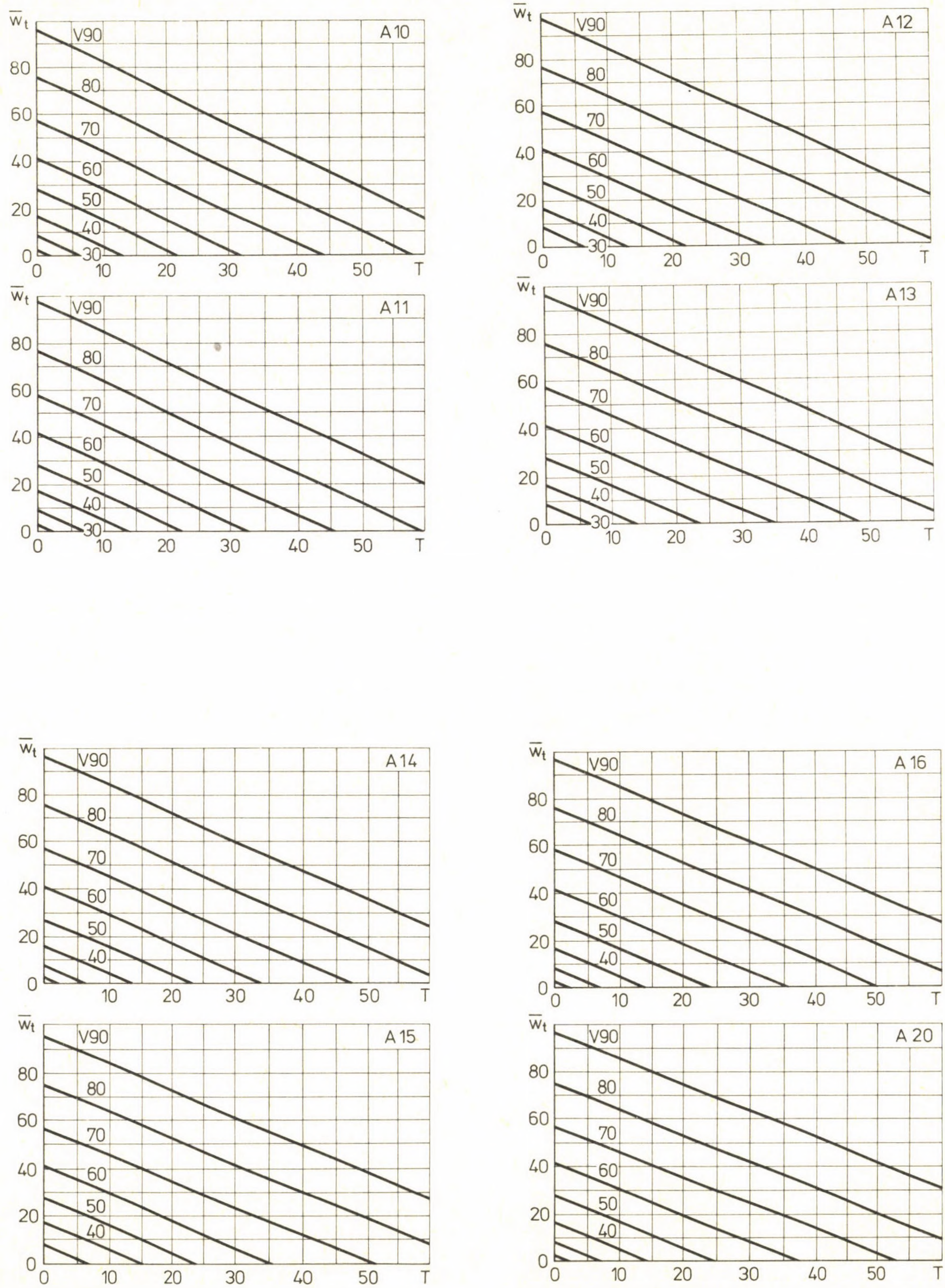
A. 4

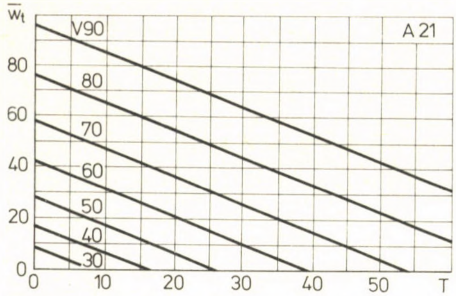
Colour contents $\bar{p}_t$ for different Coloroid saturations of different Coloroid hues if mixing is made by means of the enclosed discs

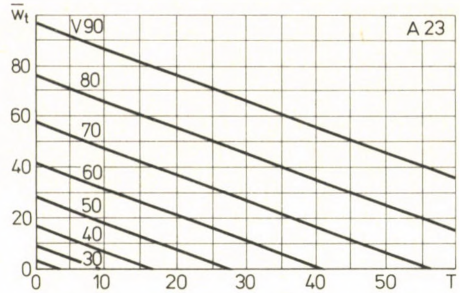


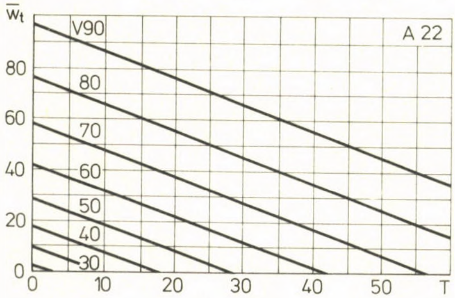
A. 5

White contents $\bar{w}_t$ for different Coloroid saturations of different Coloroid hues if mixing is made by means of the enclosed discs




A 21
$\overline{w}_t$
V90
80
70
60
50
40
30
0 10 20 30 40 50 T


A 23
$\overline{w}_t$
V90
80
70
60
50
40
30
0 10 20 30 40 50 T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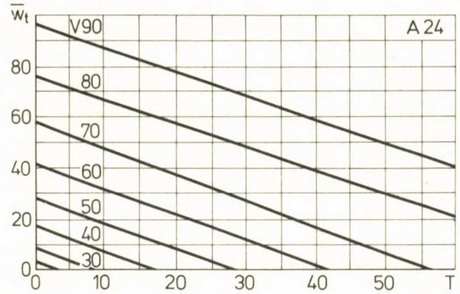
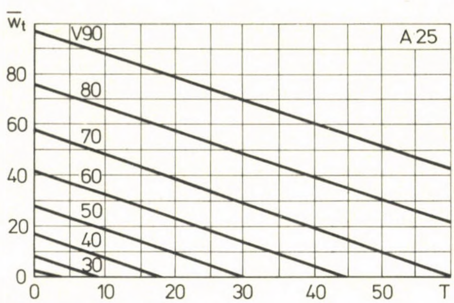
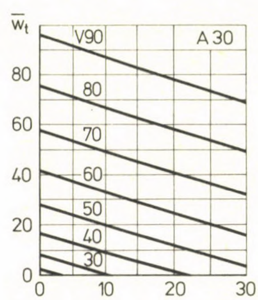
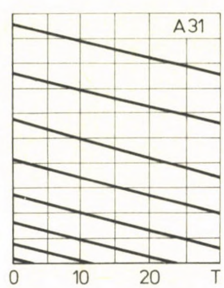
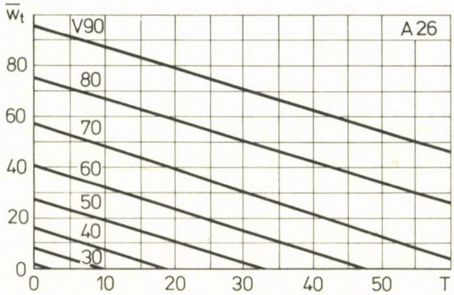
$\overline{w}_t$
V90
80
70
60
50
40
30
0 10 20 30 40 50 T


A 24
$\overline{w}_t$
V90
80
70
60
50
40
30
0 10 20 30 40 50 T


A 25
$\overline{w}_t$
V90
80
70
60
50
40
30
0 10 20 30 40 50 T


A 30
$\overline{w}_t$
V90
80
70
60
50
40
30
0 10 20 30


A 31
0 10 20 T


A 26
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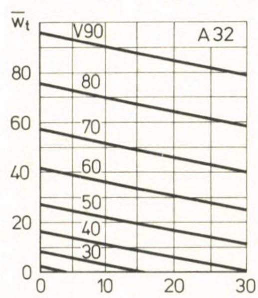
V90
80
70
60
50
40
30
0 10 20 30 40 50 T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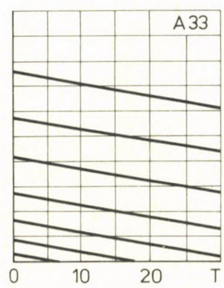
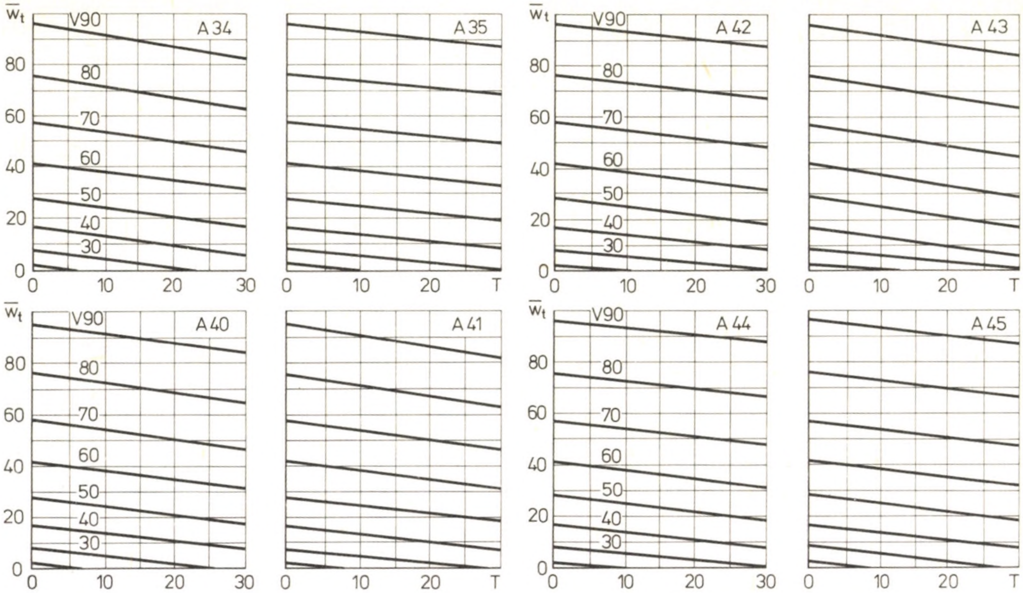
$\overline{w}_t$
V90
80
70
60
50
40
30
0 10 20 30


A 33
0 10 20 T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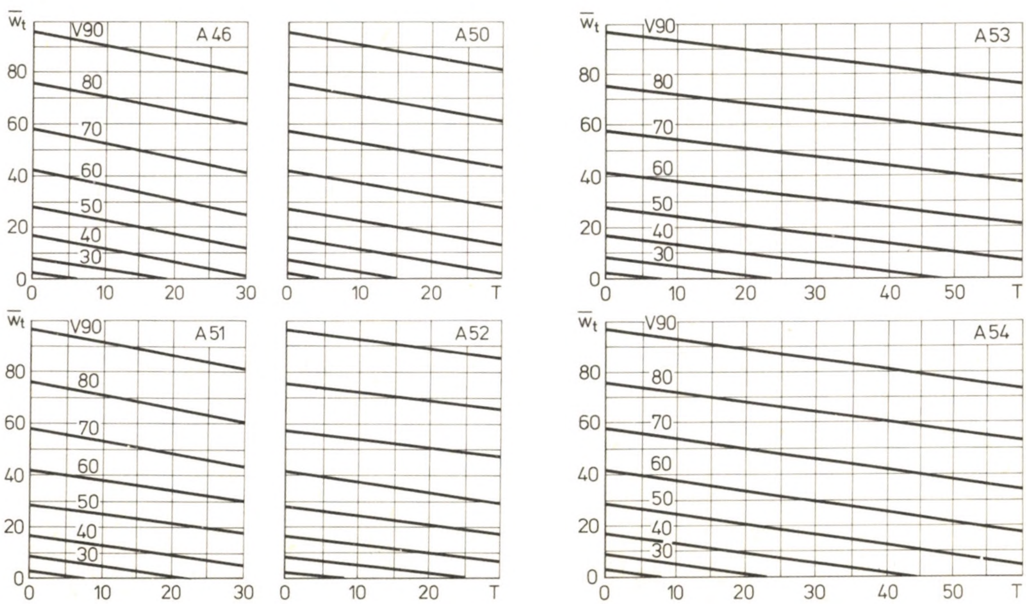
A 35
A 42
A 43
A 40
A 41
A 44
A 45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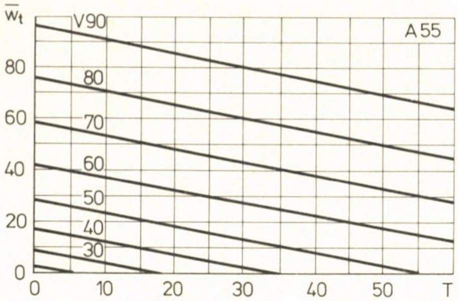
A 50
A 53
A 51
A 52
A 54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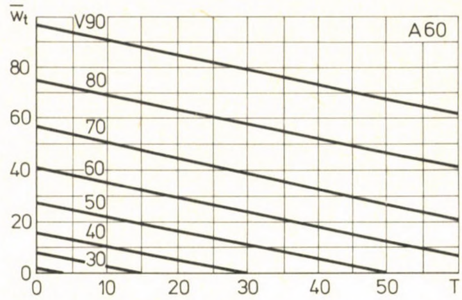
V90
80
70
60
50
40
30
0 10 20 30 40 50 T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V90
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60
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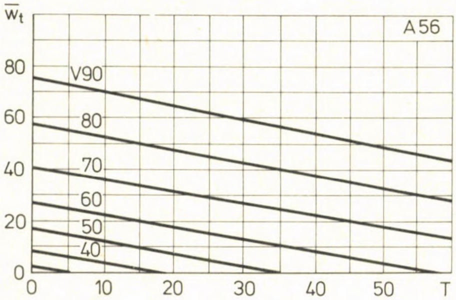
40
30
0 10 20 30 40 50 T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V90
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70
60
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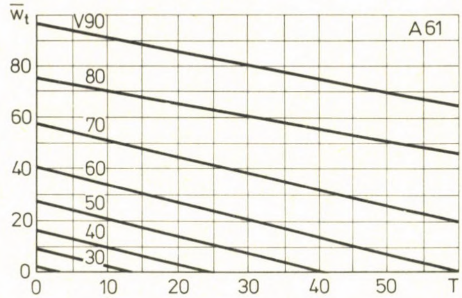
40
0 10 20 30 40 50 T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70
60
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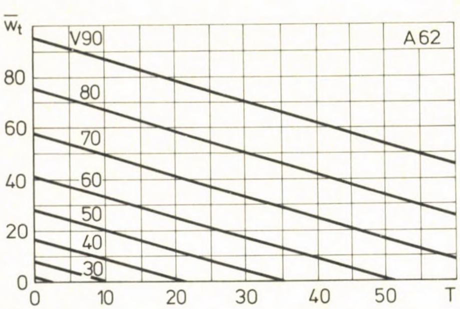
0 10 20 30 40 50 T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V90
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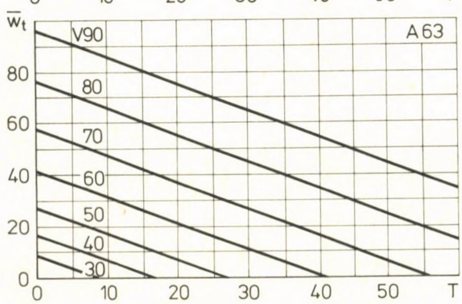
0 10 20 30 40 50 T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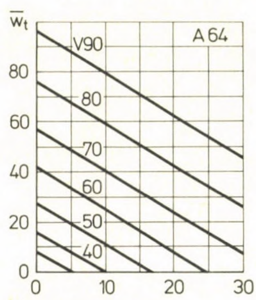
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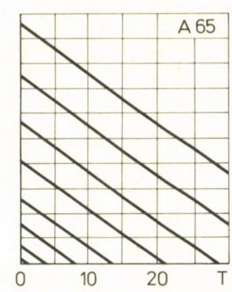
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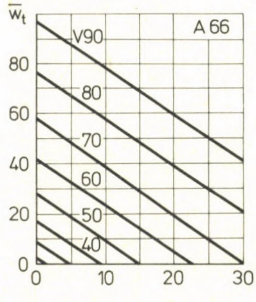
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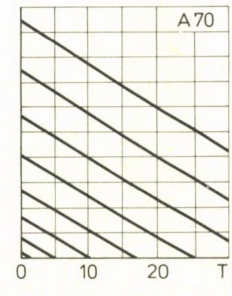
0 10 20 30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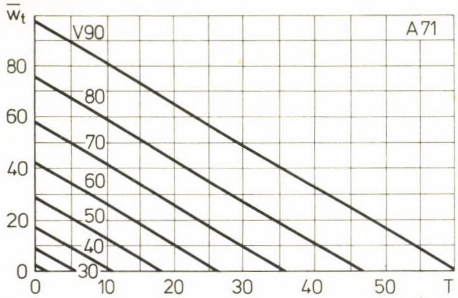
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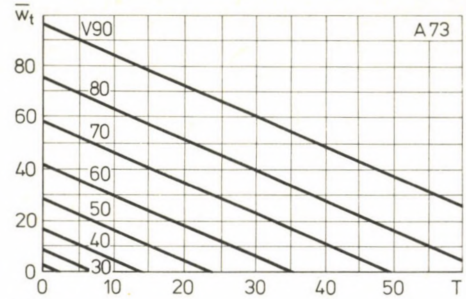
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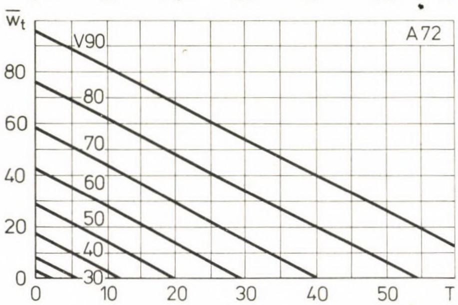
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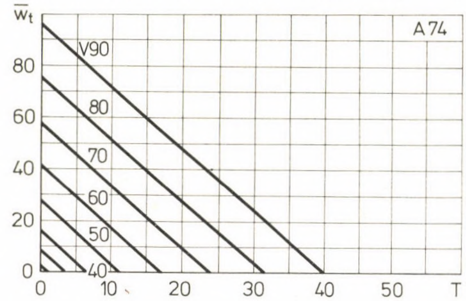
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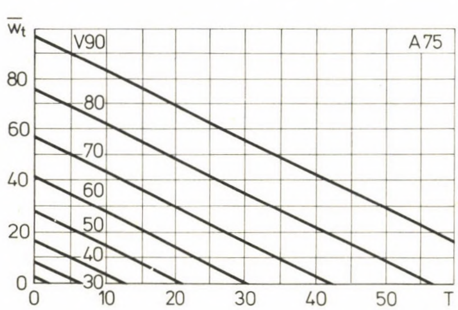
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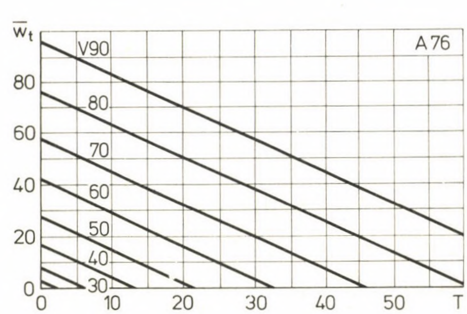
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V90
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80
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T

