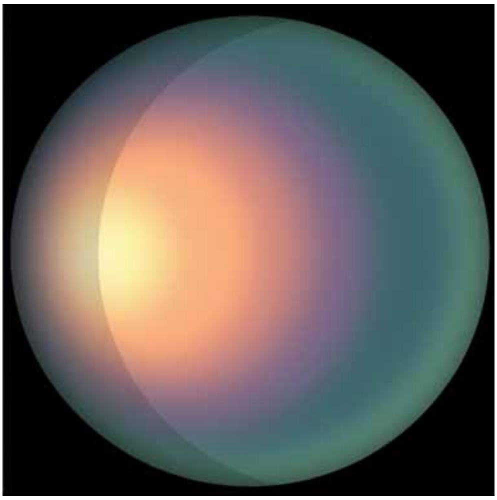
Department of Art

Colour and Light

Concepts and confusions

Harald Arnkil (ed.), Karin Fridell Anter, Ulf Klarén



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Colour and Light – Concepts and confusions

Harald Arnkil (ed.), Karin Fridell Anter, Ulf Klarén

Aalto University
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Foreword

The experiences of colour and light are interdependent and cannot be analysed separately. The colours of the environment influence our experiences of light and the need for lighting – and vice versa: the intensity, quality and distribution of light are essential for our perception and experience of colour. The aesthetics of colour and light play an important role in the fields of art, design and communication. In the built environment they influence our experiences and feelings, our comfort or discomfort and our physiological well-being.

A profound understanding of the interaction between colour, light and human beings calls for an interdisciplinary approach which up to now has been rather rare. As a result researchers and practitioners have often had difficulty in understanding and relating to one another's methods and results, although they work with similar questions. One important aspect of this is the absence of common and generally accepted concepts. These were the starting points for the interdisciplinary research project *SYN-TES: Human colour and light synthesis – towards a coherent field of knowledge*, carried out in Konstfack, Stockholm during 2010–11.

The SYN-TES project was funded by the Swedish Knowledge Foundation (KK-stiftelsen) and was supported by several Swedish companies working within the area of colour and light. The project has gathered internationally acknowledged scientific and technical experts within a number of fields working in colour and light. These include art, architecture, psychology and healthcare sciences, as well as leading companies dealing with lighting, colour and window glass.

SYN-TES has brought together researchers from five Nordic universities and institutions: The Aalto University School of Arts, Design and Architecture, The Centre for Visualization at Chalmers University of Technology, the Department of Environmental Psychology at Lund University, The Perception Studio at the University College of Arts, Crafts and Design (Konstfack), the Department of Architectural Design, Form and Colour studies at the Norwegian University of Science and Technology (NTNU) and the Faculty of Health Sciences at The Sahlgrenska Academy of the Gothenburg University.

Multidisciplinary research is one of the founding ideas of the publisher of this volume, the Aalto University, and its School of Arts, Design and Architecture has a long record of teaching colour and related subjects to students of all its faculties. It is therefore most fitting that this volume is published in this series of scientific papers.

The texts in this book were written within an epistemological subproject of SYN-TES. The aim is to present different scientific approaches in a broader epistemological perspective, to clarify conflicting use of concepts and to suggest possible ways of improving inter-disciplinary understanding. The texts are the result of long and intense discussions between the authors. Early drafts of some of the texts and the whole of *Light and Colour Concepts and their Use* have been discussed by the entire SYN-TES group.

C. L. Hardin is one of the most prominent philosophers of colour alive today. We are very pleased to include his extensive *Introduction*, which takes a look at the problem of bridging the gap between conscious experience and scientific data, with particular regard to the variability of human colour experience. Ulf Klarén, in *Natural Experience and physical Abstractions*, discusses different epistemological theories concerning perception, their evolution and their implications for our understanding of colour and light. In *Seeing and Perceiving* Harald Arnkil takes a closer look at these seemingly simple concepts, providing a starting point for discussing our visual experience of the world. *Light and Colour: Concepts and their use* by Karin Fridell Anter provides an overview of different approaches that have led to diverging uses of terminology and concepts within this field. Some of the most problematic terms and concepts are further discussed by Harald Arnkil in *Lightness and Brightness and Other Confusions*.

15th October 2011

Harald Arnkil

Karin Fridell Anter

Ulf Klarén

C.L. Hardin

Introduction

Question: A tree falls in the forest when nobody is around to hear it. Does it make a sound?

Answer: It depends on whether you take ‘sound’ to mean compression waves in the air or auditory sensation.

Thus we dispose of an equivocation posing as a philosophical problem. And yet, lurking beneath the surface of this bit of sophistry are serious questions. There is the metaphysical mind-body problem: how do conscious sensations find a place in a natural world fully describable in terms of energy distributions in space-time? And there are the twin sciences of physical and psychological acoustics in which the relevant variables such as frequency and pitch are at the same time distinct and deeply entwined.

Now suppose that you are looking at three yellow patches. The first of them is a coloured shadow. In a room whose ambient illumination is daylight, there is a spotlight with a blue filter, shining on an opaque object that casts a shadow. The shadow looks yellow. The second patch is produced on a video display. The third patch is a paint chip. Are all of these patches really yellow—in the same sense of “yellow”? We could reply that “really” here suggests that there is just one underlying concept of colour before us when in fact there may be an equivocation. Let’s see why there might be a problem with the idea that there is one preferred concept of colour.

Here is how the argument might proceed. In the first case, a spectrophotometer would indicate that the spectral profile of the shadow is identical with the profile of the ambient illumination, and this is not yellow. This result is confirmed visually by viewing the shadow through a hole in a screen that blocks out the surrounding area. The coloured shadow is a special case of simultaneous contrast, which is a product of your visual system. Its yellowness is thus a mere appearance.

In the second case, a close-up of the video screen reveals that there are just three types of coloured lights — green, red, and blue. None of them is yellow. The area only looked yellow because of optical mixing in your eye. Once again, the yellowness is only an appearance.

We are left with the paint chip. Here we seem to have a paradigmatic case of a colour quality securely anchored to a physical object. But let's look a little deeper. First, suppose that the paint formulation is such that the chip changes its colour appearance as the illumination changes, perhaps even from one phase of natural daylight to another. Which of these illumination conditions reveals its true colour? (Other sorts of materials are even more problematic, such as dichroic glass or bird feathers whose displayed colours depend upon viewing angles).

If you think that these are aberrant conditions, put them aside, and consider a nice stable Munsell or NCS yellow chip. Unless it is large enough to cover your entire field of view (in which case its perceived colour will quickly fade into invisibility), it will be seen against some sort of surround. Let that surround be a neutral grey. But since varying the lightness of the background will alter the chip's appearance, which grey will enable us to perceive it correctly?

Or take a more extreme but instructive circumstance. Surround the paint chip with bright white light, and the yellow is replaced by brown. Alternatively, take a chip that you would normally describe as brown, keep its illumination constant, but dim its surroundings, and it will appear yellow (or, depending on the particular choice of brown sample, orange). It is important to observe that brown is not just a dim yellow, but rather a blackened yellow; if the surrounding is kept constant and the illumination is progressively dimmed, the chip will continue to appear yellow all the way down to the point of invisibility. Brown is a contrast colour, just like black itself. If a grey scale is viewed with a lamp equipped with a dimmer, as the illumination increases the grey scale expands in both directions. By adding light, not only do whites become whiter, blacks get blacker.

The upshot is that if you dismiss the yellow coloured shadow because it is a contrast colour, on the same grounds you must dismiss as well the browns and blacks of everyday life, and these are surely also paradigmatic colours. Put it another way: our yellow chip is also a brown chip. What colour it is depends not upon its intrinsic nature but upon the company that it keeps. So if colours are what we initially thought them to be, none of our samples is really and truly yellow. If we are to avoid this unpleasant conclusion, we must refine our notion of colour.

One way to do this is to factor out the observer altogether and content ourselves with regarding colours as being constituted by spectral power distributions. This is the world of physical colour. Colour in this sense can be measured with great precision and needs to be understood very well if one is to produce and control colorants of all sorts as well as the lighting under which they are to be seen. Two pigments may look identical and yet have different spectral power distributions. If each of them is separately mixed with a third pigment, the two mixtures may very well look different. Or a restorer of paintings may touch up an area and achieve a perfect match in the studio only to find that when the painting is shown in the lighting of the gallery the touched-up area is plainly visible.

On the other hand, one who thinks that colours are simply spectral power distributions may be inclined to say silly things, such as “white light is a mixture of all colours.” This despite the fact that the original decomposer of white light, Isaac Newton, cautioned, “the rays are not coloured.” Furthermore, such a devotee of physical colours would be unable to understand how it is that a monochromatic yellow light could be visually indistinguishable from a mixture of two lights that look respectively red and green. In short, he would be unable to understand how colour television is possible. This brings us back to our second case, in which we might refer to the yellow as a psychophysical colour.

Psychophysics is concerned with an organism’s behavioural response to physical stimuli. In the case of colour, we know that human visual systems heavily filter spectral energy information in their environment, reducing it, in daylight conditions, to the response ratios of three photoreceptor classes. In the first half of the 20th century, information about the actual response characteristics of the photoreceptors was unobtainable, so the colour matches made by observers under carefully controlled conditions were averaged and mathematically manipulated to yield the 1931 CIE Standard Observer. This “Observer” (actually a lookup table), along with the specification of illuminant standards enables one to calculate colour mixtures that correspond well with the colour mixtures that real people make. The CIE system and related psychophysical colour spaces have been developed and improved upon over the years. For the appropriate standard viewing and illumination conditions, the CIE Observer will predict a match between our “television patch” yellow and our paint chip. They are thus the same psychophysical colour.

Despite the mathematical sophistication and practical success of colorimetry, we must bear in mind that its proper business is mixing and matching. It is common to see coloured renditions of the tongue-shaped CIE chromaticity diagram[1]. What is intended to be an intuitive aid in reading the figure all too readily makes the unwary suppose that the colour sample represented by a point in the diagram looks like the colour of the region in which the point appears, and that a straight line from a spectral locus to the white point will be a line of constant hue, with only the saturation varying. Typically this is not the case; in the chromaticity diagram the lines of constant hue are mostly curved to a greater or lesser extent. Hue shifts with desaturation.

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[1] See figure 14 on page 61.

The domain of colour psychophysics can extend beyond mixing and matching to the whole set of behavioural responses to spectral stimuli. So understood, it could be extended to animals and machines. It is strictly third-person in perspective and treats the subject as a black box. Its aim is to discover patterns of reliable response to a controlled set of targets. Computational modellers can then develop a set of functions that will translate those inputs to their associated outputs. The set of functions could be realized in either hardware or wetware, depending on the nature of the system that is being modelled. Although the data may be artificially structured in earlier stages of development, the aim of the modellers is to refine their product so as to approximate ever more closely the conditions of the setting in which the modelled object either does operate, in the case of a natural system such as a honeybee, or is intended to operate, as in the case of a robot.

Now suppose that we have a robot capable of operating effectively in a natural visual setting. It derives shape from shading, recognizes occluded objects, sorts paint chips, separates luminance from reflectance, and so on. In short, it deals with the environment of spectral power distributions in much the same way as we do. Does it see colour?

If your answer to this question is “yes”, you will accept physical and psychophysical colour and take psychological colour to be a mere appearance. But if your answer is “no,” you will not only take coloured shadows to be truly coloured, you will regard physical colour and psychophysical colour (which is really physical colour that is filtered by a receptor apparatus) as not being full-blooded colour at all, but merely the normal stimuli for psychological colour, that is, colour as an experienced quality. Inevitably, this demands a first-person perspective, the view from within the black box.

Life inside the box can be pretty nice. In contrast to the cold impersonality of atoms and the void, it is quality rich and, well, colourful. The box provides not just a sensory rush, but a structured and supplemented array as well. Outside there is light and darks, but the inside adds whiteness and blackness. Outside there is a wavelength continuum, but inside there is a configuration of unitary and binary hues.

This is, of course, just a latter-day version of what the philosopher-mathematician Whitehead called “the bifurcation of nature.” It was introduced into Western culture by Galileo and Descartes, and philosophers have been trying to bridge the divide ever since. It would be both presumptuous and vain to undertake here the construction of yet another bridge, but it might be interesting to consider some aspects of the problem from the standpoint of colour studies.

First of all, the human body, including the nervous system, is a part of nature; it is made of the same stuff, and subject to the same laws. It is becoming increasingly difficult to think of the mind as something distinct from the physical world as more and more of the processes and features of our mental lives are not only mapped onto brain processes, but are shown to depend upon them. Just as striking is the realization that, contrary to Descartes, the greater part of our cognition and volition takes place at an unconscious level. That said, many reflective people are uncomfortable with the claim that conscious events are identical with brain events. Is my pleasure at the deployment of green in a Degas painting nothing more than a pattern of neural activity? Complexity aside, does the difference between us and robots just come down to the difference between hardware and wetware?

There is a second bifurcation that is exacerbated by the first: the split between my consciousness and yours. In Aristotle's view, qualities were part and parcel of the physical world. Perception involved a process whereby a property of the world, which he called a "form," impressed itself on the mind of the percipient (hence our word "information"). Red is out there in the world, and it imprints itself on your mind just as it does on mine, so the question of whether you and I have the same colour experience doesn't arise. But after Galileo and Descartes, the fact that a spectral pattern strikes your retina in much the same way as it does mine fails to guarantee that the colour that is generated in your mind is like the one that is generated in mine. It should come as no surprise that the question as to whether what I experience as red you experience as green is first raised in the seventeenth century in the writing of Locke. The "inverted spectrum" problem has plagued us ever since.

The progress in neuroscience that seems to have narrowed the gap between experiences and brain events can give us some measure of comfort concerning our perceptual similarities and differences. What we currently understand about colour processing in the eye-brain points to very substantial similarities between what goes on in your visual pathways and mine. However, most of the neural underpinnings of our colour vision remain mysterious. For instance, although we can find a neural analogue of the hue circle, we have not yet been able to find the brain mechanisms that underlie the difference between unitary and binary hues.

We do know that there are differences between the colour vision of one person and that of another. Everyone knows about colour-deficient people. Much less appreciated are the significant differences that exist between "colour normals," i.e., people who pass the standard tests for colour deficiencies. A "normal" or "average" observer is assumed for all colour-order systems, but of course this is a statistical concept. It is interesting to see how wide the distribution is. Sixty-two years ago, Ralph Evans remarked,

> *A rough estimate indicates that a perfect match by a perfect "average" observer would probably be unsatisfactory for something like 90 percent of all observers because variation between observers is very much*

> *greater than the smallest colour differences that they can distinguish. Any observer whose variation from the standard was much greater than his ability to distinguish differences would be dissatisfied with the match.*[2]

It is possible to determine the extent of matching differences among normal observers and to gain some insight into the causes of the variation.[3] Using an instrument called the anomaloscope, a standard instrument for diagnosing colour deficiencies, colour-normal observers are asked to match an orange test hemifield with a mixture hemifield of red and green primaries in which the observer can set the red/green ratio. For men, the distribution of ratios is bimodal, falling into two distinct groups, with 60 percent of the observers in one group and 40 percent in the other. The distribution of ratios for women is unimodal, and broader than that for men. In the last decade it has been shown that these distributions are correlated with genetically based polymorphisms of longwave and middlewave cone photopigments.

The match that an observer makes between the two hemifields of an anomaloscope is a metameric match. The two sides have different spectra, but when the match is made, they look identical. Although metameric matches are rare in nature, they are very common in the modern world; the images of colour photography and colour television are metameric or approximately metameric matches to the colour appearances of the objects that they represent, as are most colorant matches. Because of inevitable variations in viewing conditions and in observers, such matches are to one degree or another problematic and rely on the large reservoir of forgiveness that the human brain has for colour variation when the samples are not put side by side.

Observers differ from each other in their colour-matching and metameric classes, so it should come as no surprise that their opponent responses are different. In fact, the differences are large enough to be shocking, as we shall now see. The stimulus locus for a perception of unique hue has been studied with a variety of techniques for many years. Every study with a reasonably large number of observers has found a wide distribution of unique hue loci among normal perceivers. Because the studies have used different experimental protocols and different perceiver groups, the mean results do not agree well across experiments, but substantial variability among observers within any given study is a constant. It is often supposed that more "naturalistic" experiments using surface colours will reduce the amount of variance from one observer to another, so here are the results of a recent hue experi-

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[2] Evans, R. M. (1948). *An Introduction to Colour*. John Wiley and Sons, New York, 196-77

[3] See Neitz, M. and Neitz, J. (1998) *Molecular Genetics and the Biological Basis of Colour Vision*, in W. G. K. Backhaus, R. Kliegl, and J. S. Werner (eds.), *Colour Vision: Perspectives from Different Disciplines*. Walter de Gruyter, Berlin , 101-119.

ment with coloured Munsell papers.[4] A 40-step hue set of constant lightness and chroma was used. The Munsell chips are approximately perceptually equispaced, so each chip is 1/40 of the hue circle. Observers adapted to a standard illuminant and viewed the chips against a light grey background. The figure shows the range of mean unique hue choices. Each observer performed the experiment three times. This enabled a comparison of variability within and between observers.

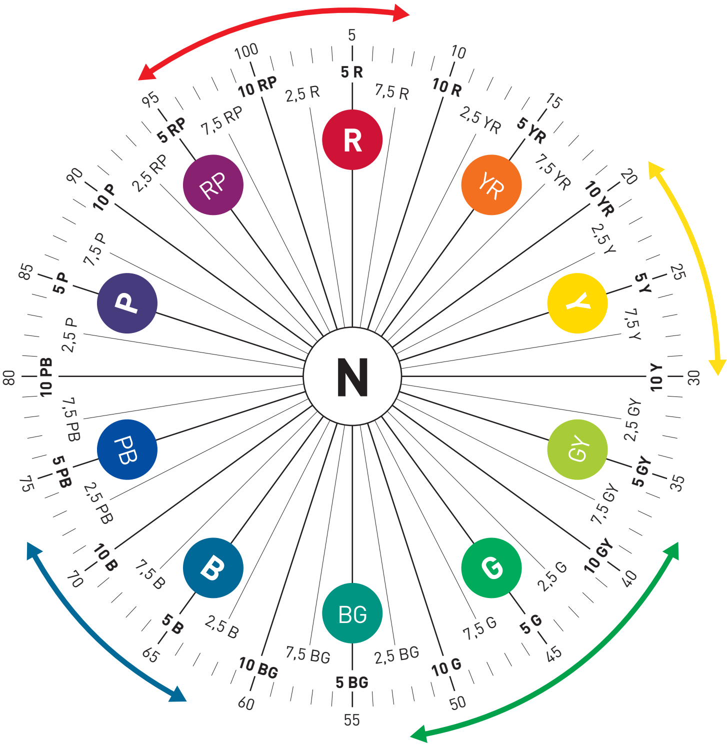

Figure 1. *Conceptual hue circle diagram of the Munsell system with the ranges of samples (marked with arrows) selected to represent the four unique hues of the Hinks et al. experiment.*

Only about 15% of the variability is intra-observer. The sum of the ranges in the diagram showing individual unique hue sample choices is 57.5% of the total. Observers can vary significantly in their individual “signatures” of unique hue choices. This suggests that there may not be a simple mechanism guiding unique hue stimulus choices. Perhaps past visual experiences are

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[4] Hinks, D., L. Cardenas, R. Shamey, R. G. Kuehni. (2007) *Unique Hue Stimulus Selection Using Munsell Color Chips*. Journal of the Optical Society of America A 26, 3371-3378.

involved. It is worth mentioning that other studies[5] have shown some variation in the average unique-hue choices from the speakers of different languages, but in every case the variation between observers speaking the same language was substantially larger than the variation across languages. Unlike the anomaloscopic matching variability, there is so far no satisfactory explanation for the variability in unique hue choices. It seems that the deeper in the brain we go, the more mysterious things become.

We should not be surprised to find such individual differences in perception. Along with its sibling, natural selection, variation is a hallmark of living things. A perceptual system need only be good enough to guide its owner to perform tasks that will sustain its species in its ecological niche, The advantages that primates gained by developing chromatic perception involved such activities as identifying predators and prey in dappled forest environment and spotting ripe fruit among the leaves, doing so in various phases of daylight and in changing shadows. There is no special premium that attaches to accomplishing these perceptual tasks with a high degree of precision or close agreement among perceivers. Biological mechanisms are typically a pastiche of earlier evolutionary endeavours. They are inherently rough, ready, and variable. The colours that we experience can be understood as natural signs of the filtered patterns of spectral power distributions in our environment. They should not be regarded as simulacra of the physical world that they represent. If we had all been born spectrally inverted, would this have made much difference in our ability to find our way around?

Keeping all of this in mind, how are we to approach the study of colour as an integral part of our human life-world? First of all, we shouldn’t take the deliverances of the senses too literally. My daily experience teaches me that the physical world is filled with coloured objects. It also teaches me that the earth moves only when there are earthquakes, that the heavens turn every 24 hours, that rocks are solid through and through, and that if there were antipodeans, they would walk with their feet above their heads. Second, we shouldn’t suppose that all scientific studies should be reducible to physics and chemistry. Geology, archaeology and botany are scientific studies and are thoroughly informed by physics and chemistry. But they, like the study of colour vision, fundamentally involve historical accident, so the phenomena that fall under them cannot be explicable in terms of universal laws. Third, most phenomena of human interest are inherently too complex to admit of rigorous analysis. This does not mean that they are incapable of a degree of mathematical analysis (this is why God gave us statistics) but that estimation and qualitative understanding are inescapable if we are to understand what is going on.

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[5] Webster, M. A. et al. (2002). *Variations in Normal Color Vision. III. Unique Hues in Indian and United States Observers.* Journal of the Optical Society of America A 19 (10) 1951-1962.

In an effort to sort out the logical geography of colour, we began with the creaky old question of the tree falling in the forest and remarked that the distinction between physical sound and auditory sensation uncovers the metaphysical mind-body problem as well as two distinct but intertwined scientific studies. We then proceeded to ask if there was, analogously, a distinction between three different senses of "colour," and in so doing uncovered the same metaphysical problem and three distinct but intertwined scientific studies. But would it perhaps be more fruitful to speak not of different concepts of colour, but of different points of view from which colour could be understood? And while we are at it, why restrict ourselves to three? Think of the designer of a multipurpose auditorium. The room must serve the needs of lectures, string quartets, operas, rock concerts, symphonic concerts, public forums, and perhaps the occasional film. She must recognize each set of purposes—many of them conflicting—and understand the physical, psychoacoustic, psychological, social and aesthetic factors that underlie each of them and yet unite all of them. Colour studies, like auditorium design, require a well-grounded pluralism with a secure grasp of common principles. And this is what you, the reader, can expect from the chapters of this book.

Ulf Klarén

Natural Experiences and Physical Abstractions – On epistemology of colour and light

> *We may, if we like, by reasonings unwind things back to – – [the] moving clouds of swarming atoms which science calls the only real world. But – – the world we feel and live in will be that which our ancestors and we, by slowly cumulative strokes of choice, have extricated out of this – – by simply rejecting certain portions of the given stuff.* [6]
>
> *– William James*[7] *1890*

Colour and light are fundamental to our experience of an outer reality. Colour and light are what we *see*; to see colour and light logically distributed in space *is* to see. What we, however, without hindrance and so vividly *experience* is a coherent, surrounding world full of life. Man is a living creature moving around in a spatial, continuously changing world. His perceptual systems and cognitive abilities receive their distinctive features from this fact.

The most important aspect of human experience is that perceptual patterns, that can be perceived and understood as spatial, are given such an interpretation in the mind. All senses contribute to the experience of the surrounding world, but vision occupies a place apart in perception; vision provides a spatial inner image.

Our vision is based on a continuous adaptation to the physical world, where colour and light are perceived from endlessly varying spatial positions and under continuously changing light conditions.

In colour research methodology has most often neglected the need for knowledge about spatial visual perception. It has set out from surface colours in even and uniform light, and although colour and light are mentally inseparable in our experience of the world around, the mutual and dynamic relation between colour and light experiences has not been given attention. As a con-

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[6] James 1890, pp 288–289.

[7] American psychologist and philosopher, 1842–1910

sequence there is a lack of common concepts defining spatial colour/light experiences.

The relationship between the physically measurable and vision is, however, very complicated. An epistemological discussion about colour and light concepts have to set out from reflections on dynamics of colour and light perception in space and on relevance of physically based concepts to human experience of the world.

The intention of this text is to give a concise overview of epistemological considerations about human experience and in particular about human experience of colour and light. It will conclude in a discussion about concept formation in the field of colour and light.

Knowledge about the world

The aim of natural science is to research, to describe, to explain and to predict occurrences in the surrounding world. Description and interpretation has to be supported by empirical facts originated from experiments, systematic observations, tests, etc.

These premises have their origin from AUGUSTE COMTE[8], the founder of *positivism*. They refer to a set of epistemological perspectives that hold that the scientific method is the best approach to uncovering the processes by which both physical and human events occur. In Comte the firm ground of reality is facts and arguments of reason in an implicit and never fully uncovered positive world ruled by laws of nature. (Comte 1975, p 21)

The positivist scientific approach is based on the idea of a ‘factual’ and ‘objective’ world beyond the reach of our senses. In spite of its starting point in empiricism the study of reality to a great extent cannot be carried out by direct observations. Of necessity descriptions of scientific facts have to be indirect – reached by quantifying and by measuring. Hence the scientific ‘true’ world could be described as an abstraction constructed by quantitative values, which are interpreted from concepts belonging to the scientific worldview. The paradigm of positivist rationality is often considered as the only reliable basis of objective knowledge; consequently, it is no surprise that human intuition and perception have been regarded as precarious or at least questionable as sources of knowledge about reality.

SUSANNE K. LANGER[9] calls attention to the fact that the word *intuitive* is often used in a confused way; intuition is supposed to be “without reasoning” and

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[8] French philosopher, 1798–1857

[9] American philosopher, 1895–1985

that without "benefit of logic" which ends in "mysticism, mixed with every degree of philosophical irrationalism – – and sheer sentimentality and romantic fancies." (Langer 1957, p 60). Just the other way round and relating to JOHN LOCKE[10] she claims that there is "no possible conflict between intuition and discursive reason" (Langer 1957, p 66). Intuition is the fundamental intellectual activity, which produces logical or semantic understanding. It comprises all acts of insight or recognition of formal properties, of relations, of significance, and of abstraction and exemplification. "Intuitions are neither 'true' nor 'false', but simply present" (Langer 1957, p 66). Hence they can be described – at least in principle.

Even if researchers in the field of science nowadays seldom are absolute positivists, the idea of an objective (non-human) world that, directly or indirectly, can be empirically uncovered has a strong position in science. A strict scientific perspective implicitly assumes an analogy between measurable facts and perceived phenomena and there is a tendency to regard deviations from this analogous relation as illusions, perceptual misunderstandings, subjective distortions or methodological mistakes.

We experience colour and light intuitively as properties belonging to the outer world, in this sense you could say that colour and light *are* the visual world. In the physical world – beyond the reach of senses – the existence of colour and light can only be demonstrated indirectly by measuring spectral electromagnetic radiation with wavelengths between approximately 380 nm and 760 nm. This radiation can be detected by the human eye, but the rays themselves are not visible. ISAAC NEWTON[11] remarked that "[t]he rays, to speak properly, are not coloured. In them there is nothing else than a certain power and disposition to stir up a sensation of this or that colour." (Newton 1704).

Experience of colour and light is dependent on electromagnetic radiation but the colour and lightness of an object are only to a certain degree dependent on spectral distribution of the radiation that it reflects. ARNE VALBERG[12] states: "The reflection properties of surfaces relative to their surround are more important for colour vision than the actual spectral distribution reaching the eyes." (Valberg 2005, p 266). C. L. HARDIN[13] concludes: "There is no simple analogous relation between the outer world and our experience of it." (Hardin 1988, p xxi).

Philosophy – and epistemology – has taken a great interest in *the relationship between* the *inner* and *outer world*. GALILEO GALILEI[14] made a distinction

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[10] English philosopher, 1632–1704

[11] English physicist and natural philosopher, 1643–1727

[12] Norwegian neurophysiologist, 1938–

[13] American philosopher, 1932–

[14] Italian philosopher, 1564–1642

between primary and secondary sensory qualities. According to Galilei – and later to John Locke (Locke 1975, pp 135–141) – *primary characteristics,* such as hardness, mass and extension in space and time are properties of objects, whereas *secondary characteristics,* such as colour, texture and shape, are produced by the mind. Galilei thought that "colours – – are no more than mere names so far as the object in which we locate them are concerned, and that they reside in consciousness. Without a living creature experiencing them, they would not be there." (Galilei 1957, p 274).

RENÉ DESCARTES[15] points out that our senses often deceive us and that this is the reason why they cannot give us full certainty. His doubt principally concerns the ability of the senses as such to give us any knowledge about the world at all; he considers all perceptions of the outer world as deceptive appearances. (Descartes 1953, p 95). What we perceive is, however, not guided by our will, it comes to us involuntarily. According to Descartes, this indicates an existence of something outside of his mind, and thus, an external world. (Descartes 1953, p 134). The ultimate solution to the problem of the connection between an outer material world (*res extensa*) and an inner conscious world (*res cogitans*) is done referring to a good and omniscient God, who cannot provide human beings with conceptions of the world as mere illusions. (Descartes 1953, 137–138). Descartes claims – as Locke does – that physical objects themselves have no colour, only a power or disposition to arouse in the viewer the idea that objects have special colours. But both of them regard this "illusion" as natural, unproblematic and, in practice, possible to ignore: to the naïve – not philosophically reflecting – everyday perceivers the objects have their special colours; it is the nature of perception. A *sophisticated* perceiver, however, knows that colour is the power to make us experience the objects as coloured. (Maund 1995, pp 7–8).

Knowledge beside the world

IMMANUEL KANT[16] takes his starting point from human consciousness and the human world of experience. By introspection he tries to describe the principles of our conception of the world and ignore the outer reality, the world as independent of how we perceive it. His thesis is that beyond our senses we have no access to the outer world and that knowledge about the world is dependent on *a priori* given abilities. (Kant 2004, p 111–112). Experiences of space and time are, a priori, given and perceptual and not conceptual. (Kant 2004, pp 113–124).