A. 6

Colour Names

A	*T*	*V*	
10	5–20	95–85	yellowish white, alument
		85–60	greenish grey
		60–40	olive grey
	20–30	90–80	pale yellow, croceum
		80–65	ash yellow
		65–50	ash green
	30–45	90–80	sunflower yellow, Manchester yellow
		80–70	saffron yellow
		70–60	saffron green
	45–55	85–75	primitive yellow
		75–65	greenish lemon yellow, mikado yellow
11	5–15	95–85	shell white
		85–60	warm greenish grey
		60–40	brownish olive green
	15–30	95–85	eggshell yellow
		85–60	greenish yellow
		60–45	olive green
	30–45	95–85	pastel yellow
		85–70	linden yellow
		70–60	moss green
	45–55	90–80	primose yellow
		80–70	chamomile yellow
	55–65	90–75	lemon yellow, Empire yellow
12	5–15	95–85	warm broken white, flaxen
		85–60	warm grey
		60–40	dioxine green
	15–35	95–85	straw yellow
		85–65	absinthe yellow, Flanders yellow
		65–50	cinnamon green
	35–50	95–85	sun yellow, Leipzig yellow
		85–75	chrome yellow
		75–65	green ochre, mercuric yellow
	50–65	90–75	canary-yellow, Jewish yellow
13	5–20	90–80	chamotte white, stone yellow
		80–60	Nanking grey
		60–40	cinnamon brown, tobacco brown
	20–35	90–80	chicken yellow, Gothaic yellow
		80–70	mustard yellow
		70–60	Cassell brown
	35–45	85–80	mimosa yellow
		80–70	fiery ochre, Victorian yellow
		70–65	Baroque yellow
	45–60	80–75	light cadmium yellow, Indian yellow
		75–65	dark cadmium yellow, Mars yellow
14	5–15	95–85	golden white
		85–55	golden grey
		55–35	natural umber, Brussels brown
	15–30	90–80	cement yellow, Madeira yellow
		80–65	beige
		65–50	khaki, seal
	30–45	90–75	Chinese yellow
		75–60	golden ochre, gamboge
	45–55	85–70	orpiment
15	5–15	90–80	Chartreux white
		80–50	Chartreux grey
		50–30	umber
	15–30	90–80	Naples yellow
		80–55	banana yellow
		55–40	sienna
	30–40	85–70	cream yellow
		70–55	amber
	40–50	80–60	orange

A	*T*	*V*	
16	5–15	90–80	liver white
		80–55	Havana grey
		55–30	oxide brown, carob brown
	15–30	90–80	topaz yellow
		80–60	Cassel golden brown
		60–45	burnt ochre
	30–40	85–70	India yellow
		70–55	oxide yellow
	40–50	80–65	fiery orange
20	5–15	90–80	broken warm white
		80–55	cement grey
		55–30	earth brown, Anatolian brown
	15–25	90–75	Roman ochre
		75–60	brown beige
		60–50	orange brown, Arsigont
	25–35	85–70	Pompeian yellow
		70–55	orange ochre
	35–60	80–60	Indian orange
21	5–10	90–80	cream white
		80–50	white coffee
		50–30	chocolate
	10–20	90–75	caramel
		75–55	dark red ochre
		55–45	light red ochre
	20–30	85–75	light satinochre
		75–60	carrot yellow
		60–55	Pompeian orange
	30–40	80–70	tangerine
		70–60	Persian orange
22	5–10	90–75	tobacco smoke white
		75–50	sepia
		50–30	peanut
	10–25	90–75	ecru
		75–55	bamboo yellow
		55–40	burnt sienna
	25–30	80–65	American yellow
		65–55	Californian orange
	30–40	70–60	yellowish orange, English orange

A	*T*	*V*	
23	5–15	90–75	orange white
		75–55	caramel brown, Sahara brown
		55–30	nigger brown
	15–35	85–70	female complexion
		70–55	copper orange, sandarac
		55–45	agate brown
	35–45	75–55	fiery orange
24	5–15	90–75	peache white
		75–50	Castilian brown
		50–30	Mummy brown
	15–30	85–70	peach pink
		70–60	terra-cotta
		60–45	onion brown, henna
	30–35	70–60	cadmium orange, Etruscan orange
25	5–10	90–70	rose of dawn
		70–50	shell red
		50–30	shell brown, coffee brown
	10–25	85–70	light orange red
		70–55	brick red
		55–45	autumn red, Memphis red
	25–35	70–55	fiery red, madder
26	5–10	85–70	pink of dawn
		70–45	Damascene red
		45–30	garnet brown
	10–25	80–65	Venetian rose
		65–55	Venetian red
		55–45	rusty brown, Pontian red
	25–35	65–55	orange red, tulip red
30	5–15	85–65	pale red, alabaster red
		65–45	Derby red
		45–30	caput mortuum
	15–25	75–60	Pastel red
		60–45	ferric oxide red, terra pozzuoli
		50–45	Pompeian red, miniate
	25–35	60–50	cinnabar, vermilion

A	*T*	*V*	
31	5–20	80–65	Damascene rose
		65–45	Damascene red
		45–30	burnt umbra, mahogany
	20–35	70–60	cherry
		60–50	cockscomb red, bauxite red
		50–40	wine-red, claret
	35–40	60–45	primitive red, Imperial red
32	5–10	80–65	Pompadour rose
		65–45	bolus red
		45–30	Van Dyck brown
	10–20	80–65	bole, sanguine
		65–50	Bordeaux red, cinnabarite
		50–40	deep red, sultan red
	20–30	75–60	germanium red, cenobrium
		60–50	crimson
33	5–15	80–65	carmine
		65–40	grey carmine, rosroside
		40–25	Dresden red, copper brown
	15–25	75–60	rose mallow, Jerico red
		60–40	German red, Vienna red
		40–35	Burgundy red
	25–35	65–50	flamingo red
		50–40	carmine, Turkish red
34	5–15	80–60	white cornelian
		60–40	grey cornelian
		40–25	realgar brown, syricum
	15–25	75–50	alpine rose
		50–40	dark cornelian
	25–30	65–55	pastel ruby
		55–45	fiery ruby, scarlet

A	*T*	*V*	
35	5–15	80–65	whitish magenta
		65–45	greyish magenta
		45–25	blackish magenta, Lemnos earth
	15–25	75–65	cyclamen rose, Bengali rose
		65–50	Persian red
		50–40	dark magenta, du Barry red
	25–35	65–50	cyclamen red
		50–45	magenta, Bengali red
40	5–10	80–70	whitish purple
		70–45	greyish purple
		45–25	blackish purple
	10–20	80–50	primrose purple
		50–30	dark purple
	20–30	70–50	pastel purple, krapp purple
		50–40	red purple, purple of Indes
41	5–15	80–65	amethyst rose
		65–40	amethyst grey
		40–25	vitriol
	15–25	75–45	amethyst
		45–30	dark amethyst
	25–35	65–35	fiery amethyst
42	5–15	80–70	orchid white
		70–45	orchid grey
		45–25	amaranth violet
	15–30	80–50	impatiens violet
		50–35	dark orchid
	30–35	60–40	crimson violet, magenta
43	5–15	80–65	pastel violet
		65–40	greyish violet
		40–25	aubergine
	15–30	75–60	bell-flower violet
		60–45	thistle violet
		45–30	Parma violet
		30–35	violet

A	*T*	*V*	
44	5–15	80–65	whitish violet
		65–40	greyish violet
		40–25	ferric violet
	15–30	70–50	heliotrope violet
		50–35	dark violet
	30–40	65–50	violet
		50–40	fiery violet
45	5–10	80–65	whitish violet
		65–40	greyish violet
		40–25	blackish violet
	10–20	75–50	pastel violet, violet of Azon
		50–30	iris violet
	20–30	65–45	lilac
		45–35	fiery violet, Victorian violet
46	5–10	80–55	indigo white
		55–35	indigo grey
		35–25	indigo
	10–20	75–55	lavender, Bordeaux violet
		55–35	chrome violet, veronica violet
		35–25	Chinese indigo
	20–25	65–45	light violet blue
		45–30	dark violet blue, Spanish violet
50	5–10	80–60	geranium blue
		60–35	lido blue
		35–25	Oxford blue
	10–20	75–60	anemone blue
		60–35	King's blue
		35–25	crocus blue
	20–25	65–30	fiery violet blue, houri blue
51	5–15	80–70	mauve blue
		70–40	antimony blue
		40–25	Babylonian blue
	15–25	75–55	cornflower blue
		55–40	lapis lazuli
		40–30	princely blue
	25–30	65–45	light ultramarine blue
		45–35	dark ultramarine blue, Scythian blue
52	5–15	80–55	whitish cobalt blue, ceruse
		55–35	lime blue
		35–25	Berlin blue
	15–25	75–55	larkspur blue
		55–40	knightly blue
		40–30	dolphin blue
	25–35	65–45	light cobalt blue
		45–35	dark cobalt blue, smalt
53	5–20	80–70	smoky blue
		70–45	greyish manganese blue
		45–25	Paris blue
	20–40	75–65	blue-bell
		65–50	gentian
		50–35	Egyptian blue
	40–55	70–40	manganese blue
54	5–20	80–70	whitish cerulean
		70–45	cyanide blue
		45–25	Persian blue
	20–45	80–70	pastel blue, Nuremberg blue
		70–50	sea blue, Medici blue
		50–40	Copenhagen blue, fjord blue
	45–55	75–60	light cerulean
		60–50	dark cerulean, fiery Medici blue
55	5–20	80–65	light Coventry blue
		65–50	Coventry blue
		50–25	deep azure, anthracene blue
	20–35	80–65	sky blue
		65–50	blue bird's blue
		50–40	Delphoi blue
	35–50	70–55	light azure
		55–45	dark azure

A	*T*	*V*	
56	5–15	80–75	turquoise blue
		75–40	turquoise grey
		40–25	deep turquoise blue
	15–30	80–65	hyacinth blue
		65–50	China blue
		50–35	Babylon blue
	30–45	75–55	light turquoise blue
		55–45	dark turquoise blue
60	5–20	85–70	ice green
		70–45	myrtle green
		45–25	petroleum green
	20–40	80–60	faience green, praesinus
		60–40	Capri green, aquamarine
	40–50	75–50	turquoise green
61	5–20	85–70	crystal green
		70–45	opal green
		45–25	fierce sea green
	20–35	80–70	verdigris
		70–50	water green
		50–40	sea-green, glaucous
	35–50	75–60	light chromoxide hydrate green
		60–45	dark chrome green
62	5–15	85–75	helio-green
		75–45	greyish green, Pannonian green
		45–30	ape green
	15–35	80–65	salad green
		65–45	cabbage green
		45–40	Triton green
	35–45	75–60	light permanent green
		60–45	dark permanent green
63	5–15	85–70	dust green
		70–45	dirty green, French grey
		45–30	car green
	15–35	75–55	camellia green
		55–40	Spanish green, Schweinfurt green
	35–45	65–45	emerald green

A	*T*	*V*	
64	5–15	85–70	pale green
		70–50	lime green
		50–30	fierce green
	15–30	80–60	nickel green
		60–45	chromium green
	30–40	70–50	peacock green
65	5–15	85–70	pus green
		70–50	pistachio green
		50–30	palm green
	15–20	80–60	patina green
		60–45	Neptune green, Luxor green
	20–30	75–50	Triton green
66	5–10	85–70	rock green
		70–50	cactus green
		50–30	pine green
	10–15	75–55	light malachine green
		55–40	dark malachine green, Hungarian green
	15–20	70–45	signal green
70	2–5	85–70	greenish grey
		70–50	almond green
		50–30	Berlin green
	5–12	80–60	Nile green
		60–40	Danube green
	12–20	75–60	elder green
		60–50	acacia green
71	2–5	85–70	pale green
		70–55	senna green, appianum
		55–30	Paris green
	5–15	80–70	pastel green, Metternich green
		70–55	spinach green
		55–45	Alpine green
	15–20	75–60	Transylvanian green, Lincoln green
		60–50	primitive green

A	*T*	*V*	
72	5–10	85–75	linden green
		60–45	Aquino green
	20–25	80–50	leaf green, Theban green
73	5–10	85–70	mineral green
		70–50	lavendel green
		50–30	ivy green
	10–20	80–55	aloe green, jasper green
		55–45	brass green
	20–25	75–50	viridian green
74	5–15	85–75	antique green
		75–55	algal green
		55–30	dark green
	15–25	85–75	Chinese green
		75–60	parsley green
		60–50	onyx green
	25–35	80–70	apple green
		70–55	foliage green

A	*T*	*V*	
75	5–15	85–70	quinine green
		70–55	welted green
		55–30	Arabian green
	15–30	85–70	absinth green
		70–55	Calcedonian green
		55–45	Gallic green
	30–40	80–60	spring green
76	5–15	85–75	mildew yellow, baryte yellow
		75–55	diamantine green, bile green
		55–30	old green
	15–30	85–70	pumpkin yellow
		70–60	banana green
		60–50	chlorophyll green
	30–45	80–70	King's yellow
		70–60	King's green

A. 7

Colours in complementary, triadic and tetradic harmony positions in the Coloroid Colour Circle