We approach the manifoldness of the external world with what he calls *transcendental consciousness;* by representation of space and time and by a num-

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[15] French philosopher, 1596–1650

[16] German philosopher, 1724–1804

ber of mental categories perceptions are intuitively structured into objective experience of objects arranged under concepts. (Kant 2004, p 193–197). Kant says that “concepts without perceptions are empty; perceptions without concepts are blind.” (Kant 2004, p 156). We cannot know what objects may be in themselves apart from "our mode of perceiving them." (Kant 2004, p 125). Sense qualities – for example colour, sound, etc. – and the unknown matter of the world together form what Kant calls ‘content’ (*Inhalt*) and this content is given its mental (human) form by our inner categories and analytic abilities. (Liedman 2006, pp 233–236). Experience of colour and light are subordinate to apprehension of space. According to C. D. BROAD[17] human beings can in Kant be seen as “centres of innate systems of spatial references, of which they are perpetually and immediately aware.” (Broad 1979, p 22).

To Kant colour and light are primarily perceptual *links* between an outer reality and the inner world; colour and light have no meaning until they have found a given position in space and time and in an inner conceptual structure, and thereby become logically integrated parts of an individually experienced world as a whole.

EDMUND HUSSERL[18] and the phenomenology he presents connect to this perspective. His project is to bring about a strictly scientific epistemology based on human consciousness and mere phenomena. According to Husserl we have only direct access to accidental and individual experiences (phenomena); these alone can be taken as a pretext for an epistemology on scientific ground. (Husserl 1989, p 45). Hence Husserl’s standpoint is quite the contrary to the positivist scientific view, which implies that the only veritable is the outer ‘objective’ world.

Knowledge as part of the world

MARTIN HEIDEGGER[19] claims – in contrast to Husserl – that it is not possible to understand how the world gets a meaning if we do not find out *how* human beings exist *in the world*, because this is what influences how the world is perceived. To Heidegger the human world is a complex of meanings. It is not enough to look at the world: meaning originates in human interaction with the world around, when *using* the world. (Heidegger 1986, p 69). From epistemological reasons Husserl reduces his descriptions to man himself and to his individual consciousness: he sets a limit to the external objective world. Heidegger moves this limit “out into” the surrounding world.

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[17] American philosopher, 1887–1971

[18] German philosopher, 1859–1938

[19] German philosopher, 1889–1976

MAURICE MERLEAU-PONTY[20] proceeds in the same direction. He widens, defines and reconstructs the concept of the world of meanings that Heidegger tries to describe with his concept *being-in-the-world* (Heidegger 1986, p 313). To human beings perception is the direct access to the world. We exist in the world before being able to reflect upon it. The human world is created in interaction and communication between the body and the surrounding world, and knowledge must be constituted as interplay with the world. Merleau-Ponty wants to show that *I think* of necessity must be based upon *I perceive* – *percipio* precedes c*ogito*. (Merleau-Ponty 2002, pp 250–252). He describes the coherence of consciousness and nature: the perceived world establishes the development of the human and social world, which forms a significant connected whole of cultural, social and political contents and expressions. It can change and be reinterpreted, but can never totally be taken in or controlled by the individual. It is implicitly present in all perceptions. (Merleau-Ponty 2002, p 403–408).

KARL POPPER[21] in a similar way describes the human and social world with what he calls *World 3*, the content of which is the totality of thoughts, theories and formulations in culture: scientific theories, poetry, art, etc. (Popper 1997, p 61). According to Popper, *World 3* has a (more or less) independent existence of established tradition of objective knowledge that cannot easily be influenced by individuals. (Popper's *World 1* and *World 2* describe direct perception of the world and a personal inner world respectively). (Popper 1997, p 62).

To Descartes and Locke objects are entirely objects and consciousness entirely consciousness, and the surrounding world, in principle, what it appears to be. Merleau-Ponty (and Popper) present more ambivalent relations between human consciousness and the external world; to man the world is neither entirely nature nor entirely consciousness. None of them outweighs the other: neither nature (nor culture), nor consciousness. (Merleau-Ponty 2002, pp 96–98).

From a scientific perspective and without any connection to philosophical considerations Arne Valberg points out that many properties that we normally attribute to the external world (like contrasts, movement and depth) rely heavily on perception. In the light of these facts he finds it understandable that there are philosophers regarding all vision as an illusion. He also remarks that it is almost impossible to distinguish between 'neural' and 'cognitive' levels of perceptual patterns (Valberg 2005, p 28); vision is even to a natural scientist as Valberg (as to Merleau-Ponty) neither entirely nature nor entirely consciousness. What Merleau-Ponty, from a philosophical perspective, and Valberg, from a scientific point of view, claim is that human experi-

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[20] French philosopher, 1908–1961

[21] Austrian-British philosopher, 1902–1994

ence derives its origin from multiple sources that are external as well as internal.

Our visual experience of the world does not emanate from a series of static retinal images. Our vision has access to a dynamic flow of continuously varying retinal information interplaying with complex information from all other senses, about spatial colour and light relations, about spatial movements, about our present position in space. In accordance with Merleau-Ponty's 'human world' JAMES J. GIBSON[22] describes an ecological approach to perception; there is a tight perceptual attunement between human beings and their environment. The perceptual relationship between the outer world and the human inner world is natural and without hindrance. The perceptual systems have developed for millions of years interplaying with the surrounding world (Gibson 1979).

ALVA NOË[23] referring to Gibson, comments that "the perceptual world (the environment) – – is not a separate place or world; it is the world thought of from our standpoint (or any animal's standpoint)." (Noë 2004, p 156). It is the world "for us" [24], the special human perceptual niche, in ecological balance with the human environment. Gibson and Noë regard man as ecologically integrated in a world, where appearances are genuine features of the environment; hence colour and light, in Gibson's ecological sense, are *natural* but *non-physical* (Noë 2004, p 155). We know nothing more except that they exist and give us impressions and order in time and space. The Swedish perceptual colour notation system Natural Colour System (NCS) is *natural* in Gibson's sense.

One world, several aspects

The ultimate aim of human perception and cognition is to achieve and maintain a constant and coherent world. Gibson calls attention to the fact that the perceptive registration process is successive, but it is nevertheless experienced as if it were simultaneous. (Gibson 1958, p 184).

Human perception is often described as structuring information from the outer world. Attention is not so often called to the fact that one of the most basic functions of the perception process is to select and discard information in order to make it more comprehensible. The flow of potential information in the outer world is immense. The human perceptual niche is narrow and

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[22] American psychologist, 1904–1979

[23] American philosopher, 1964–

[24] *For us* refers to Immanuel Kant, who makes a distinction between *the-thing-in-itself* (*das Ding an Sich*; the world beyond the phenomena) and *the-thing-for-us (das Ding für uns*; the world as experienced through our knowledge. (Kant (2004, pp 325–327).

limited to what is required for human life and survival. Gibson describes our senses as perceptual systems: instead of five separate senses he prefers to talk about five modes of external attention. (Gibson 1966, pp 166-167) MANFRED ZIMMERMANN[25] estimates the potential capacity of the human visual system at 10 million bit/second (which would mean the ability to discriminate 10 millions colours). In information theory the concept *bit* is used as a measure of quantity of information; it indicates a smallest perceivable unit in the information flow. It does not describe content of information only perceivable quantity of information. The total information capacity of all senses together is supposed to be about 11,2 million bit/second and the information capacity for our conscious experience of the world around is not more than 40 bit/second. (Zimmermann 1989, p 172). Principles for selection and reduction of information correspond to human existential needs. Every creature has its own special access to the world. William James compares the work of our senses with the work of sculptors:

> *Other sculptors, other statues from the same stone! Other minds, other worlds from the same monotonous and inexpressive chaos! My world is but one in a million alike embedded, alike real to those who may abstract them. How different must be the worlds in the consciousness of an ant, cuttlefish or a crab! (James 1890, pp 288–289).*

Reducing information and selecting what in a given context has to be attended to requires some kind of *attention structure*. An attention structure – conscious or unconscious – directs attention to certain aspects of a phenomenon. In science such a perceptual principle is usually called a *theoretical perspective*. (Eneroth 1994, p 24). Acquiring knowledge is to develop attention structures. (Gardner 1994, p 24).

Merleau-Ponty discusses how we experience the surrounding world in different ways depending on situation. He makes a distinction between two modes of attention: *the reflective attitude* and *living perception*. (Merleau-Ponty 2002, p 355). This distinction is significant to our perception of colour. Strictly speaking it is not possible to find out how we perceive colour in *living perception,* since every question that directs our attention towards a colour gives, of necessity, rise to a reflective attitude.

When perceiving colours, our vision does not recognize the absolute intensity or the absolute spectral distribution of radiation that reaches our retina. Instead *distinctions* and *relations* are registered. Our visual system is developed for a continuous spectrum of light and gradual changes between different illuminations, and under these circumstances we perceive colours as more or less constant. Our visual sense adapts to current light conditions: what we perceive as white in a given illumination functions as a perceptual "anchor"

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[25] German neurophysiologist, 1933–

both for perception of lightness (Gilchrist et al. 1999) and hue (Klarén and Fridell Anter 2011).

But even if we experience that an object has almost the same colour in a different light, we can at the same time perceive a slight tone of colour that reveals the character of the light. For nominally achromatic surfaces this effect is more obvious than for nominally chromatic surfaces. We experience that the surface is white but we feel at the same time that it is illuminated with a light of a special quality and intensity. This involves not only light coming directly from the light source, but also light reflected from surrounding surfaces.

Depending on *modes of attention,* a nominally white wall lit by 'warm' sunlight can be seen (with a reflective attitude) as slightly yellowish or (with living perception) as the "proper" or "real" colour of the wall experienced beyond the perceived colour. As a suggestion one could call this colour *constancy colour* [26] (Fig. 1). (See also *Lightness and Brightness and Other Confusions* in this volume).

According to Alva Noë, different kinds of visual appearances can be experienced simultaneously. Noë gives an example from shape perception: When a circular plate is held up at an angle, we are able to experience circularity in what we simultaneously perceive as an elliptical shape. In the same way, we can experience, say, a white constancy colour in a surface that we simultaneously perceive as having a hue caused by light. (Noë 2004, pp 131–132).

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[26] Ewald Hering's concept *memory colour* (Gedächtnisfarbe) touches on this phenomena, but confines to expected colours in objects: "What the layman calls the real colour of an object is a colour of the object that has become fixed, as it were, in his memory; I should like to call it the memory colour of the object". Hering (1920). *Constancy colour* refers to a natural perceptual 'skill'; we make 'hypotheses' of what the colour is from perceived visual information in a given context. Merleau-Ponty says that the "real" colour persists "not as a seen or thought-of quality, but through a non-sensory presence." (Merleau-Ponty 2002, p 356). See also Klarén and Fridell Anter, 2011.

Figure 2. *View of a winter day in Norway: The nominally white snow can be seen as slightly bluish and yellowish as effects of sunlight and shading or as pure white as a whiteness anchor. Beyond the perceived colours we feel the constancy colour, the 'proper' or 'real' colour of snow.*
(Photo: Ulf Klarén)

All these colour and light interactions are what makes us perceive space. Normally we have no difficulties in making distinctions between what is caused by the light and what by the qualities of surfaces. Perhaps we do not pay attention or give interest to the accidental colour of direct light, of reflected light or of shadows; but intuitively the logically distributed colour variations caused by light, reflections and shadings are indispensable spatial qualities.

Human experience of colour and light in space is both perceptual and cognitive. What we call adaptation is not limited to basic physiological reactions (Noë 2004, pp 1–3); it is an interplay between the individual and the world on many levels. These include the basic level of innate reactions, the level of perceptive skills based on direct experience of the world and the level of cultural context.

Human aesthetic coherence

GOTTLIEB BAUMGARTEN[27], the originator of *aesthetics* as a specific academic discipline, tries to describe in his philosophical project a knowledge that implies a coherent intuitive understanding that is given to us directly by sense experiences. (Malmanger 2000, p 8). Knowledge based on the senses is not solely subordinate to logical knowledge; Baumgarten claims that aesthetic

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[27] German philosopher, 1714–1762

knowledge constitutes logical knowledge. (Baumgarten 1983, p 80). Baumgarten contributes to traditional epistemology with an intuitive (aesthetic) dimension. The tacit meaning of space, colour and light belongs to aesthetic experience. Emotions and feelings are so closely connected to perceptions that they could be regarded almost as part of the same phenomenon. They set the tone or the mood. They give an intuitive hint about our situation – not *what* it means, but *how* it is.

LUDWIG WITTGENSTEIN[28], in *Tractatus*, states: "*Whereof one cannot speak, thereof one must be silent*." (Wittgenstein 1992, p 37), but he adds that what is beyond the limits of (verbal) language manifests itself to the senses and can be demonstrated. (Wittgenstein 1992, p 122). Susanne K. Langer's aesthetic philosophy is part of the epistemological tradition from Baumgarten. Connecting to Wittgenstein she asks how we give mental and expressive form to the tacit dimension. She claims that the emotional content we experience in objects or spaces is symbolic in a special way. In the surrounding world we perceive visual qualities that are spatially logical patterns of colour, light, form and movements. Patterns of such qualities always belong to functional situations in life, each one with their own characteristic emotional content. Hence colour and form structures can give visual experience of the world. Abstracted from their normal context – e.g. in designed objects and designed spaces – colour and form patterns, according to Susanne Langer, can be experienced or used as symbols for *felt life* (Langer 1957, p 60 and p 374). Susanne Langer calls them *logical expressive* – or articulated – *symbols*. They are what we may call the artistic or aesthetic dimension in pictures, in utility goods, in architecture – in the surrounding world. (Langer 1953, p 31 and pp 51–52). Ludwig Wittgenstein says that feelings follow experience of a piece of music, just as they follow courses in life. (Wittgenstein 1993, p 19). A piece of music consists of a sequence of tones. It has a structural resemblance to courses in life – rhythm, pauses and breaks, pitches, etc. – and thus it can be used as an example. The auditive structure in music is not a course of life, but felt life abstracted in a logical expressive symbol. This is also true of perceived colour and light structures.

The ecological approach offers rational and coherent explanations for many of those perceptual phenomena that cannot completely be described by physical concepts or be explained by physical theories. It also builds bridges between perception theory, philosophical aesthetics, art theory and scientific theory about the material world. Thereby it helps to make human experience of the world a multidisciplinary but coherent field of research.

We can describe the world around with concepts based on either physical aspects or human aspects of reality. The concepts of the human experience and the concepts of the physical reality constitute two equally valuable con-

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[28] Austrian-British philosopher, 1889-1951

ceptual systems (or conceptual models) but with different bases. (See also *Light and Colour – Concepts and their use* in this volume).

Figure 3 shows levels of human experience. The two inner circles represent *categorical perception* and the *direct experience* respectively. The outer circle represents *indirect experience* culturally transferred through history, traditions, customs, trends, scientific theories, art, poetry etc. Categorical perception is in some respects determined genetically, but for the most part acquired in early life. The basic experiences of colour, light, space, perception of contours and contrasts, balance, verticality and horizontality, etc., are parts of the categorical perception, the aim of which is to build a comprehensive mental world: “A reality without well-defined borders is divided up into distinct units by our perceptual mechanism” (Gärdenfors 2000, p 40. My transl.) and not by verbal language. By natural selection man has been endowed certain perceptive and cognitive tools for survival and this is basically common for us all. We are genetically predetermined to perceive colour and light. What we perceive is not discrete colours, lightness and brightness but the relations between them. (Valberg 2005, p 266); the aim of basic colour perception is perceiving colour distinctions and colour similarities.