COMP TRI TET	TET	TRI TET	COMP	TRI TET	TET
A	*A*+34°	*A*+130°	*A*+180°	*A*+230°	*A*+326°
60	53.71	40.35	31.00	11.69	62.97
61	55.21	41.34	33.00	14.97	63.83
62	56.17	42.36	34.00	21.37	64.93
63	60.04	43.48	35.00	24.55	65.98
64	61.07	44.71	36.00	30.18	70.04
65	62.07	45.70	41.00	32.36	71.20
66	63.02	46.84	42.00	33.65	72.58
70	63.97	51.30	43.00	34.59	74.51
71	84.84	52.75	44.00	35.45	76.95
72	65.64	54.10	45.00	40.23	12.43
73	66.26	55.06	45.55	40.83	14.45
74	66.78	55.56	46.00	41.34	16.18
75	70.23	55.97	46.53	41.76	20.59
76	70.64	56.28	50.00	42.13	21.77
10	71.02	56.55	50.51	42.47	22.83
11	71.43	56.82	51.00	42.81	23.82
12	71.83	60.10	51.51	43.15	24.72
13	72.29	60.41	52.00	43.50	25.56
14	72.78	60.71	52.51	43.84	26.33
15	73.32	61.01	53.00	44.19	30.04
16	73.89	61.30	53.50	44.56	30.71
20	74.57	61.59	54.00	44.92	31.36
21	75.34	61.89	54.49	45.21	32.00
22	76.21	62.19	55.00	45.49	32.59
23	10.16	62.49	55.32	45.78	33.11
24	11.19	62.81	55.65	46.11	33.44
25	12.31	63.16	56.00	46.57	33.79
26	13.56	63.53	56.31	50.07	34.16
30	14.94	63.92	56.64	50.68	34.55
31	16.42	64.35	60.00	51.35	34.97
32	21.00	64.82	60.47	52.10	35.42
33	22.67	65.34	61.00	52.99	35.93
34	25.56	66.36	62.00	54.68	40.93
35	31.08	70.48	63.00	55.84	41.98
40	33.07	71.71	64.00	56.71	43.04
41	34.07	73.33	65.00	60.66	44.20
42	35.02	75.66	66.00	61.65	45.32
43	35.97	11.58	70.00	62.59	46.27
44	40.84	14.48	71.00	63.45	50.48
45	41.64	20.21	72.00	64.23	51.72
46	42.78	23.74	74.00	65.34	53.59
50	43.64	25.88	76.00	66.13	54.88
51	44.43	30.49	11.00	66.81	55.59
52	45.16	31.87	13.00	70.50	56.17
53	45.69	33.01	15.00	71.19	56.66
54	46.31	33.59	17.00	71.92	60.17
55	50.11	34.19	22.00	72.90	60.79
56	51.66	35.16	25.00	75.07	61.79

A. 8

Some tables for the colour preference index number system

Colour preferences of boys aged 15–16

$A=10$	T: 4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64
V																
90	19.5	19.8	20.2	20.7	21.4	22.3	23.2	24.4								
80	15.4	16.1	17.0	18.0	19.1	20.4	21.9	23.5	25.2	27.1	29.1	31.3	33.7	36.1	38.8	41.6
70	12.4	13.6	14.9	16.3	17.9	19.7	21.6	23.6	25.8	28.1	30.6	33.2				
60	10.5	12.1	13.9	15.8	17.8	20.0	22.3	24.8	27.5							
50	9.7	11.8	14.0	16.3	18.8	21.4										
40	10.1	12.5	15.2	18.0												
30	11.5	14.4														
20	14.0															
$A=11$																
V																
90	19.5	19.6	19.9	20.3	20.9	21.6	22.5	23.5	24.7	26.0						
80	15.4	16.0	16.8	17.7	18.7	19.9	21.2	22.8	24.4	26.2	28.2	30.3	32.6	35.0	37.6	40.3
70	12.4	13.5	14.7	16.1	17.6	19.3	21.1	23.1	25.3	27.6	30.0	32.6				
60	10.5	12.1	13.8	15.6	17.7	19.8	22.1	24.6	27.2							
50	9.7	11.8	14.0	16.3	18.8	21.4										
40	10.1	12.6	15.2	18.1												
30	11.5	14.5														
20	14.0															
$A=12$																
V																
90	19.5	19.5	19.6	19.8	20.3	20.9	21.7	22.6	23.7							
80	15.4	15.9	16.5	17.4	18.3	19.5	20.8	22.3	23.9	25.8	27.8	29.9	32.3	34.8	37.4	40.3
70	12.4	13.4	14.6	16.0	17.5	19.2	21.1	23.1	25.3	27.6	30.2	32.9				
60	10.5	12.1	13.8	15.7	17.8	20.0	22.4	25.0	27.7							
50	9.7	11.8	14.1	16.5	19.1	21.9										
40	10.1	12.7	15.5	18.5												
30	11.5	14.7														
20	14.0															

$A=13$	T: 4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64
V																
90	19.5	19.5	19.6	19.9	20.4	21.0	21.8	22.8								
80	15.4	15.9	16.6	17.4	18.4	19.6	20.9	22.4	24.1	25.9	27.9	30.1	32.4	34.9	37.6	40.5
70	12.4	13.5	14.7	16.0	17.5	19.2	21.1	23.1	25.3	27.7	30.2	32.9				
60	10.5	12.1	13.8	15.7	17.8	20.0	22.4	25.0	27.7							
50	9.7	11.8	14.1	16.5	19.1	21.9										
40	10.1	12.7	15.5	18.4												
30	11.5	14.6														
20	14.0															

$A=14$																
V																
90	19.5	19.5	19.6	19.9	20.3	21.0	21.8									
80	15.4	15.9	16.5	17.3	18.3	19.5	20.8	22.3	24.0	25.9	28.0	30.2	32.6	35.2	38.0	40.9
70	12.4	13.4	14.5	15.9	17.4	19.1	20.9	23.0	25.2	27.6	30.1	32.9	35.8			
60	10.5	12.0	13.7	15.5	17.5	19.7	22.1	24.7	27.4							
50	9.7	11.7	13.9	16.3	18.8	21.5										
40	10.1	12.6	15.3	18.1												
30	11.5	14.5														
20	14.0															

$A=15$																
V																
90	19.5	19.4	19.5	19.8	20.3	21.0										
80	15.4	15.9	16.5	17.4	18.4	19.6	21.0	22.7	24.5	26.5	28.7	31.1	33.8	36.6	39.6	42.8
70	12.4	13.4	14.6	16.0	17.5	19.3	21.3	23.4	25.8	28.4	31.1	34.1	37.2			
60	10.5	12.1	13.8	15.7	17.8	20.1	22.6	25.3	28.2							
50	9.7	11.8	14.1	16.5	19.2	22.0										
40	10.1	12.7	15.5	18.5												
30	11.5	14.6														
20	14.0															

$A=16$	T: 4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64
V																
90	19.5	19.4	19.4	19.7	20.2											
80	15.4	15.8	16.5	17.3	18.4	19.6	21.1	22.9	24.8	27.0	29.4	32.0	34.8	37.9		
70	12.4	13.4	14.6	16.0	17.6	19.4	21.5	23.8	26.3	29.0	32.0	35.2	38.5			
60	10.5	12.1	13.8	15.8	17.9	20.4	23.0	25.8	28.9	32.2						
50	9.7	11.8	14.1	16.7	19.4	22.4										
40	10.1	12.7	15.6	18.7												
30	11.5	14.7														
20	14.0															
$A=20$																
V																
90	19.5	19.2	19.2	19.4												
80	15.4	15.7	16.3	17.2	18.3	19.7	22.5	23.5	25.8	28.4	31.2					
70	12.4	13.3	14.5	16.0	17.7	19.8	22.1	24.7	27.6	30.8	34.3	38.1	42.1	46.4		
60	10.5	12.0	13.8	15.9	18.3	20.9	23.9	27.1	30.6	34.4						
50	9.7	11.9	14.3	16.9	19.9	23.2	26.7									
40	10.1	12.8	15.8	19.1												
30	11.5	14.8														
20	14.0															
$A=21$																
V																
90	19.5	19.4	19.5	19.9												
80	15.4	15.9	16.7	17.8	19.1	20.8	22.7	24.9	27.4	30.1						
70	12.4	13.6	15.0	16.7	18.7	21.0	23.6	26.5	29.6	33.0	36.8	40.8	45.0	49.6		
60	10.5	12.3	14.4	16.8	19.5	22.4	25.6	19.2	33.0	37.0						
50	9.7	12.2	15.0	18.0	21.3	24.9	28.8									
40	10.1	13.2	16.6	20.3												
30	11.5	15.3														
20	14.0															

Name Index

Subject Index

Coloured Figures

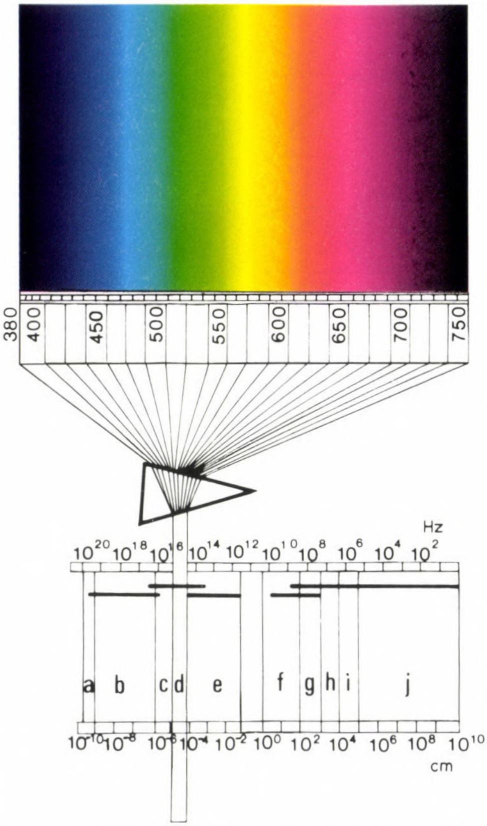


Fig. C1. Only a narrow band of radiant energy—called light—is visible; a) gamma rays, b) X-rays, c) ultraviolet radiation (UV), d) visible light, e) infrared (IR) light, f) TV waves, g) ultrashort waves, h) radio short waves, i) radio medium waves, j) radio long waves

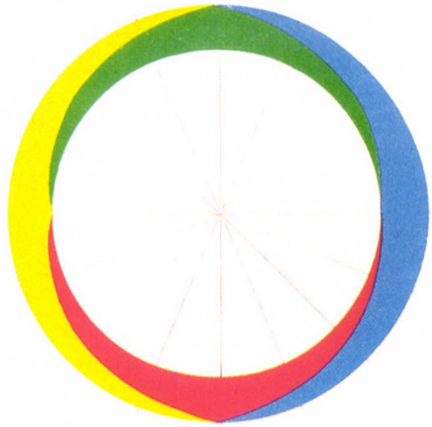


Fig. C2. Polar function diagram of primeval colours (after HERING)

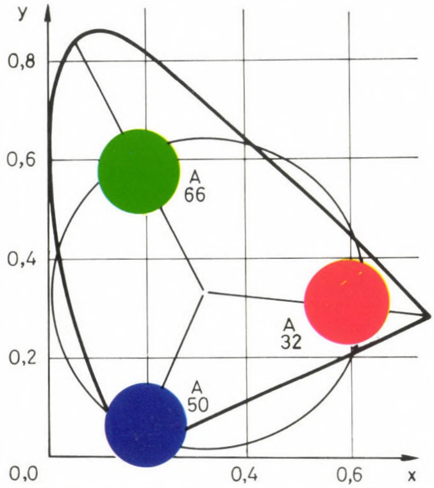


Fig. C3. Primary colours in the CIE diagram and in the Coloroid colour circle. The figure intends merely to demonstrate that primary colours are in the same relation in diagrams of both colour systems. Green *A*66 ($\lambda = 520$ nm); red *A*32 ($\lambda = 625$ nm); blue *A*50 ($\lambda = 450$ nm)

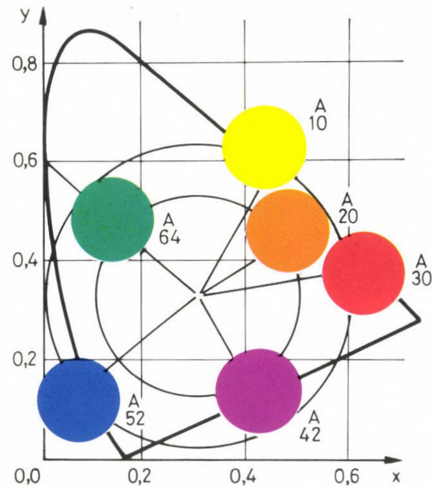


Fig. C4. Principal and auxiliary colours in the CIE diagram and in the Coloroid colour circle. The figure serves to demonstrate that primary and auxiliary colours are in the same relation in diagrams of both colour systems. Green *A*64 ($\lambda = 502$ nm); yellow *A*10 ($\lambda = 570$ nm); orange *A*20 ($\lambda = 582$ nm); red *A*30 ($\lambda = 600$ nm); violet *A*42 ($\lambda = 520$ nm); blue *A*52 ($\lambda = 480$ nm)

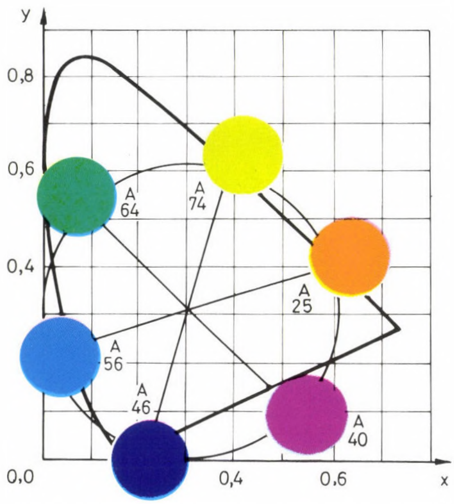


Fig. C5. Complementary pairs in the CIE and Coloroid colour systems. The figure serves only to illustrate that complementary pairs are in the same relation in diagrams of both colour systems. Yellowish green *A*74 ($\lambda = 546$ nm); orange red *A*25 ($\lambda = 594$ nm); violet *A*40 ($\lambda = -502.69$ nm); bluish violet *A*46 ($\lambda = -564.18$ nm); manganese blue *A*56 ($\lambda = 487.31$ nm); green *A*64 ($\lambda = 502$ nm)

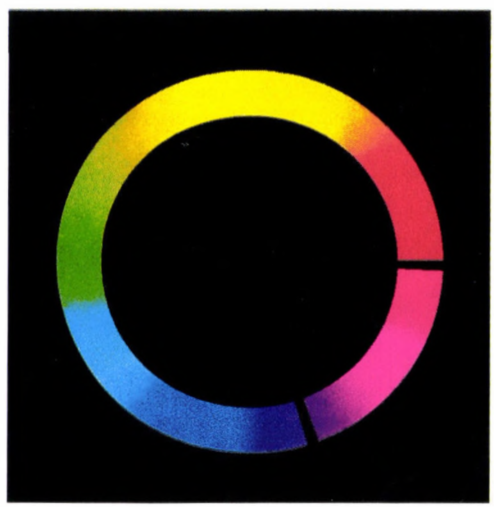


Fig. C6. Purple colours complement spectrum colours to a continuous colour circle

Fig. C7. Six-part colour circle by GOETHE

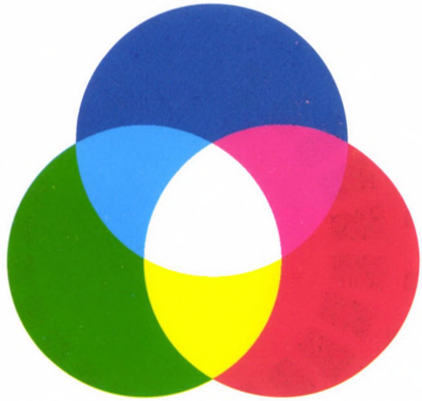


Fig. C8. Scheme of additive colour mixing using three primary colours

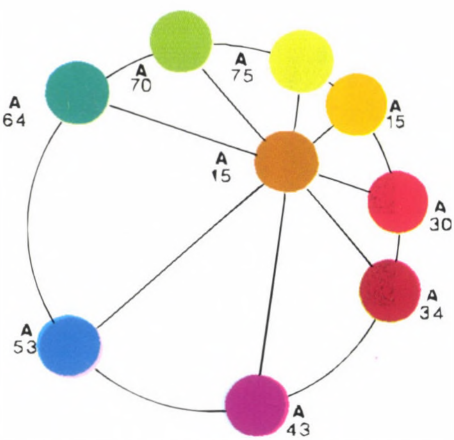


Fig. C9. Possibilities of additive mixing of the colour ochre. Numbers adjacent to each colour indicate their Coloroid hues

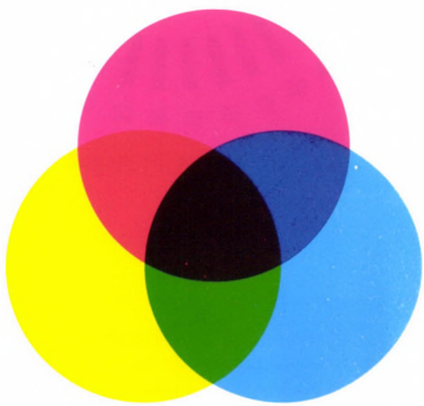


Fig. C10. Scheme of subtractive colour mixing using three primary colours

Fig. C11. Colour circle of the Ostwald colour system

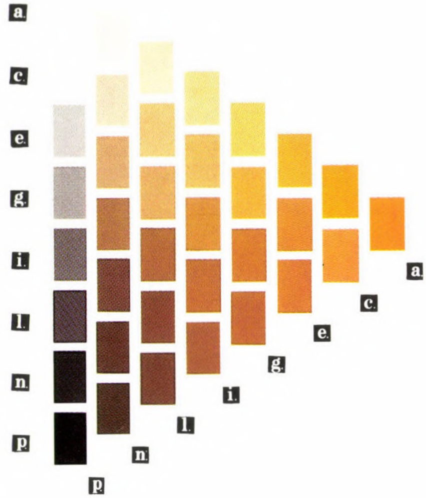


Fig. C12. Triangle of colours of equal hues of the Ostwald colour system

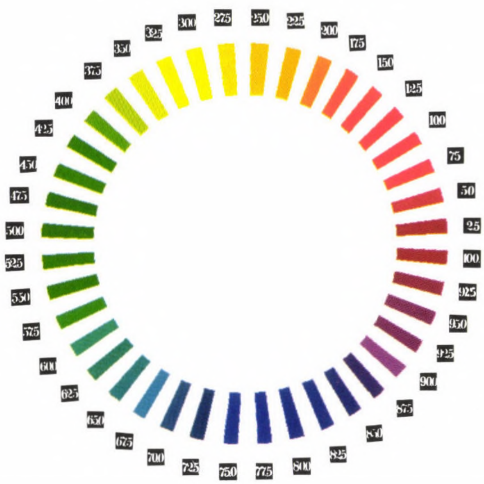


Fig. C13. Colour circle of the Munsell colour system

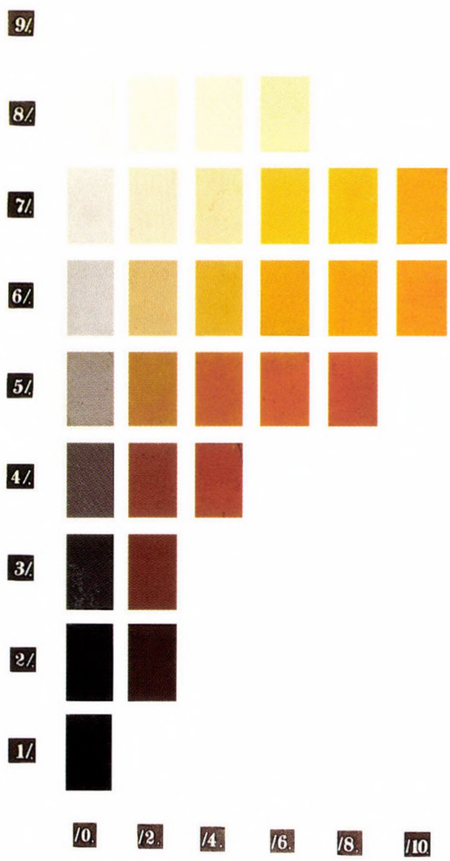


Fig. C14. Section of the Munsell colour solid with colours of equal hues in MUNSELL's "Book of Color". Numbers marking horizontal rows refer to lightnesses of colours in horizontal rows, numbers under vertical columns refer to saturations of colours in the column. Lightness numbers and saturation numbers are marked with slashes (/) put after and before the numbers, respectively

Fig. C15. Colour circle of the DIN colour system

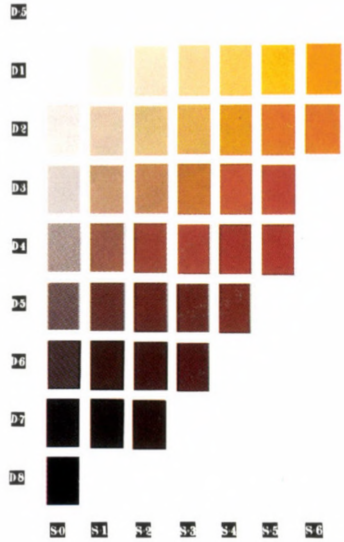


Fig. C16. Axial section of DIN $T=2$ with colours of equal hues

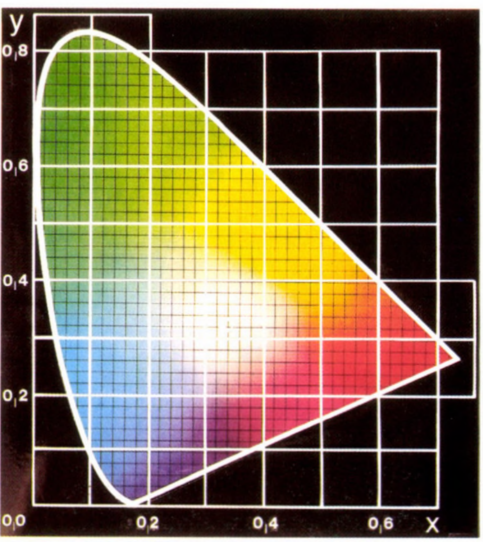


Fig. C17. CIE 1931 diagram, a colour triangle plotted in an orthogonal coordinate system

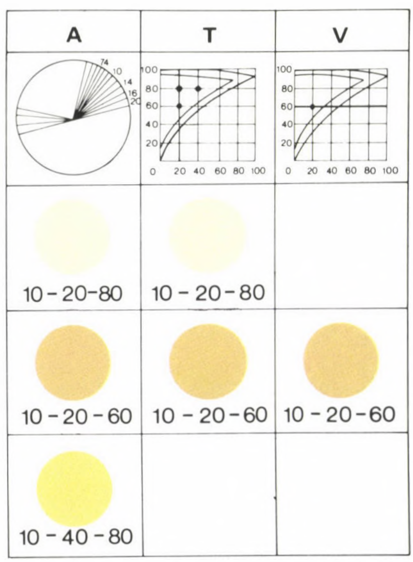


Fig. C18. In the Coloroid colour system, the three parameters of a colour are Coloroid hue (A), Coloroid saturation (T), and Coloroid lightness (V). Every colour is described by a code made up of these three numbers

Fig. C19. Coloroid colour circle

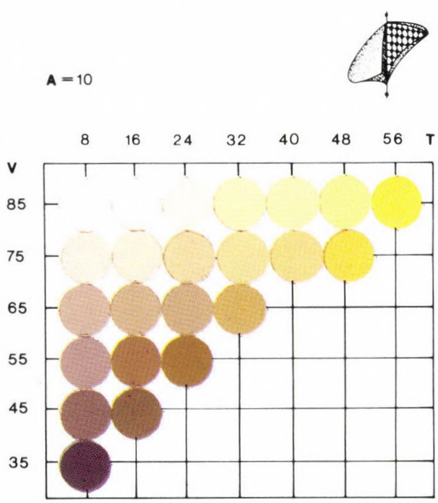


Fig. C20. Axial section of the Coloroid colour solid containing colours of hue *A*10

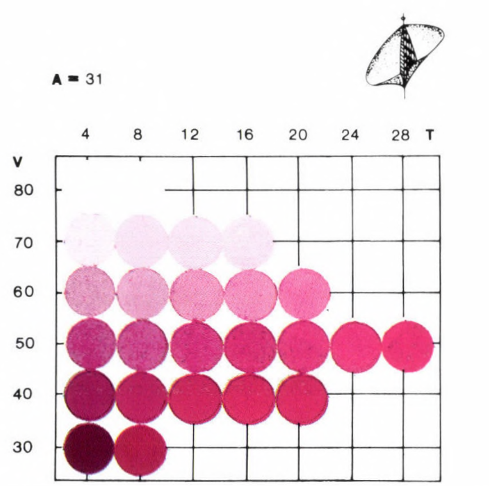


Fig. C21. Axial section of the Coloroid colour soli containing colours of hue *A*31

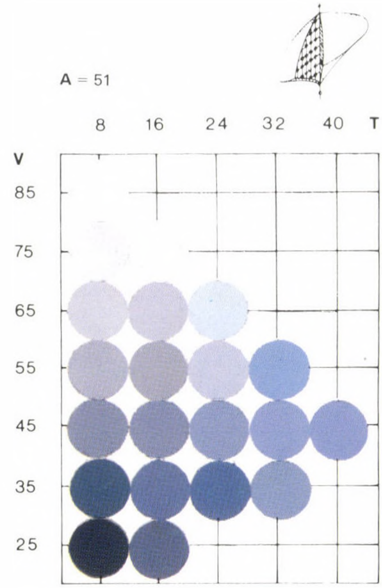


Fig. C22. Axial section of the Coloroid colour solid containing colours of hue *A*51

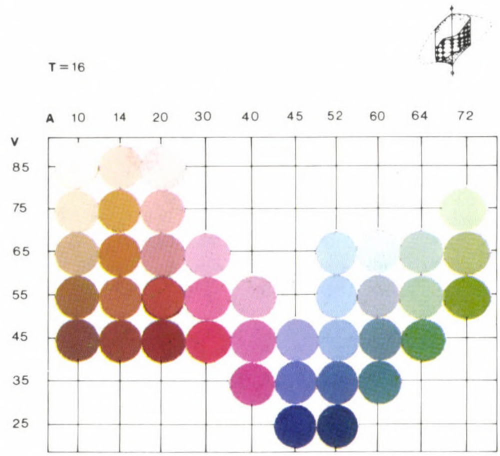


Fig. C23. Spread in plane of the coaxial cylindrical surface of the Coloroid colour solid containing colours of Coloroid saturations *T*16

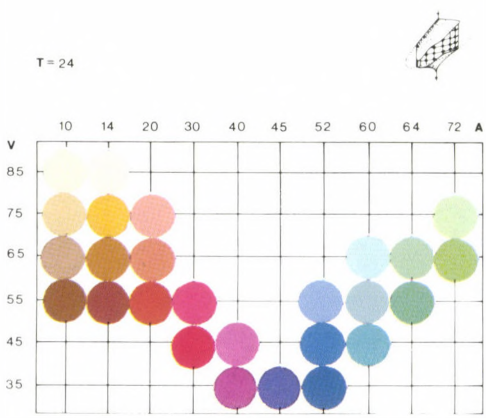


Fig. C24. Spread in plane of the coaxial cylindrical surface of the Coloroid colour solid containing colours of Coloroid saturation *T*24

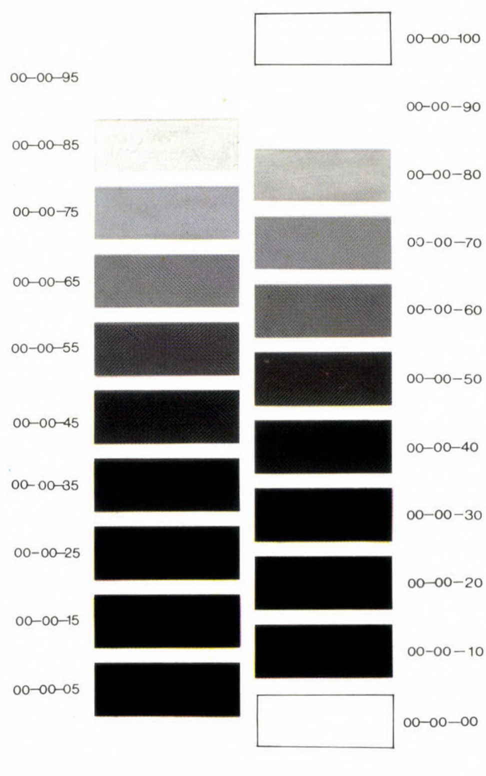


Fig. C25. Neutral colours on the achromatic axis of the Coloroid colour solid, each at intervals of five Coloroid lightness units

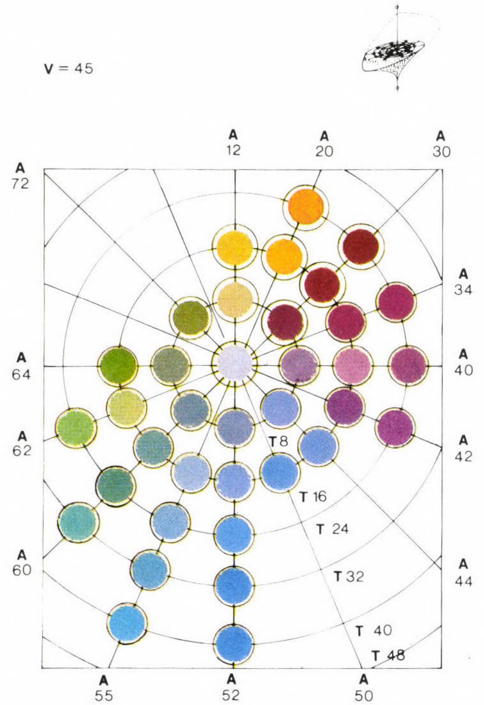


Fig. C26. Plane section normal to the achromatic axis of the Coloroid colour solid, containing colours of Coloroid lightness *V*45

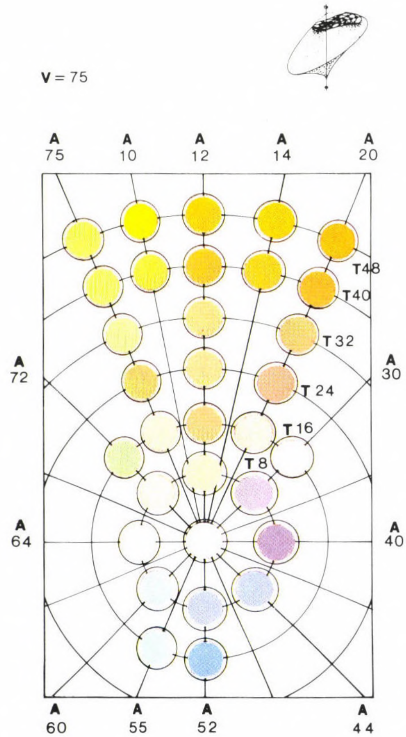


Fig. C27. Plane section normal to the achromatic axis of the Coloroid colour solid, containing colours of Coloroid lightness *V*75

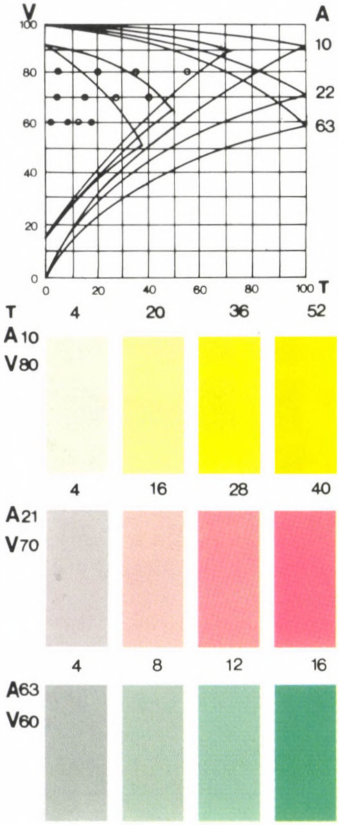


Fig. C28. Colour scales of colours of equal lightnesses and equal hues but of different saturations

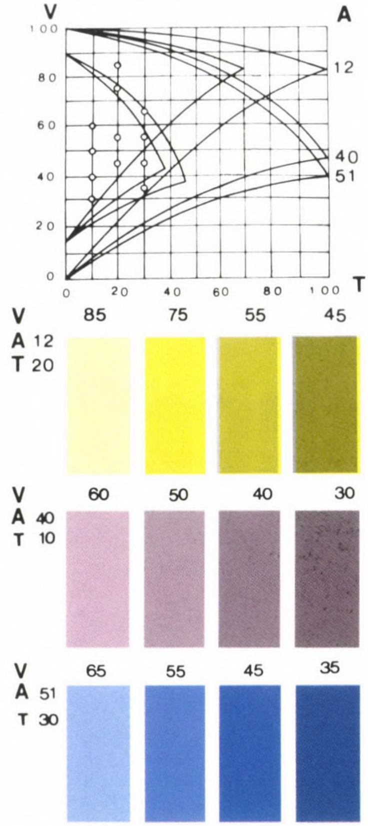


Fig. C29. Colour scales of colours of equal saturations and equal hues but of different lightnesses

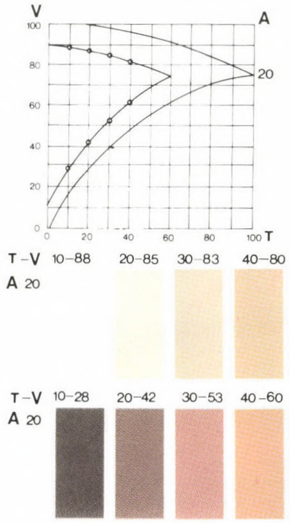


Fig. C30. Colour scale of colours of equal hues, decreasing saturations and increasing lightnesses

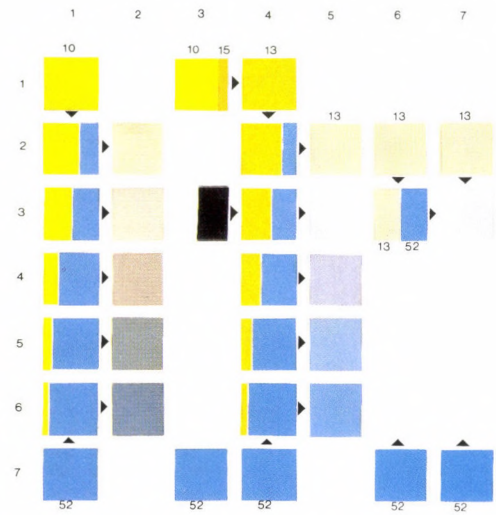


Fig. C31. Finding a complementary colour for a given colour by Maxwell disc mixing