Interplaying with the physical world humans (and other living creatures) develop perceptual skills that help to catch the spatial meaning of the logical distribution of light and shading, we gradually learn through living how to recognize and understand colour-and light in the world around. We connect special perceptual situations in the environment with conceptual meanings. All concepts are abstract and thus they belong to the outer circle. Dependent on their origin they have indirect or direct relations to the two inner circles. Concepts used to describe spatial light situations or perceptual light qualities – *spatial light balance*, *light colour*, *etc* – and concepts used in perceptual colour theory – *hue*, *lightness*, *chromaticness*, *colour contrast, etc.* [29] – aim at describing a *direct* experience. On the other hand concepts based on physical analyses with *quantitative measurements* and *instrumental* methods have an *indirect* relation to perceptual phenomena.

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[29] The colour terminology refers to the Natural Colour System (NCS) – the Swedish standard for colour notation. (Hård, Sivik and Tonnquist 1996).

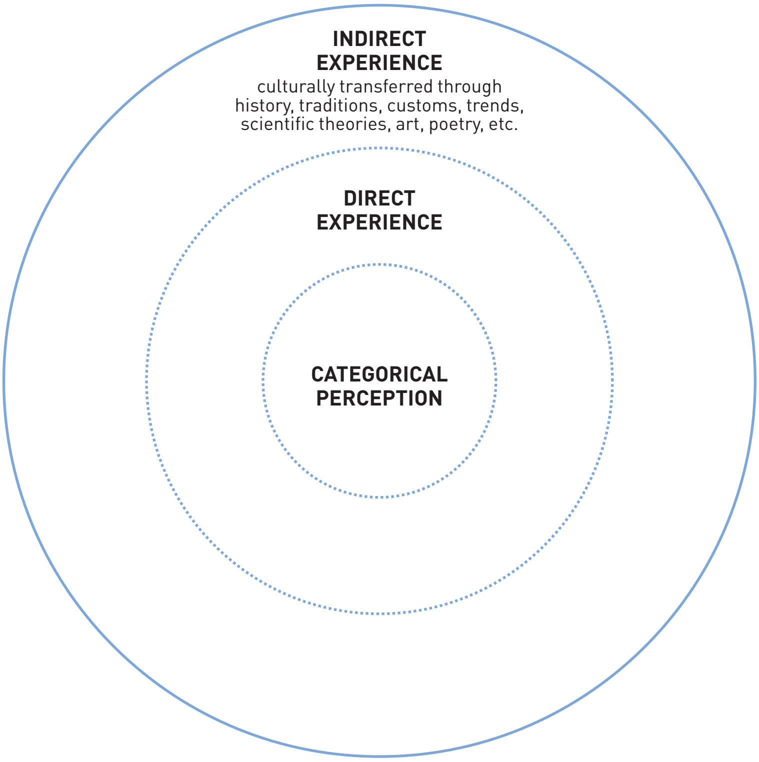

Figure 3. *The graphic model shows levels of experience - from experiences based on categorical perception through direct experience of the world around to the indirect experience imbedded in cultural expressions. The three experience levels are mutually dependent and they are all implicitly present in all perceptions. Colour and light can be understood in many ways and on all levels. They can never be separated from the coherent experience of the world. (Model by Ulf Klarén 2010)*

The three experience levels are mutually dependant and they are all implicitly present in all perceptions. A perceived distinction between a red colour and other colours is a basic (categorical) perception. The experience of the colour of a wall – whether in light or shadow – is a direct experience of the world around, and the knowledge that red has a special position in a colour system, that red surfaces absorb electromagnetic radiation in a special way, and that red houses may be of high social importance, is based on indirect experience. Our experience of the world is always a coherent whole but when using colour and light concepts it is, at the same time, important not to mix up their conceptual contexts.

What to do?

In the light of the complexity of human experience it could seem almost impossible to find a common language to communicate about the human perception of colour and light in a spatial context. Our experience is not without structure or laws and certainly there are many concepts describing human experience. You could even say that there are too many – and disparate – concepts to be useful in communication. The basic problem, however, is not the great number of concepts but the fact that they often lack a distinct position in a coherent and well-defined structure of concepts. Without a comprehensive structure of content it is not possible to see how different concepts are related to each other or in what respect they refer to different aspects of reality.

Physical abstractions

The concepts referring to abstract properties and hidden, underlying, but measurable structures of the physical world are useful as long as they are used to describe the material world. It is necessary for paint industries and light source industries to have the use of instruments to control and maintain physical standards of their products. But in the field of colour and light, visual/perceptual phenomena are too often described and analysed with the use of physically based concepts, which can give the false impression that physical measurements also measure what we see. This is not only a question of simplification. Using physically based concepts to describe perception of colour and light may be both misleading and incorrect. It is, however, no surprise that it happens all the time. In the technical world of light sources, projectors and spotlights there are very few words relating to human experience of light; physically or technically based concepts are used *instead*. We find the same tendency in art, where painters often use names of pigments to describe hues or colour nuances.[30]

Natural experiences

Apart from the scientific colour systems, which are partially or totally based on the visual perception of colour (for example the *Natural Colour System*, the *Munsell Colour Notation System* or *the OSA Uniform Color Space*[31]), there is no general conceptual standard for the human experience of colour. The aim of the perceptual colour systems is to offer standards for colour dis-

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[30] Today pigment names for artists' paints rarely even refer to the genuine pigment, which adds to the confusion.

[31] The *OSA-UCS* is a colour space first published in 1974 and developed by the Optical Society of America's Committee on Uniform Color Scales.

tinctions and colour similarities. Perceptual colour systems make it possible to systematically describe perceptual patterns of colours in a spatial context. KARIN FRIDELL ANTER's[32] surveys of perceived colour of painted facades may serve as an example of that kind of studies. (Fridell Anter 2000).

Concepts describing colour and light as integrated in a spatial whole have to be based, however, on coherent spatial experiences. Spatial perception demands spatial relations and directions, size gradients, enclosure, etc. DAVID PRALL[33] remarks that

> *[y]ou cannot make a spatial whole except with elements the very nature and being of which is spatial extension – – The elements must lie in an order native to their being, an order grasped by us as constituted by relation. We call structures intelligible – – so far we find them capable of analysis into such elements so related. (Prall 1936, p 39).*

Colours as such have no spatial extension. They have no formal structure except colour qualities related to other colour qualities (i.e. contrasts in lightness, whiteness, blackness, hue or chromaticness). If colour phenomena are abstracted from their natural connections to light and spatial order, causal relations behind them become inconceivable and mystified.

A possible starting-point for concept forming for colour and light in space could be the phenomenological/psychological tradition, with concepts such as DAVID KATZ's[34] definitions of spatial modes of appearance of various colour and light phenomena (Katz 1935), Gibson's concepts of ecological optics (Gibson 1979) and Alva Noë's concepts of enactive perception (Noë 2004). The noticeable correspondence between Katz's phenomenology and Gibson's ecological optics indicates a possible way to a coherent ecologically based phenomenology of colour and light and a well defined conceptual system *in spe* of describing colour and light as parts of a human experience of the world.

In this respect artistic visual experience is of a considerable value. Painters and lighting designers are experts in colour and light phenomena. The observations of spatial visual qualities that they take as a starting point for their studies of pictorial space have not been paid attention to and have not been studied systematically. Painters and lighting designers aim to construct logical expressive symbols for appearances of colour and light in space. (Klarén 2006, p 294). They study the perceptual coherence of order and significance; intuitively they use it and present it in their works. Art represents a special

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[32] Swedish colour researcher, 1950 -

[33] American philosopher of art, 1886 -1940

[34] German psychologist, 1889 -1953

kind of reflective experience. “But to learn the language of the studios is not enough”, as Susanne Langer remarks (Langer 1953, p ix–xii). The working vocabulary of the artists has to be defined and systematized. Pictorial art could be an important source for phenomenological investigation and in this way it could contribute to the study of perceptual consciousness and to the generation of better concepts defining human experience of colour and light.

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Harald Arnkil

Seeing and Perceiving

Människan
tittar
men ser icke
Människan
ser
men varseblir icke
Människan
varseblir
men uppfattar icke
Människan
uppfattar
men förstår icke
Människan
förstår
men tror icke
sina ögon

We look
but do not see
We see
but do not perceive
We perceive
but do not apprehend
We apprehend
but do not understand
We understand
but do not believe
our eyes

– L-G. Nordström[35]

Introduction

What do we mean when we say that we *see* something? To grasp the complexity of what it is to see and to not see, try the following: describe in words everything you see before you just now – not just the objects and surfaces, but everything you see: colours, textures, shadows, highlights, reflections, all visual qualities down to the minutest details. The task is overwhelming even when viewing the simplest of scenes. One very quickly becomes aware of the many levels to seeing: the optical, the symbolical, the holistic, the detailed, and so on. It also takes but a moment's reflection to realize that only a fraction of what we are looking at each moment is "taken in" into our consciousness, processed and stored for later reference. There simply isn't room for all

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[35] Translation from the Swedish: Harald Arnkil. Lars-Gunnar Nordström (b. 1924) is a Finnish painter of the geometric abstract and constructivist tradition.

the sensory data pouring in from all directions. The brain – and the whole living organism – must choose what is relevant (see also *Natural Experiences and Physical Abstractions*, p. 23 in this volume). Perceptual psychology abounds with tests and demonstrations of visual attention showing how selective our vision is. In given situations our brains can choose to ignore huge stimuli in preference for much smaller or weaker ones – and not always to our advantage. Most of the time our visual system works just fine – largely due the process of selection and filtering, which keeps most of the irrelevant and confusing sensory data out of our visual experiences.[36] But there is more going on in our brains and minds when we see. While the brain discards irrelevant stimuli, it enhances others. It achieves this on mainly two levels: the inbuilt automatic level of visual processing and the more conscious level of visual *attention*. An example of the automatic processing is edge detection; another is simultaneous contrast, which is sometimes involved in the former.[37] These kinds of 'hard-wired' mechanisms help us to separate objects from their backgrounds and edges of objects from the borders and gradients of light and shadow. All this happens without the intervention of our consciousness. An example of visual attention is keeping your eyes (and hopefully your mind!) focused on the words and lines of this text amid all the myriads of stimuli surrounding you.

How the brain chooses what is relevant for each situation is a subject that is beyond the scope of this article. It is worthwhile, though, to consider for a while *why* it does this and what are the consequences for our perception of colour and light. Starting from the notion that the proximal stimuli for vision, the patterns of radiant energy on the two retinas (that are sometimes called retinal images)[38], are physically some two or three centimetres diameter in size. They are also two-dimensional, although projected onto a convex spherical surface. From these two proximal stimuli we, our brains and bodies, are able to create a perception of the world that is not only spatial, but surrounds us entirely, is infinite. It is in our ecology that our perceptions are integrated into this spatial whole in a way that provides us with information primarily concerning our position *in* and relation *to* the spatial whole. This spatial per-

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[36] Zeki 2002, pp 5–6.

[37] Simultaneous contrast, also known as colour induction, is the perceived hue or lightness shift of a colour when juxtaposed spatially with another colour. The 'subjective' contrast colour occurs simultaneously with the 'objective' stimulus colour. Simultaneous contrasts are most apparent in juxtapositions of the centre–surround type.

[38] The notion of the *retinal image* was first criticized by James Gibson (Gibson 1986). Gibson says that the spatial features of the world are perceived directly. According to this view the staring point for perception is in the *optic array* surrounding us. Our movement through this array creates, among other things, an *optic flow* rather than a series of static retinal image for analysis by the brain. There are no retinal images, static or otherwise, argues Gibson. Instead there is a constantly moving pattern that is the proximal stimulus for integrating space, colour and objects through our interaction with the world.

ception is entirely integrated with and dependent on movement or the possibility of movement. It is also highly dependent on the perception and apprehension of the directional quality of light, affording objects their plasticity though shadow-formation.

The human visual sensory apparatus, the whole eye-cortex mechanism, is a marvellous tool. Yet it has its limitations and peculiarities. It has evolved to operate mainly in *photopic* conditions, that is in daylight, which allows us perception of detail and colour. We are diurnal animals and our vision serves purposes of orienting and acting in the daytime. Our ability to perceive detail, colour and contrast at night, in *scotopic* conditions, is heavily compromised in favour perceiving movement and large forms. In between these two extremes there is the *mesopic* zone of dim lighting, of dusk and early dawn, where acuity of vision is low, perception of contrast and movement are diminished and colours of objects and surfaces are distorted in comparison to our daylight experience. There are many other constraints to our vision and these constraints contribute to our experience of the constancy of the world.[39]

Our visual organism has evolved over millions of years to provide us with information about a three-dimensional, dynamic world with objects and spaces in light and shadow. Much of this is tied up with the way we have adapted as a species to the process of natural selection. This does not mean, however, that we are mechanical slaves of the inbuilt mechanisms of our brains. The brain of course does nothing of its own accord. It is we who use our brains and not the other way round. We have considerable freedom in choosing what to attend to. But this freedom has its limits, which probably works for our benefit. Nevertheless, there is always – even after filtering and enhancement – much more available to us in a scene than we need for appropriate actions. We are able to extract several levels of information and meaning from the same visual stimulus. Some of these levels are concerned with alternative scenarios of action or interpretation, others with alternative meanings and aesthetic qualities.

Training the eye

Let’s imagine three round green apples on a table. They are arranged at slightly varying distances from one’s vantage point. We see that they are roughly spherical, although the retinal images created by them are flat discs. We see that they are green all over, although due to light and shadow they are, say, lighter and yellower on one side and darker and greener on the other – plus all the transitions in between – and there is a near white highlight on

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[39] There are very good (ecological and economical) reasons for these limitations, of course, but it is seldom that we pause to consider their benefits for a common experience of the world and hence our ability to appreciate such forms of non-verbal communication as art. For a further discussion of this see Zeki 2002.

each apple. We see that the farthest apple is the same colour as the other two, even though it is in shadow while the other two are in stronger light. We see that all the apples are (approximately) spherical, although one apple is occluded by another so that only a part of it is visible. We also see that the apples are all the same size, although the retinal image of the farthest apple is smaller than that of the nearest one. However, due to the visual phenomenon of constancy scaling, they are seen to be *more* similar in size than they would be in a photograph or classical perspective image of the same scene.