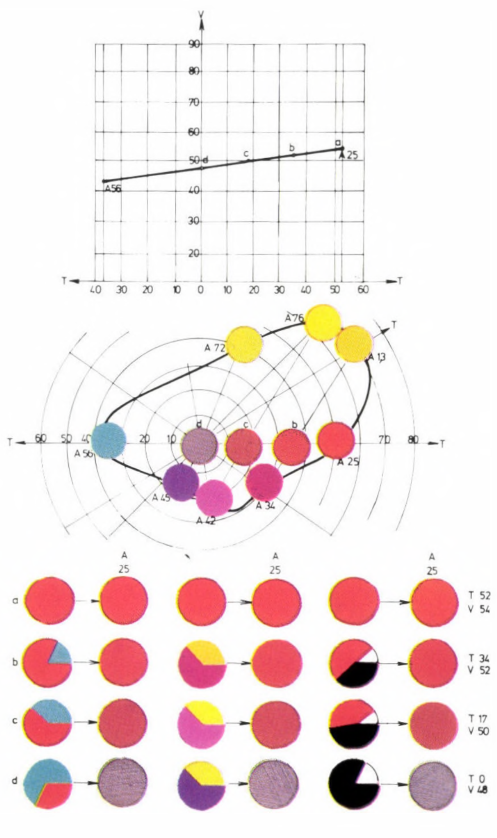
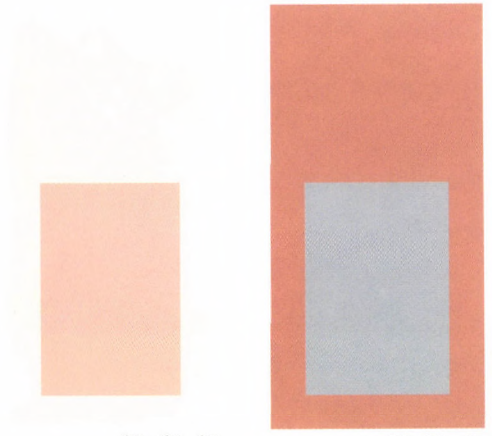


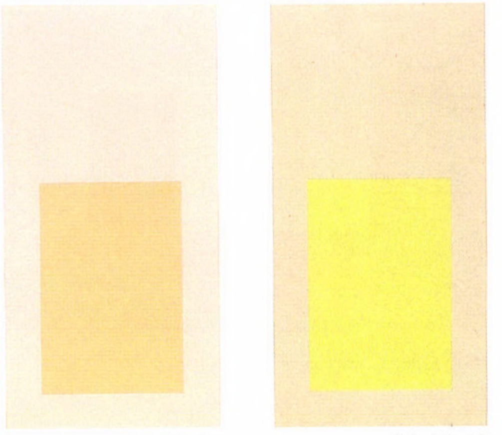
Fig. C32. There are different ways of mixing a diametral scale of colours a, b, c, d of equal hues but different saturations and lightnesses: 1) It may be produced from the pair of complementaries of Coloroid hues *A*25–26. 2) Every scale member from a different pair of complementaries. 3) From a saturated colour of Coloroid hue *A*25, and white and black. For all three methods, proportions to be set on the Maxwell disc are indicated. Regular relationships between hues, saturations and lightnesses of admixed and mixed colours are apparent. Colour discs annexed to this book may be placed along the curve in thick line. Thereby it may be read off the diagram what colour discs in addition to those in the diagram suit to mix different scale members



62–24–65
22–24–65

20–20–45
56–20–45

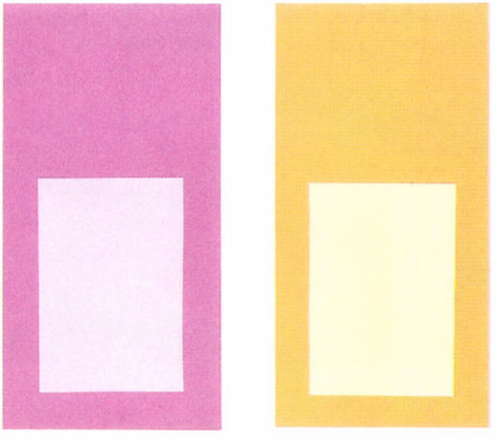
Fig. C33. Surfaces in hue contrast. Saturations and lightnesses of both contrasting colours are identical



21–20–65
21–36–65

76–12–50
76–20–50

Fig. C34. Surfaces in saturation contrast. Hues and lightnesses of both contrasting colours are identical



40–10–30
40–10–60

16–40–65
16–40–85

Fig. C35. Surfaces in lightness contrast. Hues and saturations of both contrasting colours are identical

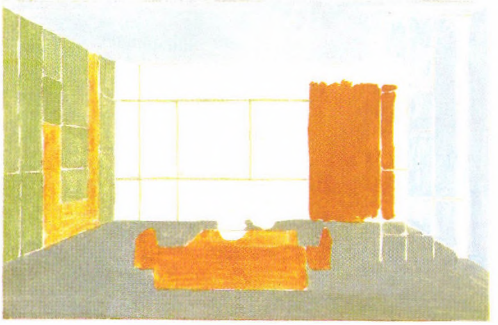


Fig. C36. Complex of cold colours

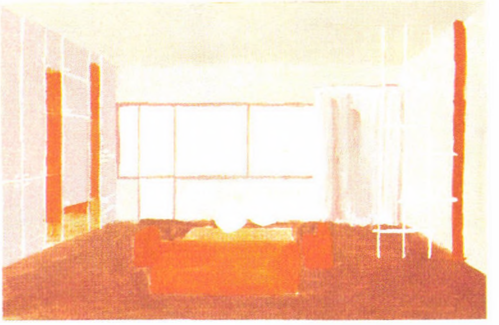


Fig. C37. Complex of warm colours

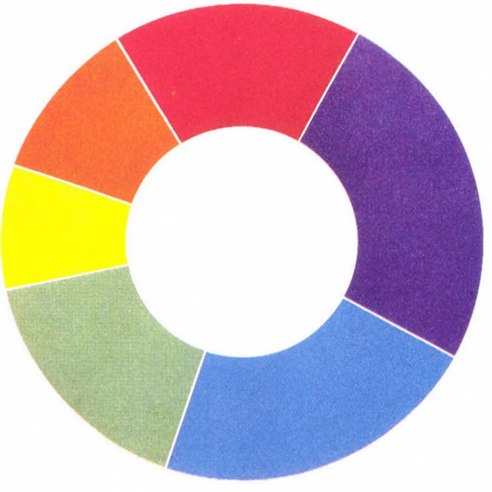


Fig. C38. Principal and auxiliary colours balancing each other by surface areas (after Itten)

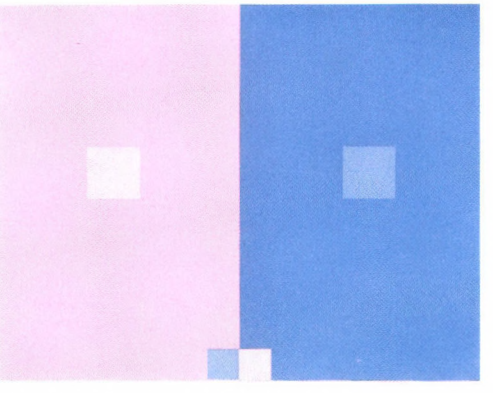


Fig. C39. An example of simultaneous contrast. Patches of different colours in the top appear to be identical against a proper background

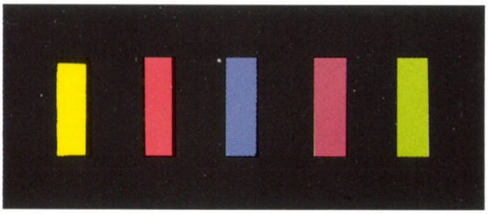


Fig. C40. Colour appearance also depends on surroundings. A black background emphasizes light colours

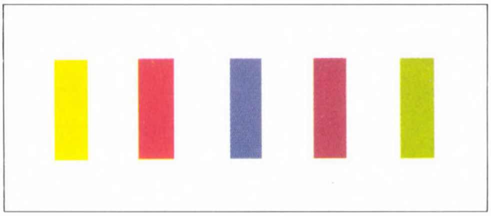


Fig. C41. Colour appearance also depends on surroundings. A white background emphasizes dark colours

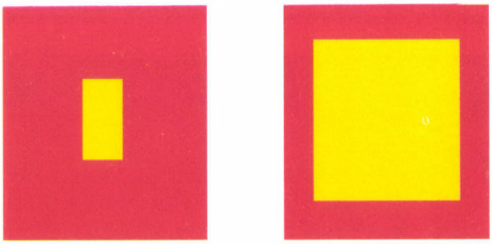


Fig. C42. Spatial effect of colours is also influenced by surface area

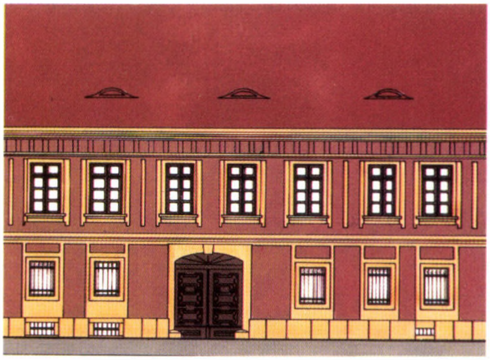


Fig. C43. Architecture is hardly noticeable because walls and courses are of the same colour

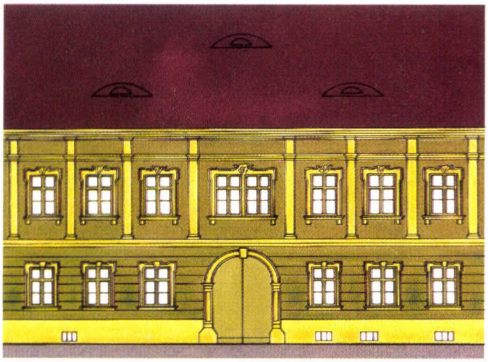


Fig. C44. Courses and walls of different colours are conspicuous

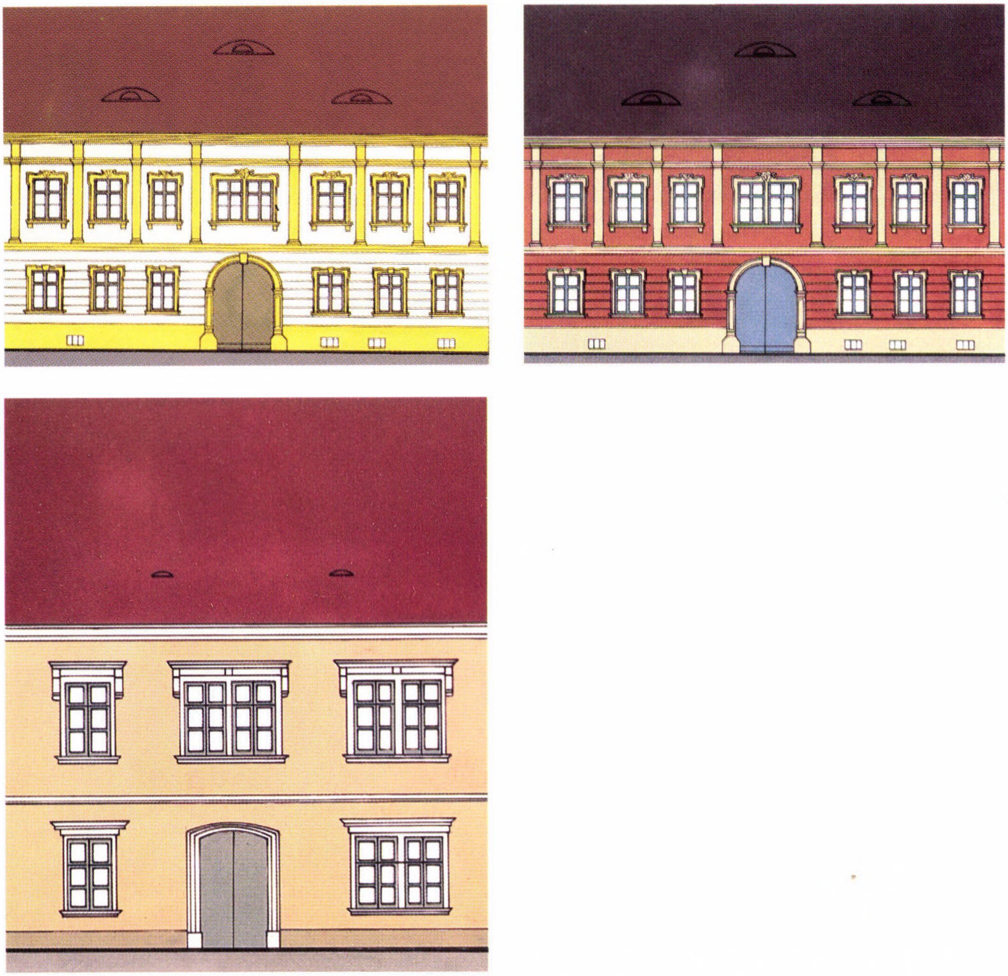


Fig. C45. Lighter or darker, less or more saturated colours for courses than for walls lend a different character to the building

Fig. C46. For a rich architecture, colour of the course, for a poor architecture, that of the walls is characteristic of the façade

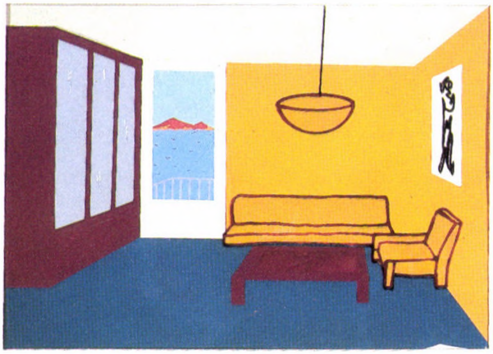


Fig. C47. A wall colour of a lightness between those of floor and ceiling is felt as pleasant

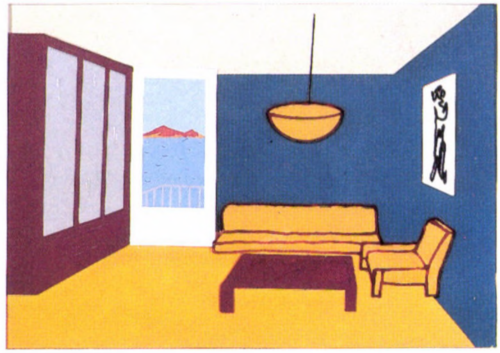


Fig. C48. A wall colour darker than that of the floor is felt as unpleasant

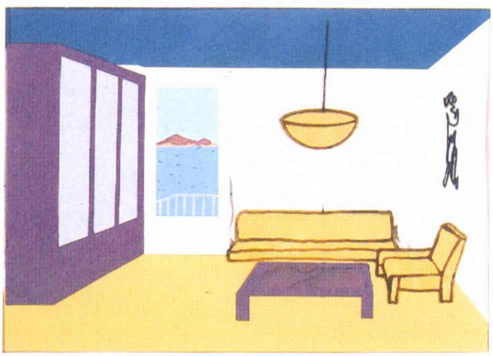


Fig. C49. A room where the ceiling is the darkest is depressing

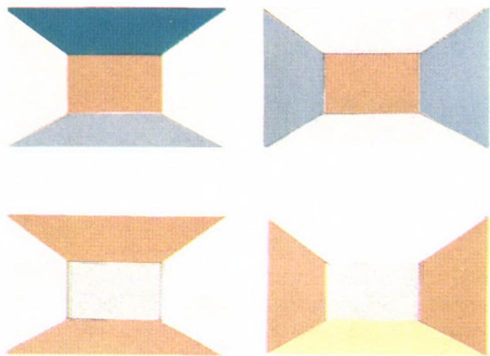


Fig. C50. Room schemes with ceilings, floors and walls of different colours

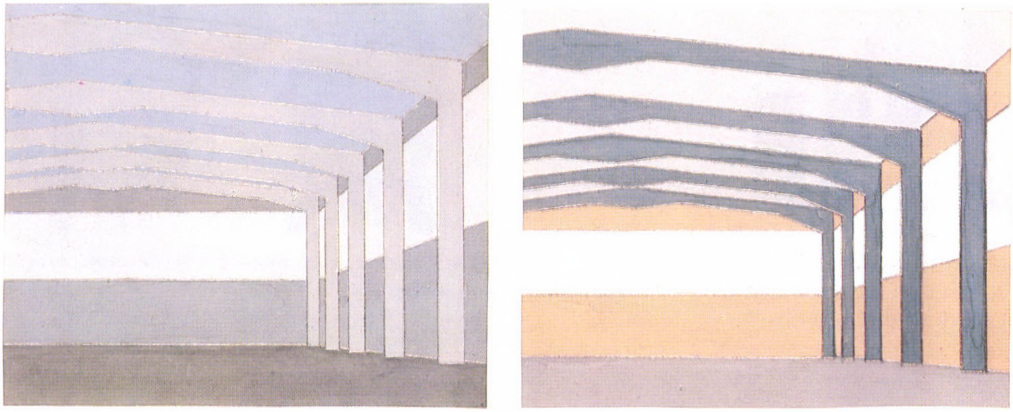


Fig. C51. Hangar interior. On the left side: uncertain space sensation. On the right side: definite space sensation