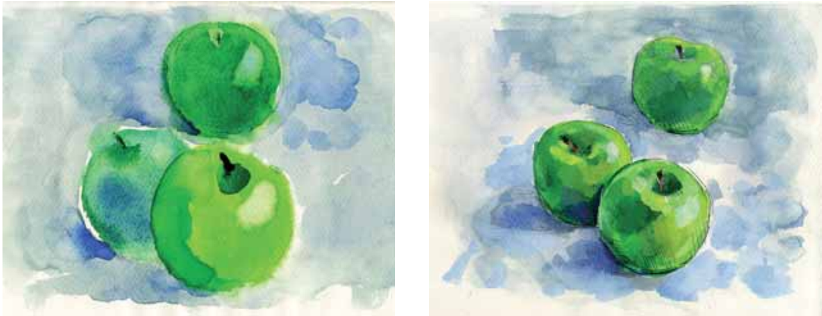

Figure 4. *Two interpretations of the same three apples.*
(Images: Harald Arnkil)

The above scene could be translated into a flat image in several ways[40], revealing the multiple levels of seeing. One artist might concentrate on the apples' chromatic differences in the lights, highlights and shadows, another one might ignore them and depict them as uniform green. A photorealist would make a careful note of the optic size difference. Another artist might paint all three apples the same size in accordance with constancy scaling and knowledge of the apples' physical similarity. And so on. All depictions would be correct and accurate in their own way, but if displayed side by side in an exhibition, they would appear strikingly different. Viewers, who were familiar with the original scene, might be surprised (or delighted) by the different 'interpretations'. They might find that they have missed out on something that one of the artists has emphasized or made apparent. Like artists of a given school, we are all – to a certain degree – 'trained' to notice and to see particular aspects of our visual environment. This occurs mainly through shifts of focus and attention that are directed by our intentions. A botanist might be trained to notice minute variations of colour in greenery or a fisherman to forecast the weather from a combination of colours and forms in sky, clouds and water. But it is highly unlikely that the Ukiyo-e -artists of 18th – 19th Century Japan did not *see* shadows or the converging optical effects of

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[40] The idea, developed during the Renaissance and after, that the perspective image is the ultimate scientific interpretation of space, is of course based on the idea of a 'retinal image'. Translating space experience into a flat image by using perspective was then a task of figuring out how that retinal image is created – a matter of optical science. (See Kemp 1990).

parallel lines although they almost entirely excluded shadow and linear perspective in their pictures.

Seeing as a visual process

Visual perception is often described as a linear process that starts with the stimuli of the outside world and ends in perception and experience. This process involves several parallel paths of neural activity. Various aspects of visual information, such as shape, movement, size, orientation and colour, are treated by separate processes that connect and interact with each other. Although many advances have been made in the study of the individual neural processes and specialized brain areas, it is still not known how the separate processes are integrated into a coherent visual experience. E. Bruce Goldstein has outlined the visual process in *Sensation and Perception* (Goldstein, 1999) with the following chart:

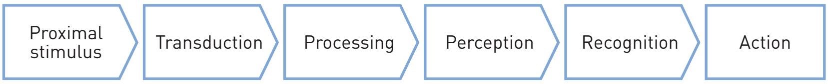

Figure 5. *The visual process* (Goldstein, 1999)

Paraphrasing Goldstein, the stages (for vision) could be further described as follows:

Distal stimulus = object or surface or light source outside the observer.

Proximal stimulus = pattern of radiant energy on the retina(s) caused by electromagnetic radiation from the distal stimulus. “The radiation energy that reaches and manages to activate the receptors in the eye’s retina”. (Hård and Svedmyr 1995, p 218, translated from Swedish)

Transduction = transformation of the above radiant energy to electrical signals in the retina.

Processing = the processing of the electrical signals in neural networks and pathways in the retina and brain.

Perception = the mental process of synthesising the signals into percepts as a result of an interaction of higher and lower brain levels in a parallel and multilinear processes (bottom up and top down processing).

Recognition = the cognitive process of conscious or unconscious interpreting of the percepts according to meaningfulness and familiarity.

Action = conscious or unconscious reaction to perception and recognition.

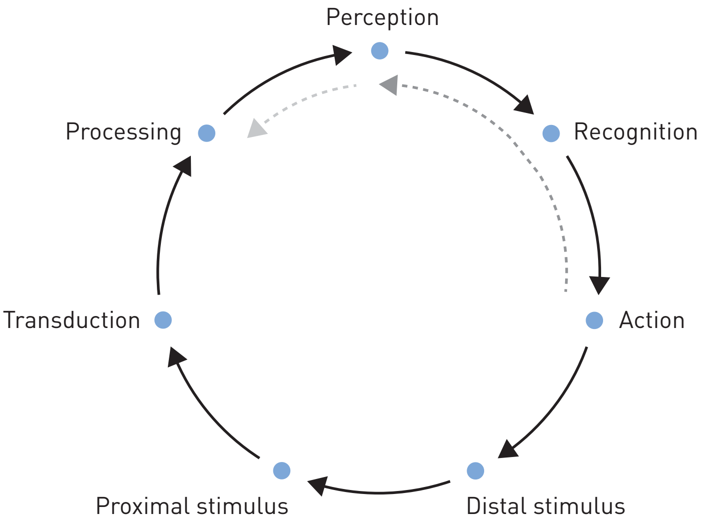

Figure 6. *The visual process as a circle.* (After Goldstein)

Goldstein emphasizes that the process is a lot more complicated and dynamic and could also be described as a circle (above). In this circle of interactions, as in the linear representation, the prime cause of visual perceptions is the distal stimulus. The arrows show the main direction of processing (bottom up). I have added the weaker anti-clockwise arrows to indicate that there is also some signalling from the top down, from the higher cortical levels to the lower. How much of this is taking place and what its effects on seeing are is still unclear. It seems obvious, though, that our actions influence recognition, which in turn influences perception. The diagram probably needs to be three dimensional to depict the process of interactions more faithfully.

Where does *seeing* come into this? How to define it? According to the above chart, more than half of the visual process occurs in the brain. Examined as neural processing, perception proper occurs quite late in this chain. Does seeing require recognition and does recognition involve conscious experience? We are faced with this question in the following examples. Richard Gregory says that the peripheral areas of the retina can produce a perception of movement in the field of vision without perception of form: “Movement is seen, but it is impossible to identify the object, and there is no colour” ... and furthermore “When movement stops the object becomes invisible.” (Gregory 2003). So we still perceive – and perhaps see – the movement, if not the object. But consider this: “The extreme edge of the retina is even more primitive: when it is stimulated by movement we *experience nothing*; but a *reflex is initiated*, rotating the eye to bring the moving object into central vision, bringing our highly developed foveal region into play for *identifying the object*.” (Ibid., my emphases). We do not *see* the movement, but we *react* to it. Only after that we may see the object.

What Gregory is saying is that at the extreme edges of the retina the proximal stimulus created no *experience* of anything, yet it triggered a reflex, an action of rotating the eyes and head to bring the stimulus into the domain of seeing. Gregory also points out that the prehistory of our vision is thus "embalmed in our retinas". (Ibid.) The cellular structures and processes being more primitive the further they are from the fovea. He also reminds us "... it is eyes quite high up in the evolutionary scale that produce signals in the absence of movement". (Ibid.) This would suggest that a proximal stimulus that triggers an automatic reflex, but does not enter consciousness as an experience, does not qualify for seeing.

Attention

Very often we have the experience of not seeing something that we know or we are told is (or was) in our field of vision. Sometimes we fail to see things happening before our eyes because our attention is focused on other things. These distracting signals can be local parts of the global visual stimulus or non-visual percepts, such as sounds or thoughts. ”Did you not notice that car coming from the left?” asks the driving-instructor. ”No, I didn’t see it at all!” replies the alarmed student, although the car (the distal stimulus) has caused, without him knowing, millions of retinal and brain cells to fire in his head. The student failed to pay attention to this particular visual percept, because he was concentrating on other, perhaps even more pressing, stimuli or thoughts. Our eyes and brains are being continually bombarded with potential information about our surroundings and our relation to them. The act of seeing is the effort to filter the relevant visual information from the irrelevant. Looking is the act of attending to parts or levels of what is seen. Visual attention has many levels and forms. If seeing is visual experience – and therefore part of consciousness – we then require attention for seeing.

There is a very famous and quite entertaining demonstration, The Invisible Gorilla by Christopher Chabris and Daniel Simons (1999), which illustrates the selective power of attention.[41] On first viewing, many people do not notice the gorilla amidst the basketball game. In fact they report that they did not see it, and when the video is replayed to them many insist that it has been changed (Chabris and Simons 1999). In other words, they had no *experience* of the gorilla moving among the players, even though the stimulus must have created all kinds of neural firing in their brains. One could also say that they did not *register* the gorilla. The failure to see the gorilla resulted from the observers concentrated attention to other features in the video. The message of the demonstration is: this is happening to us all the time. We fail so see large parts of the potential visual information reaching our brains.

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[41] See: www.theinvisiblegorilla.com/gorilla_experiment.html

An even more puzzling example of the failure to see is so-called *blindsight*. Goldstein (Goldstein 1999, p 115) cites a case reported by Weiszkranz (1987). The patient D.B. lost a part of his striate cortex in an operation to cure his migraine. As a result he was left with a scotoma, an area of blindness, in the lower left quarter of the field of vision of both his eyes. Strangely though, he was able to point quite accurately to given stimuli in this "blind area" of his vision. He could even distinguish between an X and an O -shape falling within the scotoma, describing them as "jagged" and "smooth", but adding that these feelings were not the same thing as seeing the objects. Cerebral damage similar to D.B.'s can also cause loss of sight in the entire field of vision. It has been reported that persons suffering from such damage may be able to orientate in space, managing to avoid obstacles or reach for things, without any experience of being able to see. "Blindsight is an example of **covert awareness**, an awareness about the stimulus that appears to be happening under the surface of conscious perception", says Goldstein. The important thing here is that both sight and blindsight can lead to appropriate action (pointing, moving or grasping), but in one the action is prompted by the experience of seeing, in the other by a feeling or experience of things being present without seeing. Both can be caused by similar proximal stimuli and can lead to similar action. This is just one very illustrative example of how brains deal with visual information in parallel processes rather than linear ones.

The artist's gaze

Attention is not only a matter of directing our focus on moving objects or small details. We can shift our entire *mode of attention*. Maurice Merleau-Ponty speaks of two levels of experience, *living perception* and the *reflective attitude*, which are two distinct ways into apprehending the world. (Merleau-Ponty 2002).[42] With living perception we experience the integrated whole and its constancies. The reflective attitude extracts other levels of vision from the perceived world. The neurophysiologist Semir Zeki provides a slightly different interpretation of modes of attention in his book *Inner Vision: An Exploration of Art and The Brain* when discussing the art of Claude Monet. Zeki recounts how

> *...Monet had lamented to Clemenceau that he wished that he could be born blind and that vision be restored to him suddenly, so that he could paint forms without the corrupting influence of past experience He was, then, a man trying to rid himself of the influence that might interfere with his sensations, as he saw it. How could one do this in colour? Quite simply by ceasing to be a contextual painter, that is to say, by painting the colour of every small part almost in isolation, without regard to the surround.* (Zeki 2002, p 214).

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[42] See also *Natural Experience and Physical Abstractions*, pp. 23-24 in this volume.

Zeki goes on to say to say that Monet was in fact trying to bypass the phenomenon of colour constancy that is an integral and natural part of our visual mechanism. When Monet painted a series of some thirty paintings of the façade of Rouen Cathedral, he turned his attention to the changes of perceived colour arising from the different illuminations and weather conditions. Zeki says that he was able to achieve this astonishing series by his supreme 'cerebral powers', or one might say, visual intellect. According to Zeki, Monet was "…using the knowledge in his brain to deliberately paint something that departed from what he was actually seeing." (Ibid.) Zeki argues, that Monet was, in fact, working in precisely the opposite way to how he had had wished in his conversation with Clemenceau. Instead of attending to what the eye 'sees' only, he used his memory (Monet finished the works in his studio) and his knowledge of light, accumulated over a lifetime of painting outdoors. Paul Gauguin is reported as exclaiming that Monet painted with his eye, but, Great God, what and eye! This famous quote presupposes modes of attention that deploy different parts, indeed different *levels*, of the eye–brain mechanism. What Zeki is saying is that to see and to depict objects as remaining constant in colour despite substantial changes in their illumination is natural to us. To do otherwise requires a special mode of attention that demands a trained eye and brain. Zeki concludes that "Perhaps it would be better to say that 'Monet painted with his brain but, Great God, what a brain.' " (Zeki 2002, p. 215). To paint like Monet requires both living perception and the reflective attitude – an awareness and apprehension of the difference between the two.

The parts and the whole

We do not see or perceive space as spectators of events unfolding before us; neither is our visual experience of space an exploration of stimuli waiting to be revealed to us. We experience space as active participants; our spatial experience is created in the interaction of outer stimuli, our intentionality and our actions.[43] Our intentionality has many levels: the personal, the social and the biogenetic. The biogenetic intentionality stems from the process of natural selection that has moulded our species into what it is. This intentionality governs our ecology, which in turn impresses on – and sets constraints on – how we see and perceive.

Seeing is the integration of our perceptions into a total visual experience. In order to try and understand spatial experience, object recognition and the perception of colour and light, we can try to break down and analyze this totality into its components. This can be done in many ways, but not all of them contribute to a deepening of the understanding of the human experience of light colour and space. We need many approaches to understand how we see and experience space, light and colour. Some of these are of necessity

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[43] See: Noë 2004.

highly specialized and focused – and sometimes quite abstract – in their scope. They, however, need to be integrated into a holistic understanding of the human experience in order to gain meaning.

When we walk in the street or forest, we are able to perceive a multitude of features and integrate them into the experience of seeing. These features are interlaced as details and layers that we are able to examine also separately without destroying the experience of the whole. External stimuli and internal intentions direct our attention from one layer of perception to another. Our attention moves freely between layers and details while our experience of the world remains constant. We are able to separate the invariant and constant quality of the colours of objects and surfaces from the ever-changing and inconstant quality of lighting. From these we are able to apprehend the quality of the light and the atmosphere afforded by its variations. This apprehension is an essential component of the aesthetic experience of the world.[44]

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[44] See also Natural Experience and Physical Abstractions in this volume.

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Karin Fridell Anter

Light and Colour – Concepts and their use

Introduction

Light and colour are things that all seeing persons perceive, and therefore have often reason to comment, refer to and discuss. Still, such discussions surprisingly often end up in misunderstandings or disagreements, based on the fact that both terms – *light* and *colour* – have several and often conflicting meanings. This is especially true, and especially problematic, amongst people who work professionally with one aspect or other of either colour or light or both. As it has been expressed by Anders Liljefors, professor of architectural lighting: "The lighting technician knows exactly what 'light' is, and the architect knows exactly what 'light' is, but they talk about different things".[45] The conceptual confusion creates problems when it comes to such as quantifying the amount of light or discussing light qualities, or specifying an exact colour and its characteristics.

This article is an attempt to sort out the confusing terminology of colour and light and thus contribute to a better understanding between different disciplines and professions. The analysis starts from the means by which we can identify that which we name *colour* or *light*, and the methods we use for its quantification and description.[46]

Basically there are two different approaches in formulating words dealing with colour and light. The original one is based on our visual experiences of the world we live in. The other one is based on physics as a scientific way to explore nature, and is only a few centuries old. There are also several attempts to formulate concepts and measuring systems that combine the approaches of experience and physics.

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[45] Professor Anders Liljefors in oral communication 2010.

[46] The scientific approach and several of the colour concepts are based upon Green-Armytage 2006.

Light and colour as experienced through the senses

The original concepts of colour and light refer to what we can experience with our visual sense. Words for *light* are very old in the development of languages (Fig. 7) and differences between light and dark are referred to in some of the earliest surviving pieces of literature.[47]

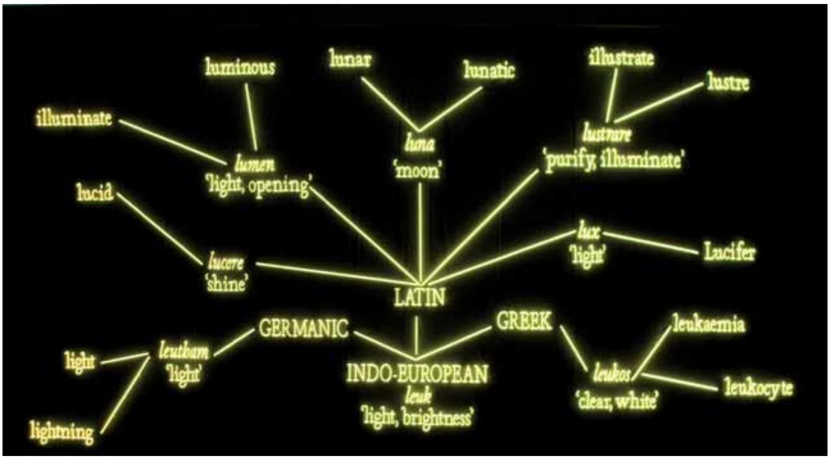

Figure 7. *Words deriving from the Indo-European words for light, as shown in the Art Gallery of New South Wales, Sydney, Australia.*

Our visual system provides the most important starting point for perceiving and apprehending space, and the experience of space is fundamental and prerequisite for our survival as a species and as individuals. This experience is both perceptual and cognitive, and it depends on shared biogenetic preconditions as well as on the implicit knowledge and former experiences of the individual. Our visual mechanism (eye and brain) is, with rare exceptions, anatomically and functionally identical from person to person,[48] but due to such factors as individual life experience and different motives and expectations, we see and experience the world in different ways. This means that the only way to know what a person sees is by asking or in some occasions by analysing the person's behaviour in relation to visual stimuli.

Human experience is spatial and holistic, dynamic and contextual. In a complex real life situation there are no fixed relationships between our visual

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[47] Two examples of this are Genesis 1:2–5 and the Gilgamesh epic Tablet XI.

[48] There are several types of defective colour vision. The most common is characterised by a difficulty to distinguish reds from greens. This deficiency is much more frequent among men than among women (different sources give it as about 7-12% in males and less than 1% in females), and varies between different parts of the world.

experiences and any physically measurable characteristics of the world. It also means that visual phenomena can be validly described and specified only within experienced totalities. Neither colour nor light nor any other visual quality can be seen and experienced in isolation, as a single and unrelated phenomenon – on the contrary, visual experience is always one and undivided. Colour and light interact with other, non-visual, phenomena in constructing our mental visual experience of space.

Thus concepts and methods aiming at describing human experiences have to be understood contextually. An example from a field different from colour and light is *tall* - a word that is quite easily understood if the context is clear (e.g. referring to the size of people) but that cannot be directly translated to physical terms (a *tall* man and a *tall* tree are not the same height and people from different parts of the world would have different standards on how tall you have to be to be *tall*.)

With all this in mind – what meanings could be attached to the words *light* and *colour* with reference to human experience? And, secondly, what concepts could be used for denoting specific aspects of light and colour experience?

Perceptual aspects of 'light'

In the experience approach, light is understood as the phenomenon that affords visibility to physical objects, surfaces and spaces. It is apprehended as coming from artificial or natural light sources. However, the experience of light cannot be measured in absolute terms. You can evaluate for example how bright or dark a room is, but this evaluation, because of its complex spatial context, cannot be quantified.

In everyday life light is referred to in descriptive terms without any ambition or intention to be precise. For example the terms *lightness* and *brightness* are used interchangeably in everyday language (See *Lightness and brightness* in this volume). Still, such descriptions catch very much of our experiences and can easily be understood by persons sharing the same references. Examples of this are 'morning light' and 'divine light' – terms that could be called *conventional light concepts*. The only way to determine whether the term is relevant for the specific experience is by casual or attentive observations and by referring to what we see, have seen, or have indirect experience of.

Conventional light concepts are used in visual tradition, art, poetry etc. and their interpretation is highly dependent on the common cultural references of the people who use them. Many visual professions, such as pictorial art, theatre and cinema, have by means of practice developed their own tradition of conventional concepts, which can be used with rather high precision within the profession but are almost unintelligible to others.

A scientific approach to visual experience demands attentive observations. Pictures made for this purpose can convey what has been observed, but for communication and analysis of the observation there is also a need for more specific terms than the conventional or artistic ones. The concept of *perceived light* denotes attentively observed light, which can be described by concepts, such as *light level, light distribution, shadows, reflections, glare* and *the colour of light*. These concepts, which have been specifically investigated and presented by Anders Liljefors (2005), all denote aspects of light as a visual experience, aspects that cannot be identified or quantified in any other way than through attentive visual observation.

Examples of perceptual concepts related to light

Conventional and artistic approach
Dark, light, bright, illumination, shadow, highlight, reflection, mixing, blending, morning light, dusk, haze, penumbra, harsh light, soft light, dazzle, glitter, warm light, cool light, Mediterranean light, Nordic light, divine light

Visual research approach
Brightness, light level, light distribution, shadow, reflection, glare, colour of light

Perceptual aspects of ‘colour’

Like light, the word colour is used conventionally without much need for concept definition. All humans with non-defective colour vision can broadly agree on how to name the colours we see around us, according to conventions and traditions within each culture. Also in literature and other artistic or symbolic contexts a colour or a combination of colours can be described and understood with the help of basic colour terms like *red* or *blue* or by words alluding to a know material or situation, like sand or sunset. Just as for light, the only way to determine whether the term is relevant for the specific experience is by casual or attentive observations and by referring to what we see, have seen or have indirect experience of.

Examples of perceptual concepts related to colour

Basic colour terms: red, blue, green, yellow, white, black, brown, grey

Conventional colour names and colour names in e.g. fashion and clothing industry: aqua, buff, Burgundy, coral, cream, light blue, olive green, turquoise

Terms referring to artistic work: primary colour, secondary colour, tertiary colour, tint, shade, broken colour, pastels, earth colours

Perceptually specified colour terms: hue, value, lightness, whiteness, blackness, nuance, chromaticness, chroma, elementary colour, mode of appearance

When it comes to scientific work, the concept *colour* has to be specified. One definition is that given by the Natural Colour System, Swedish standard for colour notations. It is entirely based on visual experience and defines colour as that which the human being in any given situation sees as colour, and which makes it possible to distinguish objects and fields[49] using their colour differences (*colour discrimination*), and to characterise objects and fields with the help of, for example, colour names (*colour identification*) (Hård et al. 1996). Starting from this definition we can make further specifications of colour as a visual quality.

With attentive seeing we can identify the *perceived colour* (Fridell Anter 2000, p 23) of a specific surface or object, a quality that is not constant but varies with the viewing situation and between persons. The perceived colour can be described and categorised only by attentive observation and cannot be measured with photometric, colorimetric or any other instruments. (Fig. 8) Depending on the detail of level of our attention, we can concentrate on the *perceived identity colour*, that is the main colour impression of a surface that is perceived to be uniformly coloured, or on the *perceived colour variations* that for one reason or another can be found within the ‘uniform colour’, if we look for them carefully enough. (Billger 1999, p 11). We can also experience that which is commonly referred to as the ‘real’ colour of the surface. This

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[49] ’Objects and fields’: from the Swedish *föremål och fält*. ’Field’ here refers to the same concept and phenomenon as film colour (*Flächenfarbe*) in David Katz’s definitions of the eight modes of appearance of colour. (Katz 1935).

could be called the *constancy colour*, and is not an accidental visual experience but the natural outcome of adjusting to our visual environment.[50]

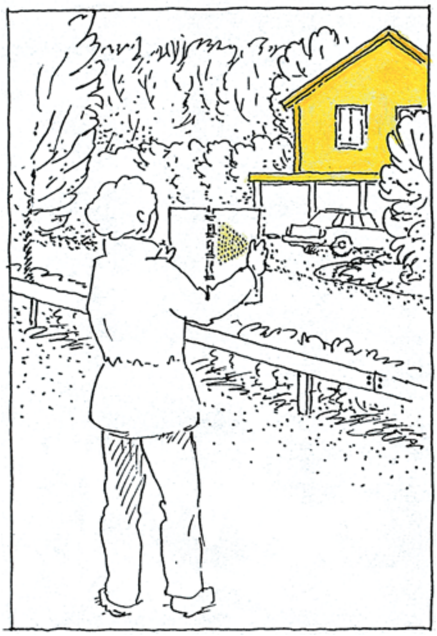

Figure 8. *One method of determining the perceived colour*. (After Fridell Anter 2000)

In the world outside laboratories the viewing conditions are constantly changing, but for scientific purposes there is a need for stable and standardized reference situations, including lighting, viewing distance and surrounding colours. As all persons do not perceive colours in exactly the same way, such a situation also includes a number of observers whose estimates are weighed to form an average.[51] For any object, its perceived colour in the standard situation can be called its *nominal colour*.[52]

One basic colour characteristic is its *mode of appearance*. We can visually judge the colour as belonging to an object, or to the light in a space, or as having a seemingly arbitrary position in space (as for example the blue colour

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[50] For further discussion about the concept of constancy colour, see the article *Natural Experiences and Physical Abstractions* in this volume.

[51] The standardised viewing conditions for the visually based NCS system are presented and discussed in Hård et al. 1996, pp 189–190.

[52] In Fridell Anter 2000, pp 24–26, I use the term *inherent colour* for what is here called the *nominal colour*. This involves a risk for misunderstanding, which is further discussed in the article *Lightness and brightness* in this volume. I therefore suggest *nominal colour* as a better term.

of the sky). This is denoted by visual concepts such as *surface colour, volume colour* and *film colour*. (Katz 1935).

A *surface colour* is perceived as being part of the surface only. One example is an opaque paint surface. A *volume colour* is perceived as permeating the whole volume of an object or substance. Examples of this are coloured glass, gas, mist and water. A *luminous colour* is perceived as belonging to a shining object, such as a light source. Here it is important to remember that these concepts are visual and phenomenological, they describe what we see and not the underlying physical cause. For example, in pictorial art, the painter can create the experience of light by skilful use of contrast – and those spots on the canvas are, as perceived, *luminous colours*.[53] (Fig. 9)

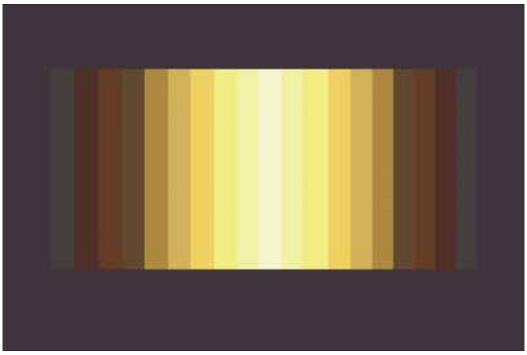

Figure 9. *This colour combination is an expressive symbol for the contrast situation perceived in shining and self-luminous objects, such as a lamp in darkness or light through an opening. (See Natural Experience, pp. 26, 30). The middle part of the figure is a luminous colour in Katz's sense.* (Illustration: Ulf Klarén)

The visual properties of a colour can be described with words such as *hue, value, nuance,* etc. Several of these terms are ambiguous and thus not scientifically usable unless they are further defined.[54] NCS (Natural Colour System) is a coherent system for colour description, based purely on visual assessment. It categorises the perceived colour in comparison to perceptual standards that are understood as inherent to the human visual system. The *elementary colours* yellow, red, blue, green, white and black are defined as having no similarity to any other colour than themselves. *Hue* is, according to the NCS, the specific colour's relative similarity to the chromatic elementary

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[53] Gilchrist et al. 2007 ; Fluorent or luminous colours are discussed in da Pos 2005. For a further discussion about visual categories such as transparency, depth, translucence, etc. see Fridell Anter 2006, p 142.

[54] The confused use of some of there terms is discussed in the article *Lightness and brightness* in this volume.

colours yellow, red, blue and green. *Nuance* is the relative similarity to white, black and an imagined fully chromatic reference colour that lacks all similarity to white or black. (Fig. 10) [55]

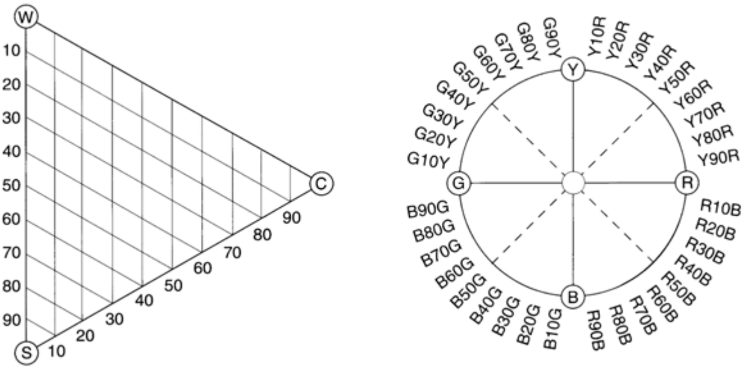

Figure 10*. In the NCS system, hue is shown in a circle and nuance in a triangle. The elementary colours are Y (yellow), R (red), B (blue), G (green), W (white) and S (black). C denotes a colour of any hue, which lacks all similarity to white or black.*

In other colour systems, such as The Munsell Book of Color[56], concepts are not purely based on perception, but rely on the existence of comparison samples. Such systems can function as experience-based references for those who are well acquainted with the parameters and samples and their visual relations. Similarly, there can exist other concepts that are agreed upon within a specific culture or group and can be used for visual assessment and communication within that group.

Light and colour according to physical theory

Physics as a scientific field has evolved from the 17th century onwards. It strives to create models for understanding the material world from other viewpoints than those accessible only through direct sensory experience. Its concepts and measurements are developed for quantification and mathematical analysis of the material world as such, and aim at formulating and explaining physical laws. An example from another field than ”colour and light”

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[55] Hård et al. 1996.

[56] A selection of colour chips based on the colour system of the American artist, pedagogue and colour researcher Albert H. Munsell, first presented in 1905.

is *length* measured in metres, where a metre is given a highly precise and fixed definition.[57]

One important driving force in the development of physics and other natural sciences has been the urge to find causal connection between physically detectable forces and human experiences. The famous anecdote about Newton and the falling apple does not, of course, imply that Newton was the first person to consciously experience *that* apples fall. Instead, he started from this commonly shared experience and managed to formulate a theory about *why* apples fall. More recent physical theory, like Einstein's theory of relativity, lacks this direct connection to sense experience, but still aims at detecting the causal relationships inherent in the physical world and consequently making use of such findings.

The theories of natural science add to understanding the material causes behind our sense experiences, but they do not distinguish between the experience and its material cause. One of the most striking examples of this is the term *light*, which is used not only for a visual experience but also for the energy radiation found to be the material precondition for this experience. Such wordings as *the speed of light* or *light-year* exemplify how *light* has come to be used for things that cannot be visually experienced. Gradually a complex physically based terminology on colour and light has been created. This terminology often uses the same words as those used to describe experience, but with strictly different definitions.

Physical aspects of 'light'

From a physical point of view light is defined as electromagnetic radiation, a form of energy that – depending on the viewpoint – can be described as waves with different wavelengths or as a shower of small energy packages called photons. The energy content is expressed in units of Joule (J) or kilowatt-hour (kWh) and the wavelength in nanometres (nm), one nanometre being one millionth of a millimetre. The total radiation energy can be measured by radiometric instruments. A spectrometer is an instrument for dividing the radiation into different wavelengths, and a spectroradiometer measures energy in narrow bands of wavelength.