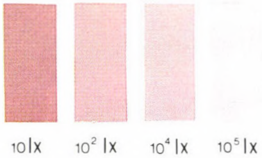


Fig. C52. Sight of the same brown at different illumination levels

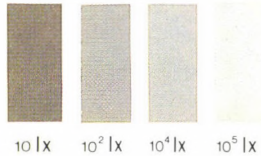


Fig. C53. Sight of the same green at different illumination levels

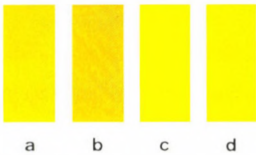


Fig. C54. Visual appearances of a yellow surface in sunshine (a), in incandescent light (b), in light of a mercury vapour lamp (c), and of low-pressure sodium lamp (d)

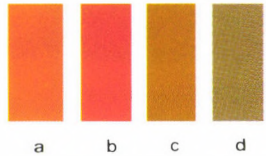


Fig. C55. Visual appearances of an orange surface in sunshine (a), in incandescent light (b), in light of a mercury vapour lamp (c), and of low-pressure sodium lamp (d)

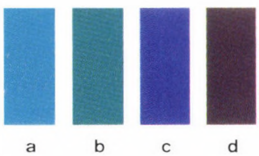


Fig. C56. Visual appearances of a blue surface in sunshine (a), in incandescent light (b), in light of a mercury vapour lamp (c), and of low-pressure sodium lamp (d)

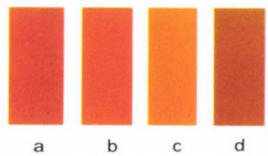


Fig. C57. Visual appearances of an orange surface in diffuse light (a), in full light (b), in side light (c) and in back light (d)

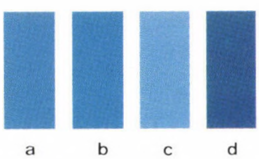


Fig. C58. Visual appearances of a blue surface in diffuse light (a), in full light (b), in side light (c) and in back light (d)

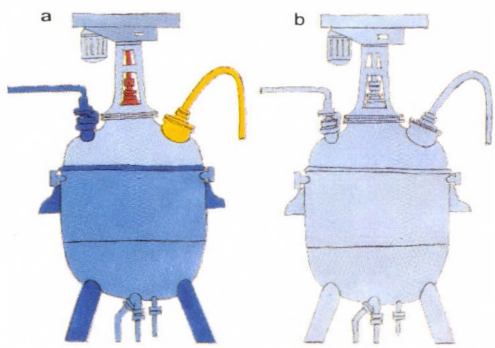
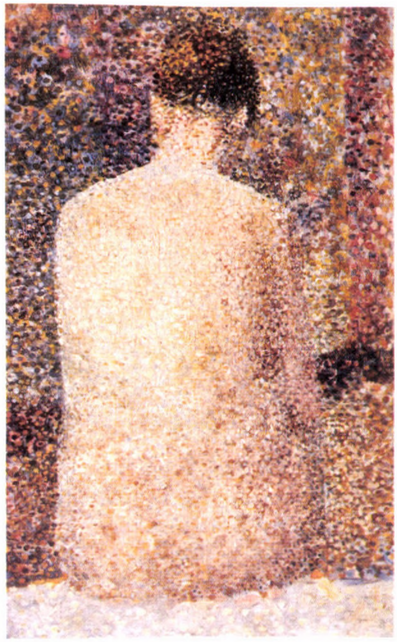


Fig. C59. Two colourations for an autoclave; a) right, b) wrong

Fig. C60. Detail of a pointillist picture (SEURAT: Sitting model)



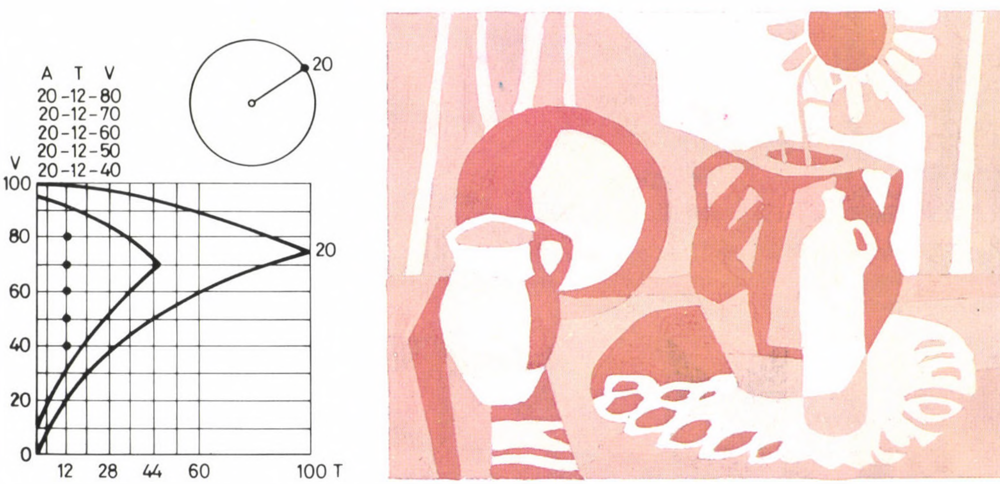


Fig. C61. Monochrome harmony. In the explanatory drawing composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

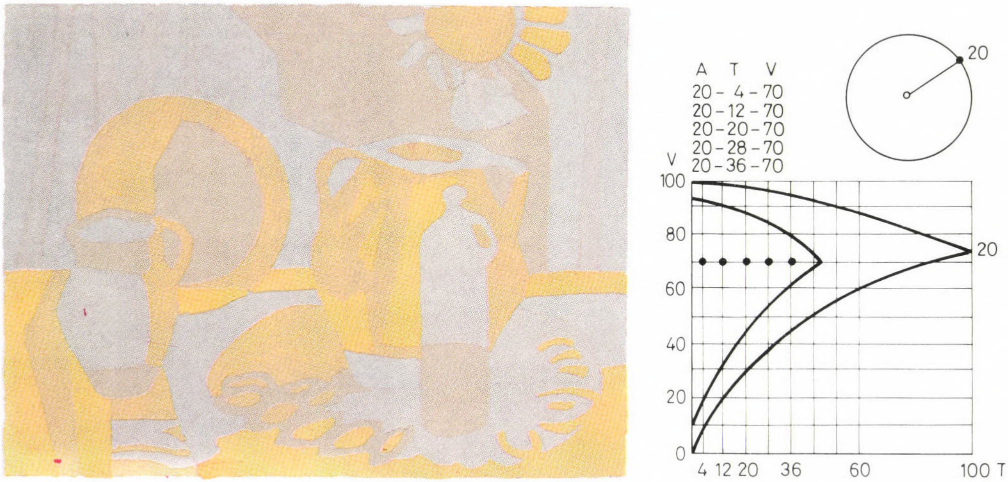


Fig. C62. Monochrome harmony. In the explanatory drawing composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

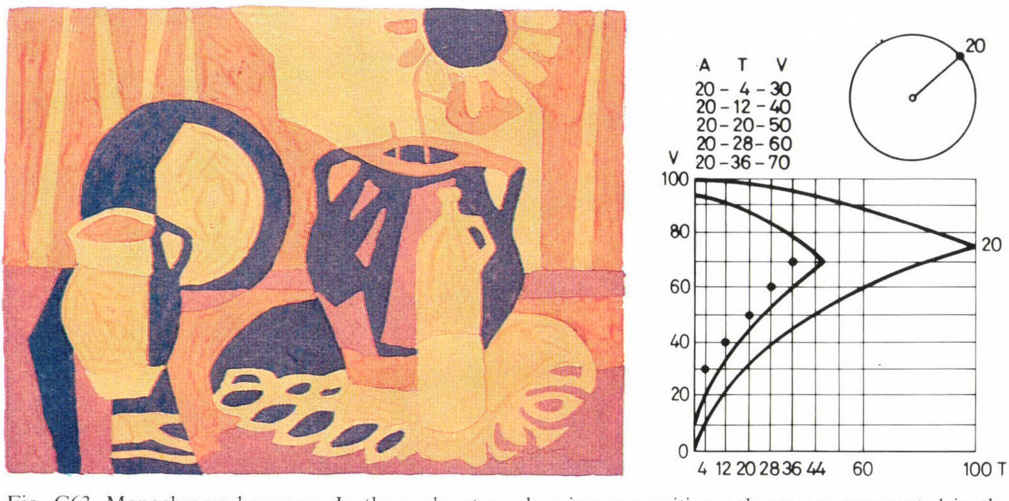


Fig. C63. Monochrome harmony. In the explanatory drawing composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

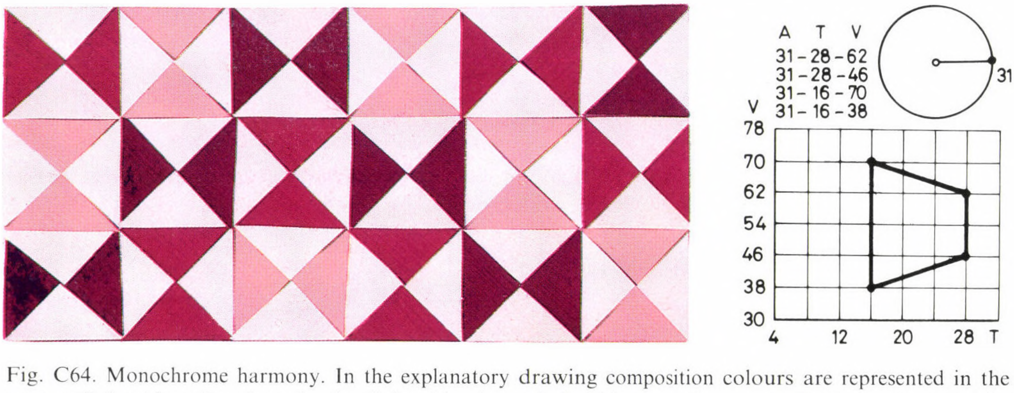


Fig. C64. Monochrome harmony. In the explanatory drawing composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

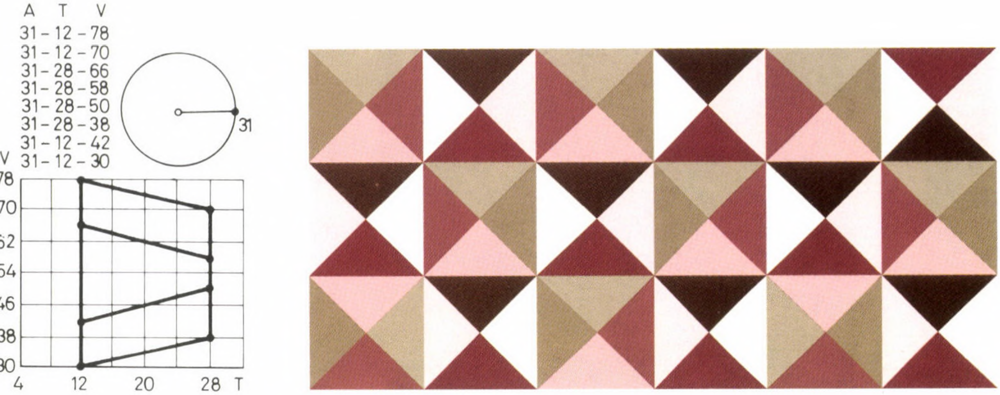


Fig. C65. Monochrome harmony. In the explanatory drawing composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

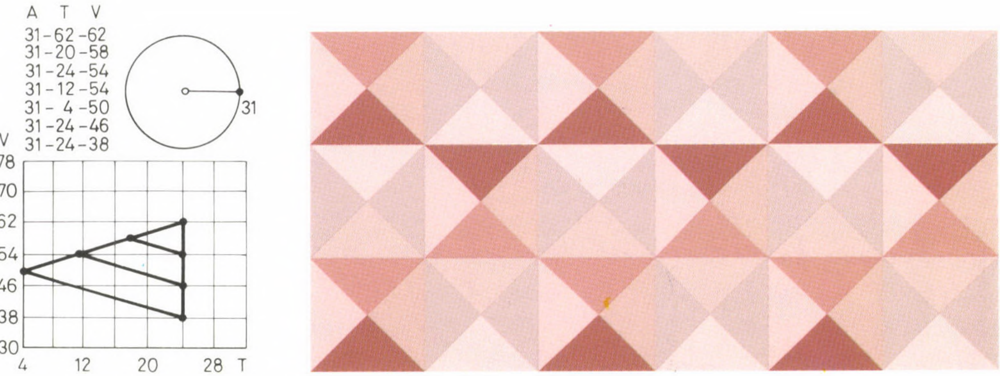


Fig. C66. Monochrome harmony. In the explanatory drawing composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

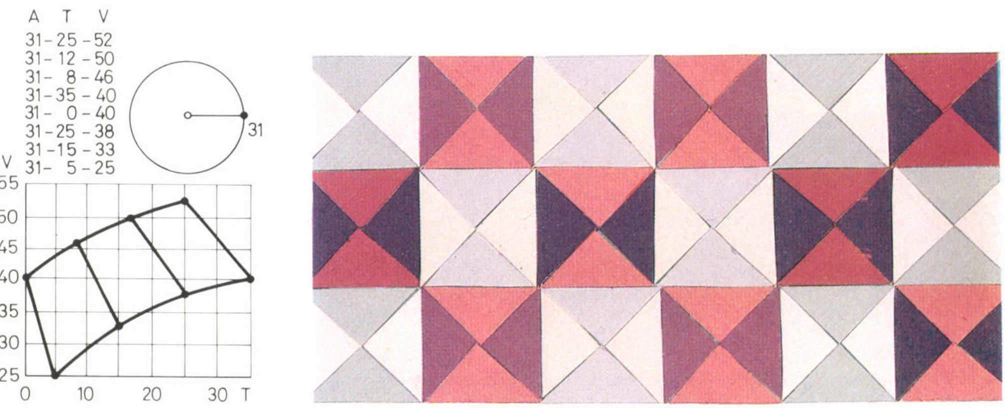


Fig. C67. Monochrome harmony. In the explanatory drawing composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

Fig. C68. Dichrome complementary harmony. In the explanatory drawing composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

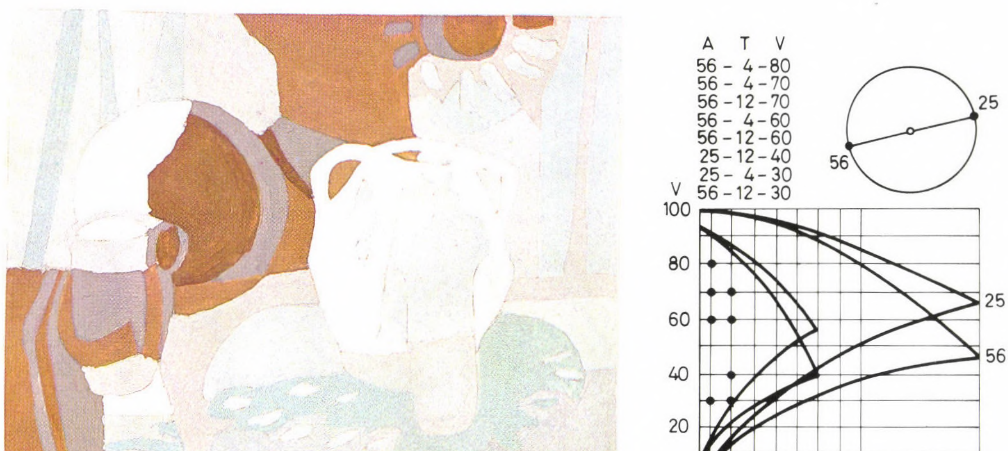


Fig. C69. Dichrome complementary harmony. In the explanatory drawing composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

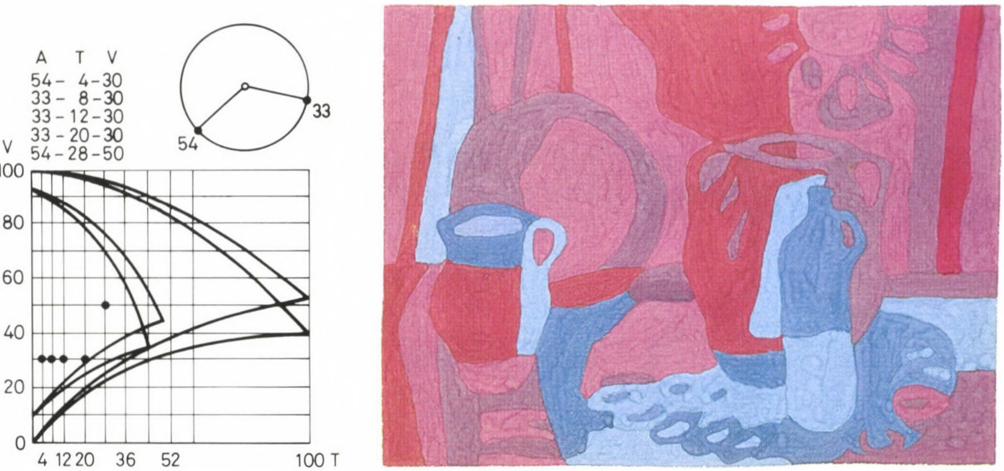


Fig. C70. Dichrome harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A, T, V* of colours in the composition are indicated

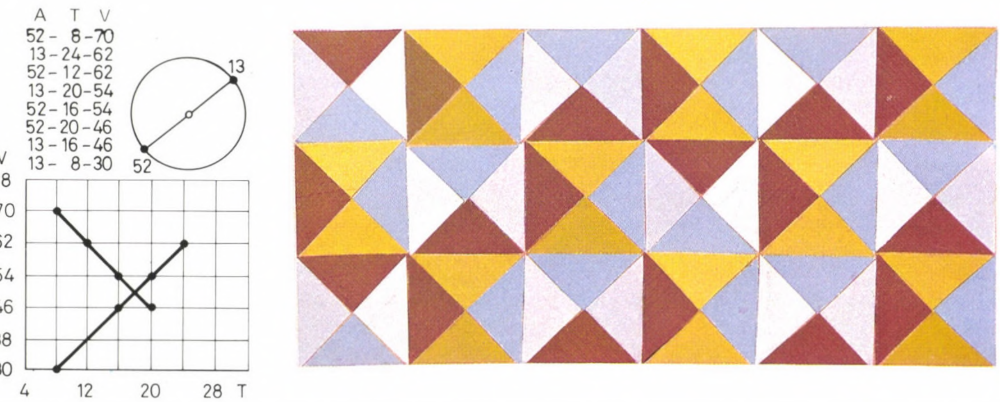


Fig. C71. Dichrome complementary harmony. In the explanatory drawing colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A, T, V* of colours are indicated

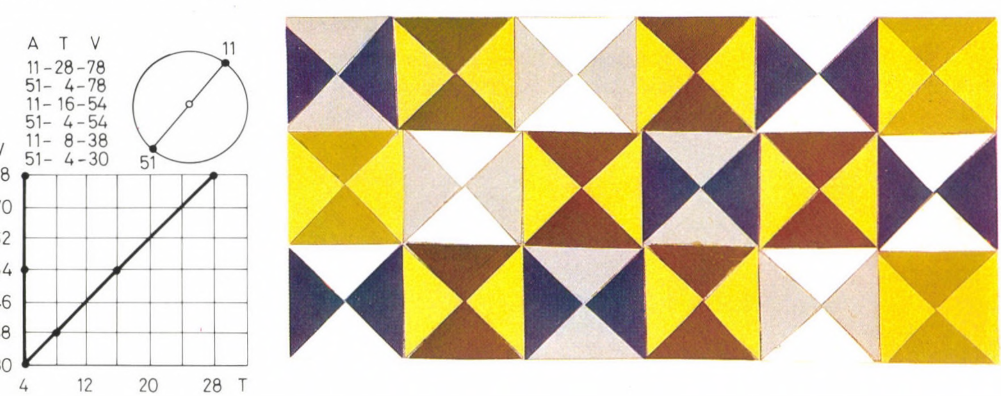


Fig. C72. Dichrome complementary harmony. In the explanatory drawing composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A, T, V* of colours in the composition are indicated

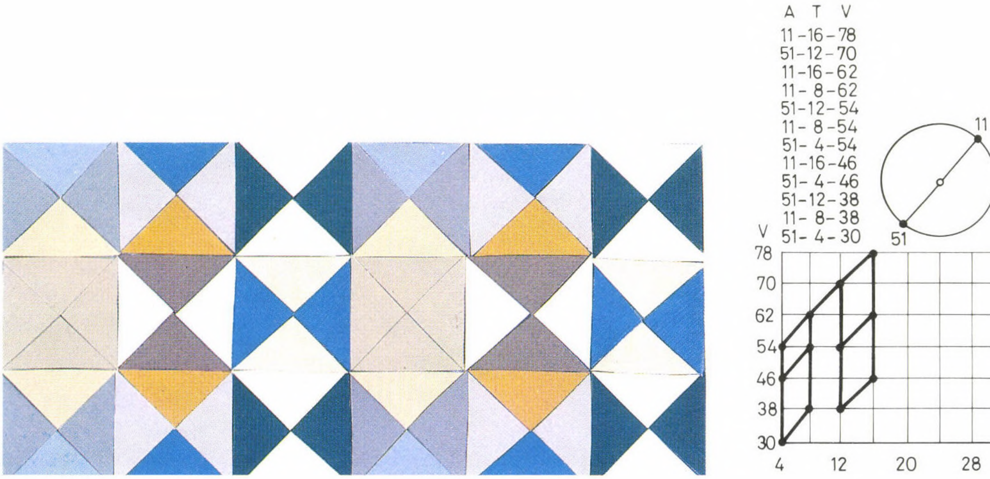


Fig. C73. Dichrome complementary harmony. In the explanatory drawing composition colours are rep-resented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colour in the composition are indicated

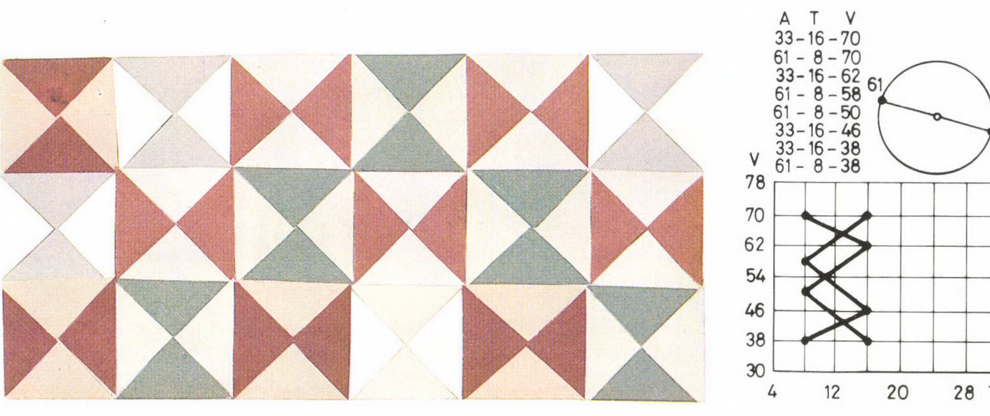


Fig. C74. Dichrome complementary harmony. In the explanatory drawing composition colours are rep-resented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colour in the composition are indicated

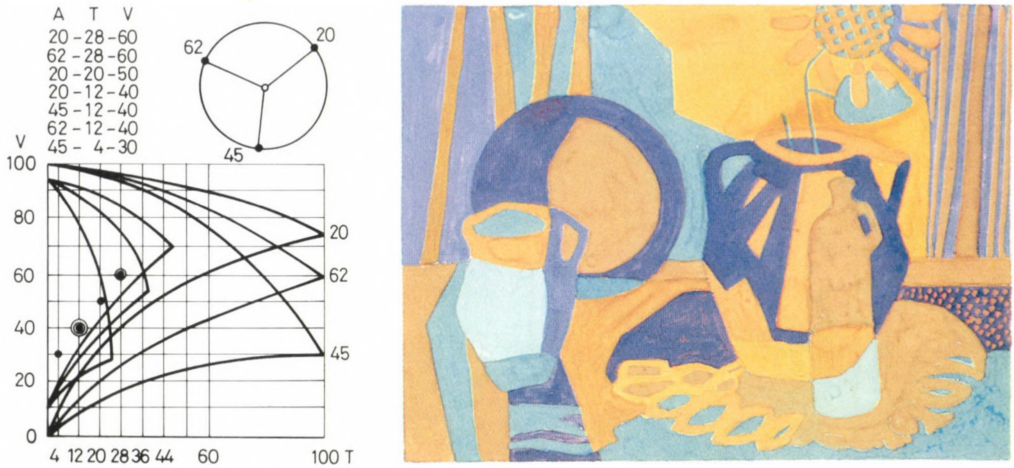


Fig. C75. Trichrome triadic harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

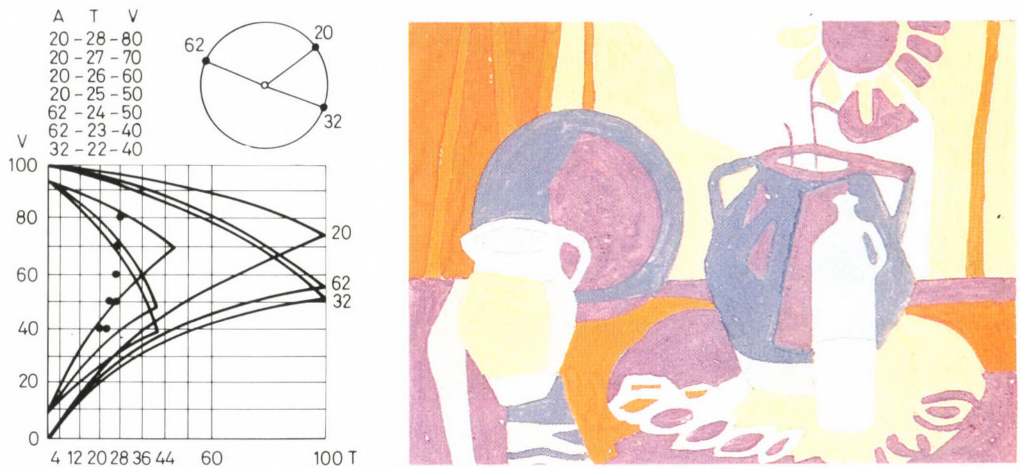


Fig. C76. Trichrome harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

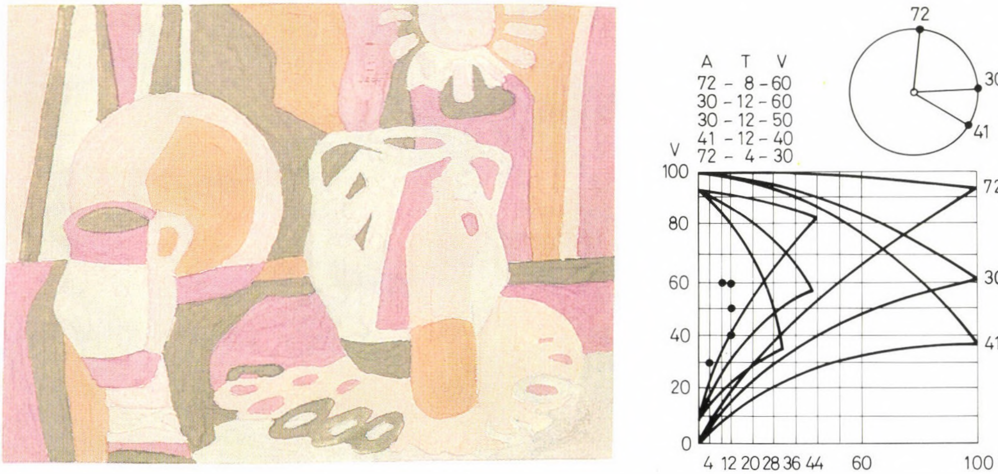


Fig. C77. Trichrome harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

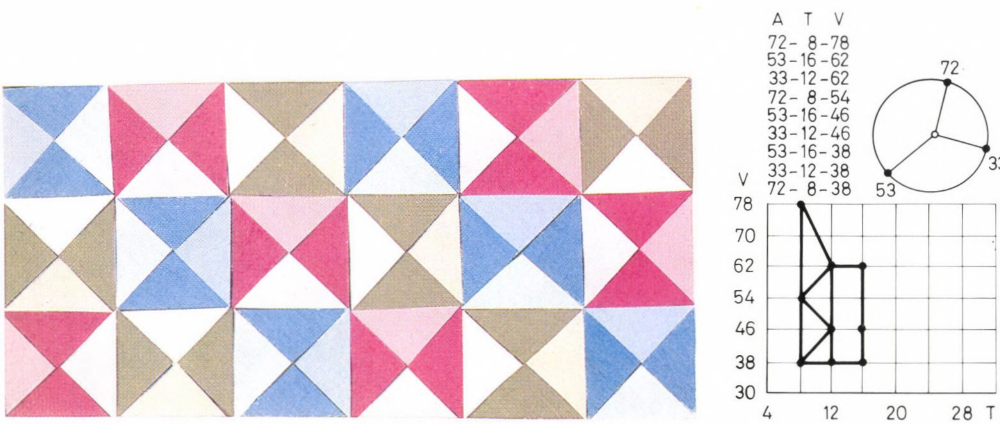


Fig. C78. Trichrome triadic harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

Fig. C79. Trichrome triadic harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

Fig. C80. Trichrome triadic harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

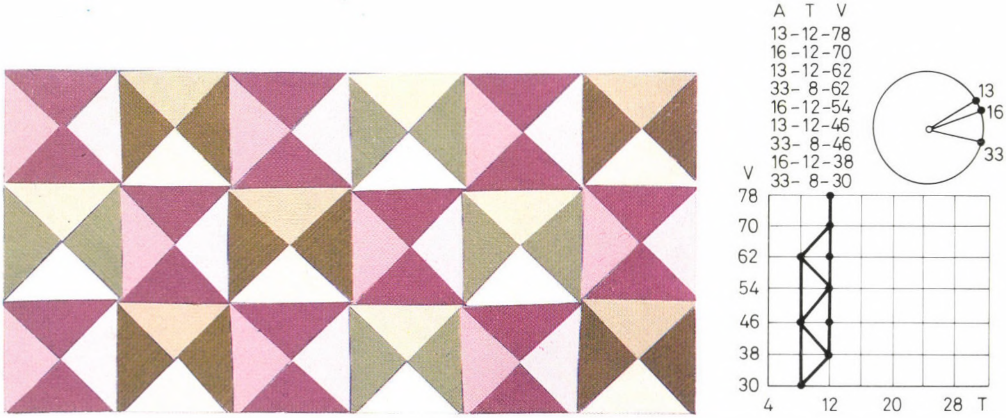


Fig. C81. Trichrome group harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