The terms *light year* and *speed of light* refer to all such radiation, irrespective of wavelength. Most often, however, the term *light* is limited to wavelengths

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[57] The metre is one of the bases for the international system of units (SI). Its definition has, however, been altered several times. Initially the metre was defined as a certain fraction of the earth's perimeter, subsequently with reference to a physical metre standard and after that referring to the spectrum of a specific chemical element. Today the metre is defined with reference to the path travelled by light in a vacuum.

between about 380 and 780 nm, which is the span that can activate the receptors in the human eyes and trigger a neural process resulting in vision.

Physical textbooks and scientists do not, however, fully agree on what wavelength span to include in the concept of *light*, and sometimes a distinction is made between *visible light* (380–780 nm) and *invisible light*. 'Invisible light' refers in this case to ultraviolet radiation with shorter and infrared with longer wavelengths than those within the 'visible spectrum'. Shorter still (gamma- and X-rays) or longer (radio waves) wavelengths are seldom or never referred to as light, but are still included in what is called the *electromagnetic spectrum*, where the word *spectrum* originally referred to a visible range of colours.[58] Even if measurements of energy are limited to what is called visible light there is, however, no direct correspondence between the amount of energy and the perceived intensity of light.

Examples of physical concepts related to light
Speed of light, light-year, wavelength, light energy, electromagnetic spectrum, absorption, radiation, emission, transmission, dispersion, refraction, diffraction, polarisation, interference, photon

Examples of physical concepts related to colour
Monochromatic, spectral power distribution curve

Physical aspects of 'colour'

Radiation with wavelengths in the span referred to as visible light can be isolated into discrete wavelengths by for example a prism. Then they cause the perception of different hues, as in the rainbow where radiation from the sun is refracted and reflected by water drops acting as prisms. This has led to the convention of presenting the different wavelengths in the form of a spectrum, made up of hues from blue (short wavelength) to red (long wavelength). Radiation within a very narrow band in this spectrum is called *monochromatic*. There is, however, no absolute relationship between wavelengths and perceived hues[59] – a reason why modern physics often abandons the traditional colour references for wavelengths in favour of terms such as *short*, *middle* and *long* wavelength.

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[58] The term *electromagnetic spectrum* is used in a non-visual sense in e.g. http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html. Accessed 26.9.2011.

[59] Wavelength information is discarded very early in the visual process. The perceived hue depends on local contrasts and the total viewing situation and also the intensity of the radiation.

Monochromatic radiation appears only in very special situations. Normally, the radiation reflected or emitted from an object consists of many wavelengths in different proportions. This can be illustrated as the *spectral distribution curve*, which is detected by the already mentioned spectroradiometer. Sometimes this curve is understood as a specification of the colour of the object, a definition of *colour* corresponding with or comparable to the physical notion of light. There is, however, no direct relationship between the physically measurable radiation distribution and the perceived colour.

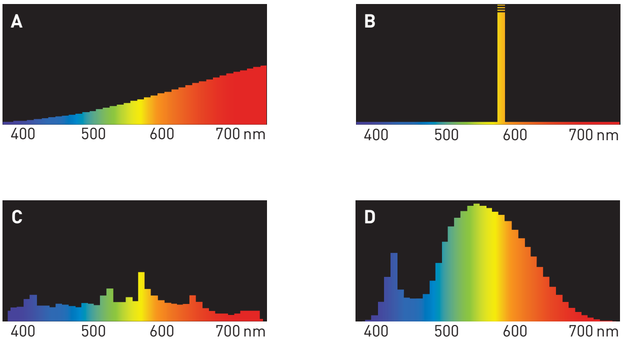

Figure 11: *Spectral distribution curves for some light sources.*
A) Incandescent, B) Low pressure sodium, C) Metal halide, D) LED

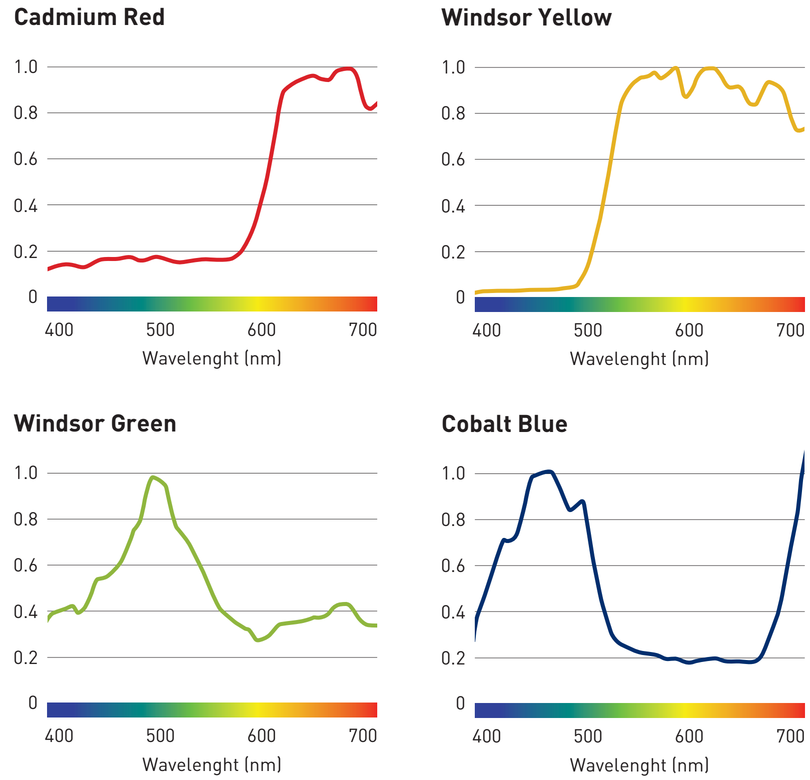

Figure 12. *Spectral distribution curves for some coloured surfaces.* (After Livingstone 2002)

Technological aspects of ’light’ and ’colour’

If physics is the science of understanding the material world, technology deals with practical applications of physics. Both terms *light* and *colour* can be used with reference to how the light or colour is made or accomplished. When you talk about such things as *sunlight, incandescent light* or *fluorescent light* you refer to the light source as such, and within each of these categories there are subdivisions that are known to and understood by professionals but may not say much to others. These technological terms reveal only little about the physical properties of light and even less about its visual characteristics.

In the paint and dye industries and by users of paints and colorants the colour can be defined by the substances they are made from, e.g. *vermillion* or *terra di Siena*. The detailed chemical contents of these substances can vary over time and place. Thus objects with one and the same *substance colour* (such as a certain yellow ochre) need not look the same even under identical conditions and need not have the same spectral profile. The way to identify the substance colour would be through chemical analysis.

A more specific technological way to identify colour is to give a formula, referring to such as mixtures of pigment pastes used in tinting machines, printed raster dots on paper or emitted radiation of standardized wavelengths from phosphors on electronic screens. In industrial applications the word *colour* often refers to the formula and the specific colour is identified through codes, such as the CMYK codes for printing, tinting proportions for paint or RGB percentages for screens. This means that one and the same *formula colour* can vary in both visual appearance and spectral distribution, depending on the accuracy of its making, the calibration of technical equipment, the combination with other materials and the situation in which it is observed. For example, the paint colour *313 Guldkatt* from Alcro is defined through a precise formula but could still vary slightly between one tinting batch and the next. In addition, it looks different on wood than on plaster and, in both cases, varies visually with the viewing situation.

The definition of colours through formulas is essential in colour reproduction within several branches of application. Many colour charts and colour sample selections, from a specific company or common to a branch, are made up from formula colours. Some examples, apart from those already mentioned, are the Pantone Matching System for print and RAL for industrial coatings. As the colours are defined by their formulas, such selections should not be used as references in other applications or situations than those that they are made for.

Examples of technological colour concepts and units

Substance colour
Established names of pigments and dyes; Colour Index Generic Names and Colour Index Constitution Numbers (C.I. pigment numbers)

Formula colour
Colour density; Formulae used in paint tinting machines; Relative emission from phosphors of three standardized wavelengths (RGB); Colour separation process in the printing industry; Relative number and size of dots printed with standardised inks (CMYK, Pantone Matching System, etc.)

Using physics to describe experience

The conceptual confusion regarding *light* makes it very difficult to discuss the relationship between the material force and the sensory experience, as they are both referred to with the same word. The same thing applies to *colour*. There is also a strong tendency in both cases to consider the physically based meaning of the word to be more correct or scientific than the original meaning based on experience.

There are, however, several attempts to build bridges between the physical world and the world of experiences. *Psychophysics* is a branch of science that investigates the relationship between sensations in the psychological domain and stimuli in the physical domain.[60] It is based on theories about the relationship between that which is physically measurable and that which is experienced by humans. Fundamental concepts of psychophysics are *the sensory threshold* and *just noticeable difference* (jnd) forming the basis of determining human sensitivity to changes in intensity, quality, extension or duration of stimuli. An example from a field different from colour and light is *decibel* (dB), which indicates the pressure of sound waves weighed against what is known about the sensitivity of human auditory sense.

Psychophysical aspects of ’light’

The stimuli for visual perception are physically measurable radiations within the wavelength span that in physical terminology is called *visible light*. There is, however, no correlation between the absolute intensity of this radiation and the resulting visual perception, light in the perceptual sense. There are several reasons for this, one of which is the sensitivity of the receptors in the eye. These receptors are of two types, rods and cones, of which the cones have three different patterns of sensitivity to wavelengths. Thus the same amount of energy will cause perceptions that are more or less visually light or bright, depending on the wavelength distribution. For example, 3 Joule of radiation with wavelength around 550 nm will be perceived as about ten times brighter than 3 Joule of very short or very long wavelengths within the range of “visible radiation”.

For the development, description and comparison of light sources it is, however, essential to understand how their emitted energy affects human vision and perception. For this reason the International Commission on Illumination CIE has developed a *standard observer*, a statistical average seen as typical for the human visual sense and also including specified viewing conditions. To obtain the data observers have been asked to do visual brightness matches between stimuli obtained by monochromatic light radiation. From these the researchers have formulated a theoretical model for human visual sensitivity to different wavelengths, called the V-lambda V(λ) curve.[61] This

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[60] The foundations of psychophysics were established by the German psychologist Gustav Fechner in 1860. For a comprehensive presentation see Gescheider 1997 .

[61] The first version of the V(λ) curve, still basically unaltered, was established in 1924. (Tonnquist 1995, p 55; Wright 1969).

curve is the foundation of the *photometric* technology, which is today the accepted method for specification of light sources and lighting designs.[62]

Thus, a *photometric* definition of light refers to electromagnetic energy weighed against a theoretical model about sensitivity of the human visual system to radiation within the so-called visible spectrum. The V(λ) curve is not an absolute truth, but a scientific theory which has been revised a few times and which has also been fundamentally questioned (Liljefors 2010). So far, though, the gathered expertise within the CIE have agreed that it is the best available tool to quantify the light that we see through measurements of physical radiation.[63]

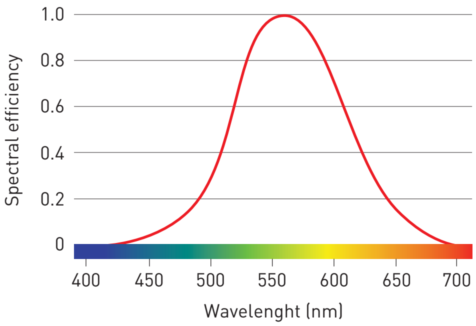

***Figure 13**. The V-lambda curve, V(λ)*

Photometric concepts and units are all based on the V(λ) curve and denote different aspects of photometric light. *Luminous flux* (measured in *lumen*) and *luminous intensity* (measured in *cd* = *candela*) are used for the light emitted from the light source, *illuminance* (*lux)* for the illumination of a surface and *luminance (cd/m²*) for the light reflected or radiated to our eye from a surface. Photometric technology includes several instruments like the spectrophotometer and the lux meter, all of them measuring radiation and weighing it against the V(λ) curve.

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[62] The V(λ) curve was developed for photopic vision, that is: human vision under full light conditions defined by a luminance of 3,4 cd/m² minimum. For lower light conditions there are other similar curves that are not further discussed here.

[63] Note that the units based on the V(λ) curve are not, and do not claim to be, applicable for measuring "light" that is not received by the human visual sense, e.g. the visual or otherwise light sensitive senses of animals or the photobiological processes in humans, animals and plants.

Examples of photometric concepts and units

Luminous flux (lumen)
Luminous intensity (candela)
Luminance (candela per square metre)
Illuminance (lux)
Luminous efficacy (lumen per watt)

The above concepts are part of the SI unit system

Psychophysical aspects of ’colour’

The psychophysical methodology for colour is called *colorimetry*. Its primary aim is to identify and quantify visual differences between colour stimuli in order to ensure production stability and to formulate levels of tolerated deviation.

Colorimetry was developed from the same basic assumptions as photometry. Observers were asked to adjust mixtures of three monochromatic light stimuli to match the colour of a single monochromatic stimulus. From this was calculated a number of models, in which every colour stimulus is characterised by three physical variables (*tristimulus values*), typically *dominant wavelength, luminance* and *spectral purity* (Tonnquist 1995, p 54). CIE has published different mathematical functions – algorithms – to be used under specified circumstances, including a choice of standard illuminants. These functions are illustrated as diagrams – ‘colour spaces’ – which can be used for specifying colour coordinates, such as CIELAB, and colour difference scales, such as ΔE (delta E). Such models can roughly indicate the appearance of the perceived colour evoked by the stimulus, but this is not their purpose and the indication is far from precise.

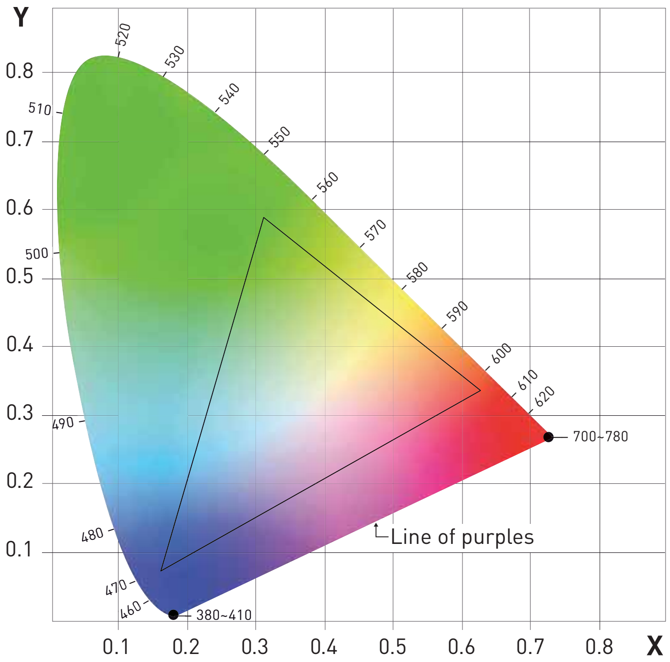

Figure 14. *The CIE 1931 colour space chromaticity diagram (with a triangle inside it describing a typical RGB gamut – for more about RGB see pp 57, 76 and 91). The outer perimeter with numbers from 460 to 780 describes the wavelengths of the spectrum. The coordinates have no absolute relation to perceived colours, but the colour space is often presented in the above kind of coloured version. For another kind of CIE colour space, the CIELAB, see figure 20 on page 87.*

Colorimetric measurements are made with spectrophotometers. To be accurate, these measurements have to be made under strictly controlled conditions, including the use of standard illuminants such as the standardised daylight simulator of D65. Another method is to use a colorimeter, which typically works with a small number of differently coloured illuminants. There is rapid development in colorimetric theory and technology, including the use of a large number of LEDs and new techniques that combine methods from both spectrophotometers and colorimeters. This has among other things resulted in small portable colour scanners, which use inbuilt controlled light sources and make colorimetric comparisons between the spectral reflectance curve of the measured surface and those of standardised colour samples.