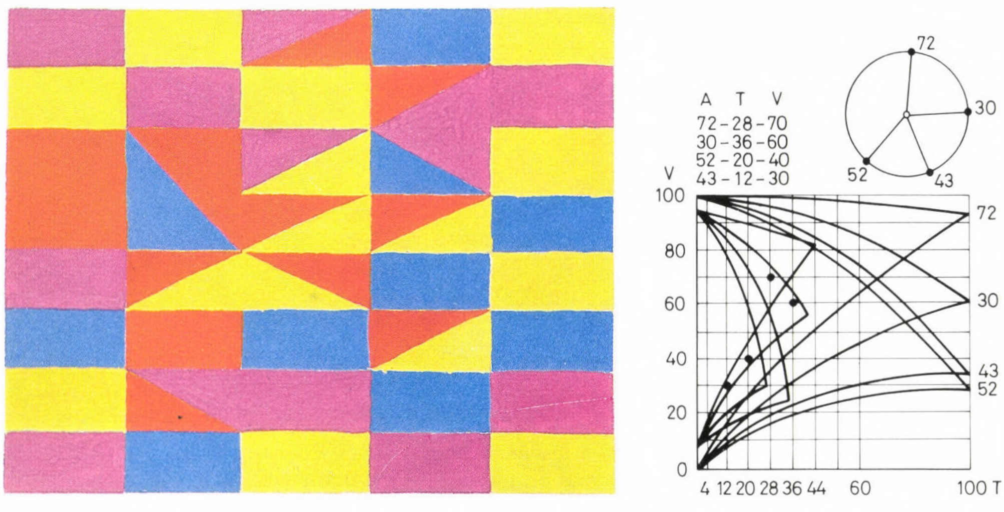


Fig. C82. Tetrachrome harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

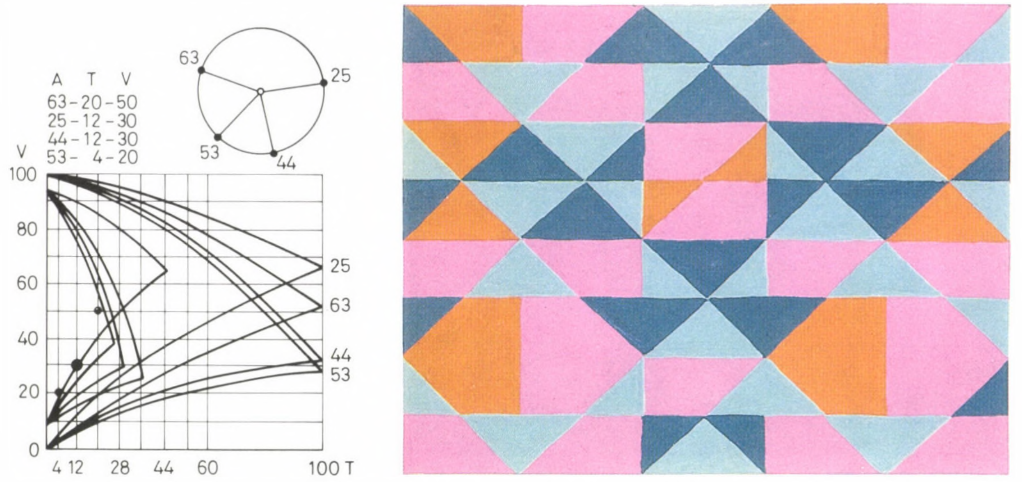


Fig. C83. Tetrachrome harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

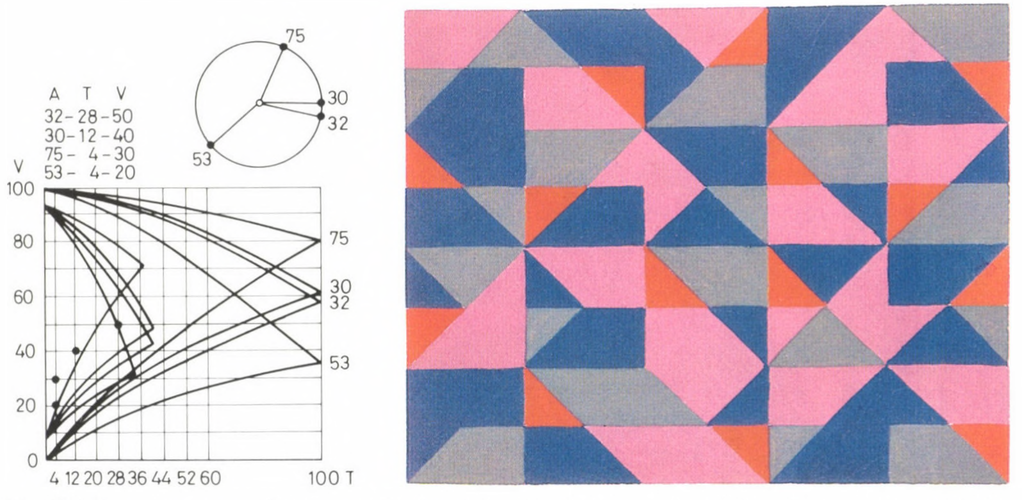


Fig. C84. Tetrachrome tetradic harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

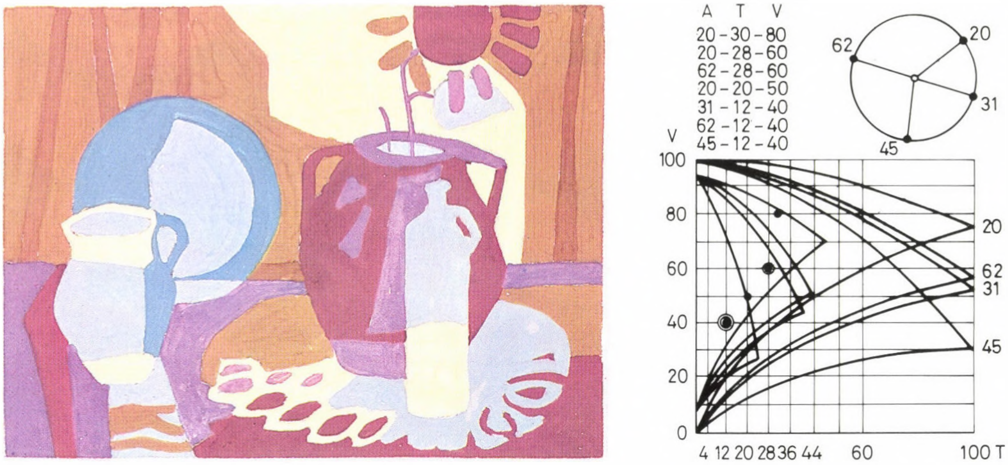


Fig. C85. Tetrachrome harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

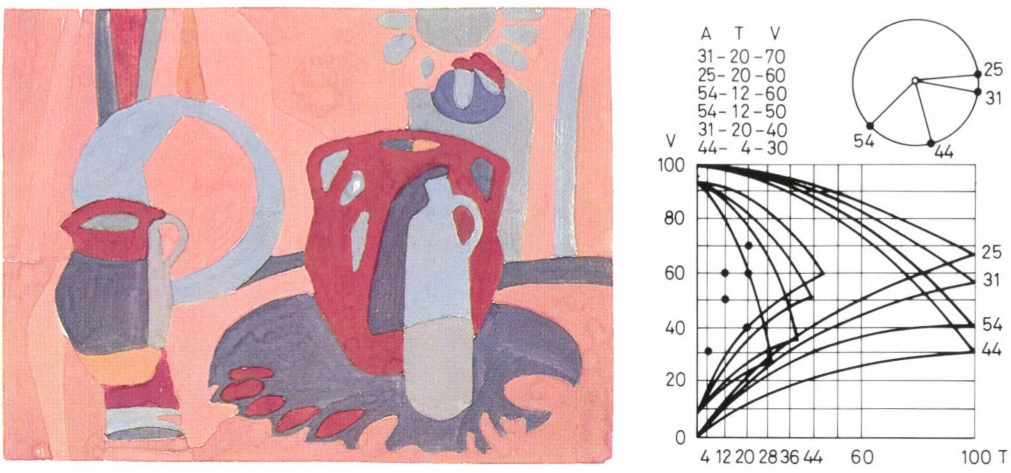


Fig. C86. Tetrachrome harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

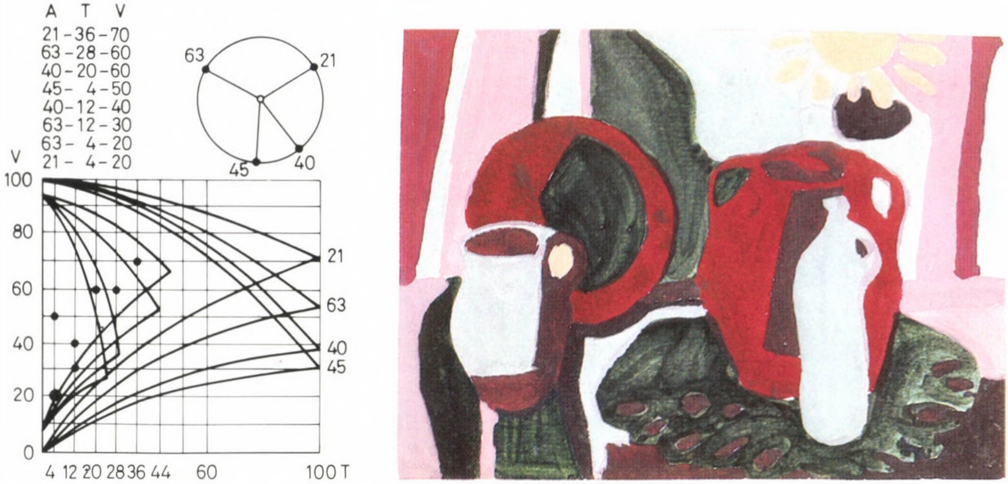


Fig. C87. Tetrachrome tetradic harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

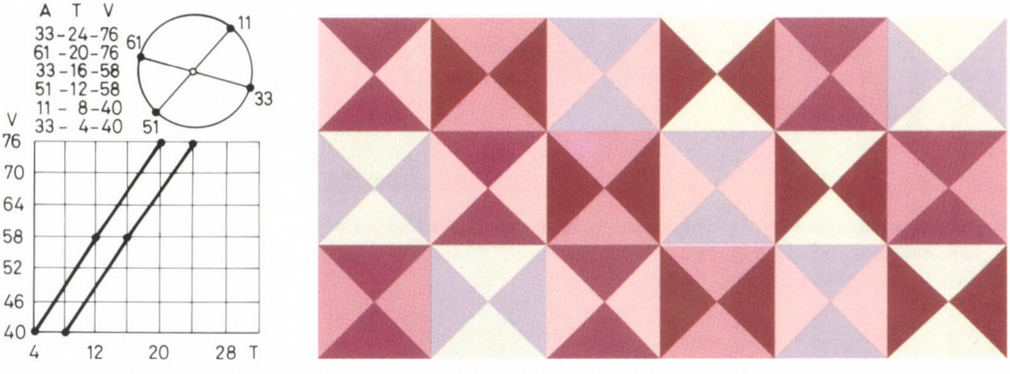


Fig. C88. Tetrachrome double complementary harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

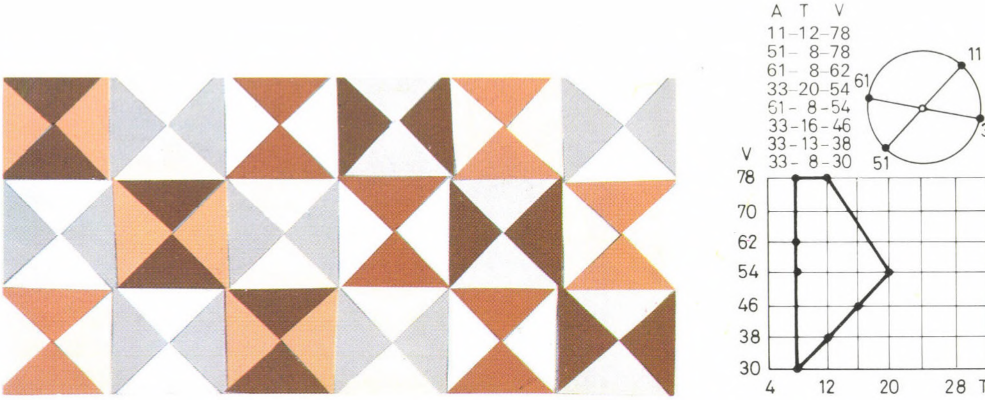


Fig. C89. Tetrachrome double complementary harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

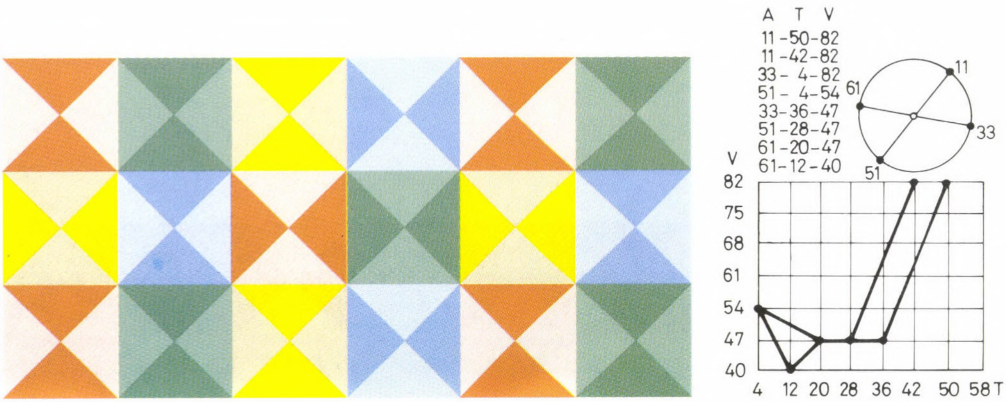


Fig. C90. Tetrachrome double complementary harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

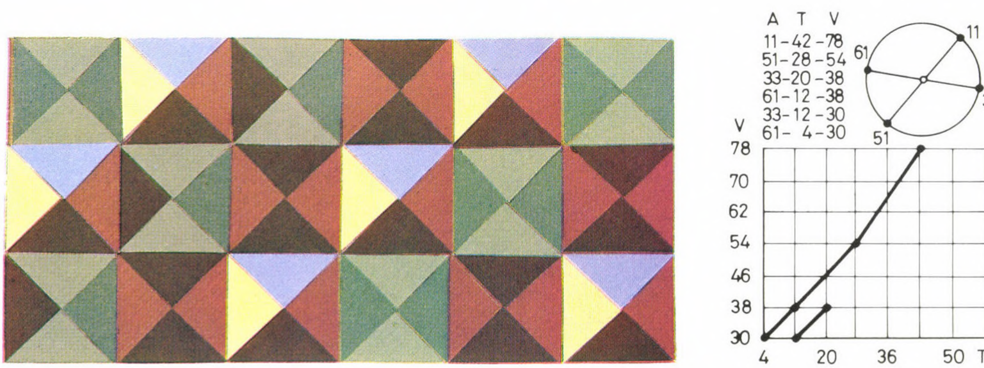


Fig. C91. Tetrachrome double complementary harmony. In the explanatory drawing, composition colours are represented in the proper Coloroid section, hues in the Coloroid colour circle. Also coordinates *A*, *T*, *V* of colours in the composition are indicated

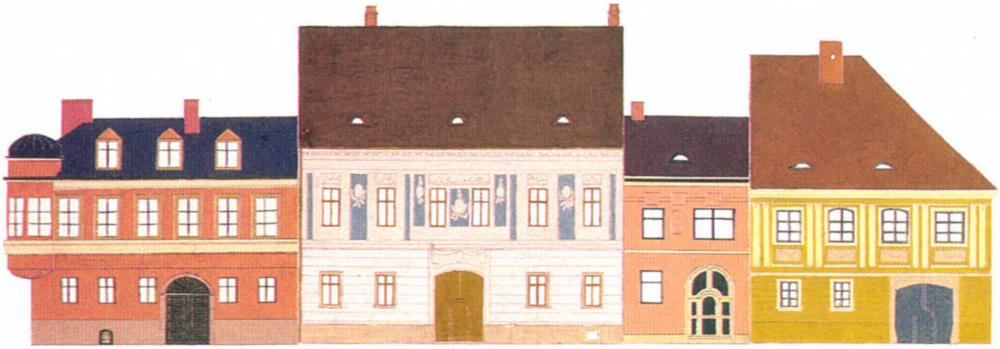


Fig. C92. A façade row in the Castle district of Buda, where buildings of exquisite form systems have been emphasized by coloration

Fig. C93. Façade row with equal saturation contrasts

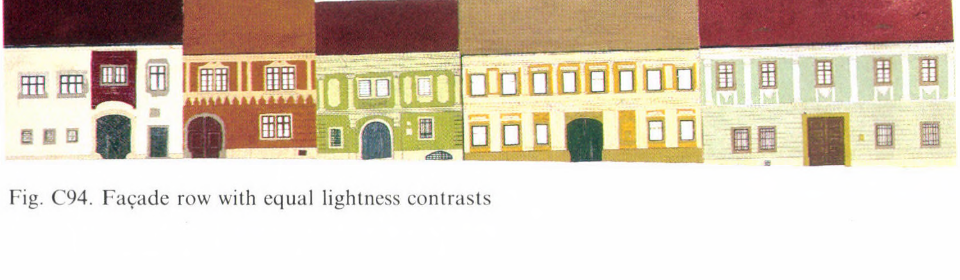


Fig. C94. Façade row with equal lightness contrasts

Fig. C95. Pictograms identifying plant units in a pharmaceutical factory: office, tabletting plant, ointment plant, analytics, laboratory, injection plant

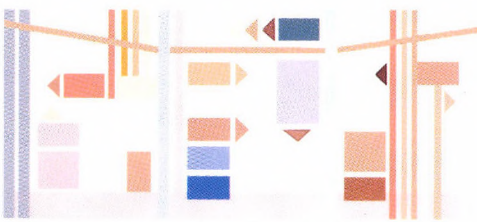


Fig. C96. Concept plan for a synthetics workshop I

Fig. C97. Concept plan for a synthetics workshop II

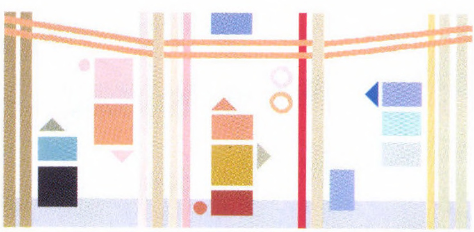


Fig. C98. Concept plan for a synthetics workshop III

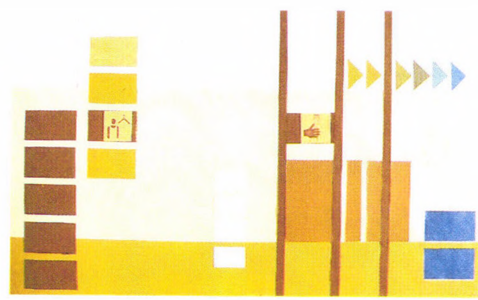


Fig. C99. Concept plan for a dressing room IV