The theoretical foundations of colorimetry are constantly developed through research, which means that methods and algorithms should not be seen as fixed entities. From the above it is clear that classical colorimetric theory, units, methods and instruments could and should not be used for describing the *perceived colour*. There are, however, more recent algorithms that attempt to tell something about how colour is perceived (‘colour appearance’). They will be discussed later in this text.

Examples of colorimetric concepts and units

Tristimulus values
Chromaticity coordinates
CIELAB diagram
CIELUV diagram
Hue angle
MacAdam ellipses

One important use of colorimetry is to measure and specify the chromatic qualities of light sources. For light sources consisting of a glowing material the *colour temperature* is expressed in Kelvin (K). The *temperature* here refers to a theoretical *black body* which, when glowing, emits differently coloured light depending on its temperature – from slightly red when starting to glow through white to bluish at very high temperatures. The *correlated colour temperature* of a light source is calculated through colorimetric comparisons between its emitted light and that of the theoretical black body.

Another important quality of a light source is its *colour rendering capacity*. One aspect of colour rendering deals with the colour gamut, i.e. how many different colours you can perceive under this light source. Another aspect deals with the character or colour differences. The colour rendering capacity of a light source is usually expressed as its Colour Rendering Index, CRI (R_a), which is colorimetrically established. In principle, colour samples with standardized reflectance curves are illuminated with the light to be controlled, and the reflected light is compared to that which appears when the samples are lit by a standardised reference light source. In practice, once you have the spectral distributions of the samples and the light sources in question, all this is done mathematically.

Physiological processes behind visual perception

The V(λ) curve and other basic assumptions behind photometric and colorimetric technology were established through psychometric matching experiments, belonging to classical experimental psychology. Since then, the understanding of mechanisms in the human visual system has made large progress through the additional input from brain research. Such new knowledge is, however, not always incorporated in the theoretical foundations of photometry and colorimetry. For example, today's understanding of the sensitivity and interaction of retinal receptors could possibly lead to the abandonment of the Vλ) curve in favour of other theories (Liljefors 2010). Should this be done, it would change all the photometric concepts, units and measuring tools – that is, the very basis for lighting technology.

Current physiological brain research works very much with finding patterns of correspondence between outer stimuli and neural responding and processing. This is done by monitoring the electrical activity of brain cells or by scanning the activity of the brain as a whole with methods such as PET and MRI. The results of such research could eventually add much to our understanding of vision and perception, and could possibly be made useful in the measuring of experienced colour and light.

The use of standardised colour samples

Colour sample selections can be made for various purposes, with various demands on production stability, physical and visual constancy, and notation accuracy. To function as references for industrial colour production and reproduction they need to meet very high demands in all these aspects. To do so, standardised colour samples are specified colorimetrically with very narrow variation tolerances. (Hård & Nilsson 1994).

When it comes to the Natural Colour System, it is based on visual concepts. Once you know the system, you do not need reference samples to understand from the NCS code how the colour looks or how it visually relates to another colour. As an illustration of the concepts and their relationships, a choice of colour samples has been made, based on visual assessments by many observers in a controlled viewing situation. Once the samples and their visual notations have been established, they are colorimetrically measured and standardised. These colorimetric specifications can then serve as references when measuring other surfaces, e.g. in a portable colour scanner as mentioned earlier. However, as there are always some differences between different instruments and measuring conditions, measurements without direct access to the reference samples cannot claim very high accuracy.

The physical colour samples can also be used as visual measuring rods. As mentioned above, the *nominal colour* can be defined as “perceived colour under standardised viewing conditions”. This means that the colour code printed on an NCS sample denotes its nominal colour. These colour samples can be used for visual measuring of the nominal colour of objects outside the standard situation, a procedure that cannot claim the same accuracy as technical measuring under controlled conditions.[64] One advantage with the visual method is, however, that it can be used also for comparing surfaces with different surface qualities, i.e. gloss, structure etc. (Fig. 15)

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[64] Fridell Anter 2000, pp 59–64. For further discussion see the article *Lightness and brightness* in this volume.

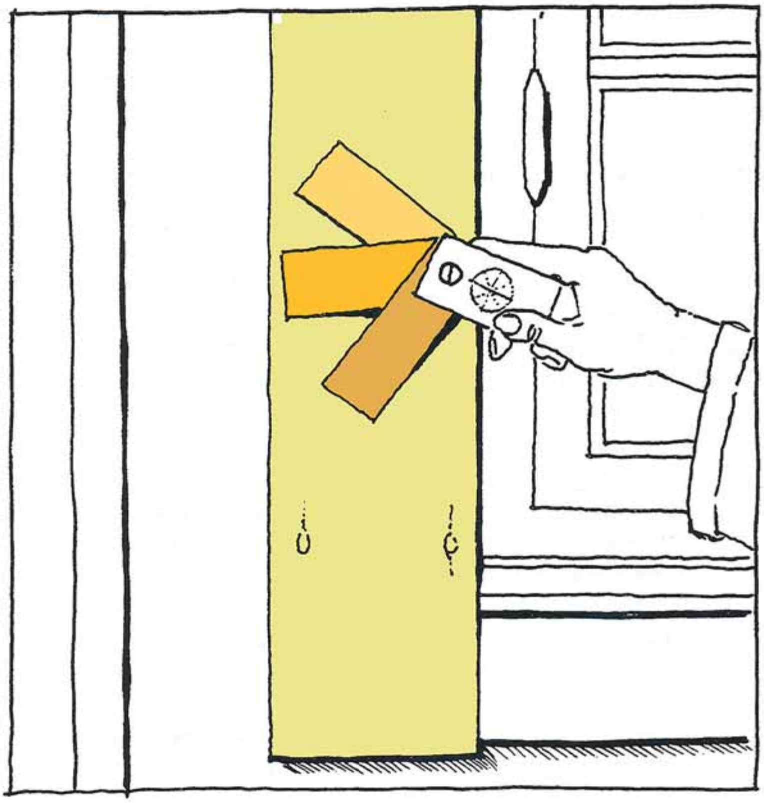

Figure 15. *Visual measuring of nominal (inherent) colour*. (After Fridell Anter 2000)

Psychophysics and perception

There is an ongoing debate on the relationship between psychophysical data and the perceived world. Can advanced photometry and colorimetry describe the complexity of perceived qualities or is it impossible to capture human perceptions in any other way than through perception itself?

The question could be raised on many levels. Basically, there is an agreement that today's photometric and colorimetric tools and theories give a good correlation to visually perceived qualities under certain specific circumstances. There is also an agreement that they could and should be further developed to obtain a better correspondence to the functioning of the visual sense. But, even so, they do not include the effect of spatial or temporal context of perception. Measurements of isolated qualities are made at discrete points and the results cannot claim to say much about the perceived totality. The growing research field of *colour appearance* strives to include more contextual factors and could possibly be developed to have a closer correspondence to perception.

Still, the most important question is not technical, but rather, philosophical. Could measurements of the physical world be made to describe that which we perceive? Or are the worlds of physics and human perception basically disparate and impossible to describe with a shared set of concepts and measurements? Many researchers, among those the author of this article, share the opinion that the way to make best use of both physical and perceptual understanding is to acknowledge their fundamental difference. We should not try to integrate them, and we should not dismiss one or the other – instead we could start from the difference between the physical and the perceived and search for meaningful correlations and relationships between them.

Conclusions: What do we mean by 'light' and 'colour'?

From all that is said above, it is obvious that the words *light* and *colour* can be used in many different ways and brought to mean very different things. One way of clarifying these differences is it to refer to the means used to specify, characterise and measure light or colour:

– Do we use photometric or colorimetric instruments?
– Do we use colour samples as visual standards?
– Do we measure electromagnetic radiation as such?
– or do we simply trust what we see?

Different ways to use words are deeply rooted in different traditions, professions and disciplines, and we must accept that these differences exist. We can, however, bridge the gap through raising mutual awareness of the different approaches. Terms that have a specific definition, like the photometric ones, should be used for their intended purpose only. For other words, that have several alternative meanings, the issue is more complicated. Here we must strive to use the words in a way that makes clear what we mean and at the same time be open for the alternative uses by others. This would both favour and be favoured by an increased interdisciplinary and inter-professional co-operation.

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Harald Arnkil

Lightness and Brightness and Other Confusions

Introduction

Literature and speech concerning colour and light is full of confusing, conflicting and contradictory usage. Take the very word *colour*. Sometimes it is used to refer to the percept, the sensation of for example redness, at others to the physical material, the paint, ink, dye or pigment acting as a stimulus for the sensation of redness. It is quite natural for words to have different meanings and usages in different environments, and the purpose of this article is not so much to provide definitive meanings to them, but to draw attention to the fact that different interpretations and meanings exist. The differences are of no great concern in everyday speech, but in professional, educational or research usage they can cause problems. Furthermore, there is hopefully something to be learned about the very nature of human interaction with light, colour and space from examining some of the different usages side by side.

There are several types of confusions between terms and concepts dealing with colour and light. One type of confusion arises from mixing concepts belonging to different academic or professional traditions. An example of this is confusing the photometrically defined measure *luminance* with the perceptually defined attribute *brightness*.

Another type of confusion is exemplified by *lightness* and *brightness*. Both terms have a specific and differentiated definition in perceptual science, but at the same time they are a very familiar part of everyday language, where their usages overlap without clear distinction as to their different meanings.

A third type of confusion often arises when general experiences or categories have to be further defined for scientific purposes. These definitions can be similar, but not exactly the same, in different conceptual systems. For example, in everyday language we can talk about such as the vividness of a colour and be rather certain that we can make ourselves understood; but in scientific usage there are many terms and concepts, such as chroma, chromaticity and chromaticness, having either the same or *almost* the same meaning.

Especially problematic is the situation where one and the same word is given alternative conceptual definitions, while having also a more or less established everyday usage. Take for example *saturation*. Even if each of the definitions is clear, it is very confusing that one and the same term can have so many slightly varying definitions.

There are also generic words and terms that have been given very specific meanings within a given scientific discourse. These can be misunderstood or confused with their more generic meanings outside that discourse. Examples of this are the terms *inherent colou*r and *identity colour*. Within the conceptual framework of their discourse these terms are well defined (and thus useful), but considered out of that framework they can be very confusing.

Colour identification through three properties

Irrespective of the starting point, be it physical, psychophysical or perceptual, any single colour can be described and identified through three independent properties. This makes it possible to organise and examine all possible colours within a three-dimensional conceptual structure, called a *colour space*. There exists, however, some variation between systems as to which exact visual properties constitute the three parameters of colour – and even more disagreement about how these parameters are defined. The end result is that there are in use today several colour systems exhibiting various ideas of colour.

It is relatively easy to build a model of colour from three variables such hue, lightness and saturation. The three dimensions lend themselves easily to a variety of geometric shapes. These colourful cubes, cylinders, spheres, cones, double cones, tetra- and octahedrons and their more complex asymmetrical variations may look convincing and beguilingly attractive as models for the parameters of colour. However, if colour is to be understood as something that is neither a property of objects nor entirely of the perceiver – but as something that happens in the dynamic interaction of the two – then no static geometric model could ever describe it.

Many, but not all, colour systems include lightness as one of its variables. Sometimes other words are used to denote basically the same thing. In the Munsell system, for example, the darkness–lightness variable is called *value*. Lightness or value typically forms a scale between maximum blackness and maximum whiteness. Although it is a basic variable it is not defined the same way in all systems. One system might define lightness in photometric terms, another with reference to standard samples. This and the conceptual confusion between lightness and brightness, is one of the topics of this article.

The second variable for specifying colour is *hue*. Typically it describes a colour's similarity to the sensation or perception of redness, blueness, greenness, yellowness etc, irrespective of the colour's lightness or intensity. As in lightness, the definition of hue can vary from one system to another – and so do the reference points, the elementary or primary colours, for its description.

The third variable describes the intensity, vividness or strength of a colour. Typically it varies between (almost) grey and strongest or most vivid imaginable. The definitions of this variable are most numerous, and its terminology includes words that are either synonymous, almost synonymous or ones that are used as synonyms although they refer to different concepts. In this article I have chosen the term *vividness* to refer to this entire family of concepts discussed in the section *Vividness of colour*.

Physic and physicists have played a decisive role in the development of modern colour science. Colour has been understood first and foremost as a phenomenon of light, the sum and substance of optics. It is far easier to define light in terms of units of energy than in units of psychophysical cause and effect – and there is still quite a way from psychophysical measures to understanding how we perceive light and colour in natural contexts.[65] What we call colour, is in the end neither a matter of physics nor neural responses, but an activity involving cognition and the whole organism–environment action–response cycle[66]. To properly understand colour one should always try to embrace this cycle of interaction – an eminently difficult task and an obvious reason for many of the confusions and misunderstandings. Another reason for conflicts and inconsistencies in the colour terminology is the fact that different professions, disciplines and approaches are talking about entirely different modes of appearance of colour, such as colour as surface colour and colour as light.

Lightness and brightness

Let us take a closer look at two terms that are confused perhaps the most often: *lightness* and *brightness*. These are concepts that have specific definitions in modern perceptual science, but which almost everywhere else are

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[65] For a further discussion of colour in the light of physics, psychophysics and perception see the article *Light and Colour: Concepts and their use* in this volume.

[66] For a deeper discussion of the active role of the perceiver in the formation of colour percepts see Noë 2004, ch 4.

continually confused with each other or with other concepts. Anders Liljefors[67] has written as follows on lightness:

> *Lightness and luminance exemplify a complicated relations arising from the visual sense's process of interpretation. How we apprehend the lightness of surface of a certain luminance depends on the arrangement of luminances in our entire field of vision. The experience of lightness is relative. For example, a room with a great variation of luminances creates a stronger impression of brightness than an evenly lit room, even when the adaptation luminances are the same in both the rooms. (Liljefors 2005)*

But what would be *brightness* as opposed to *lightness*? Anders Liljefors's text contains the word *luminance* (Swed. *luminans*), but that is a term from photometry and does not describe visual experience. In most languages there are separate words for lightness and brightness and they are used in a similar manner to their English counterparts. This is not the case in all languages, however. For example the English-Swedish dictionary gives brightness as *klarhet*, but this is something else than the concept of brightness, which is probably why Liljefors has used *luminans* in an attempt to describe the experience of brightness.

Edward Adelson gives a neat summary of the various terms connected with the perception of light and lightness in his article *Lightness Perception and Lightness Illusions* (Adelson 2000). Adelson also provides a distinction between lightness and brightness:

Luminance is the amount of visible light that comes to the eye from a surface.
Illuminance is the amount of light incident on a surface.
Reflectance is the proportion of incident light that is reflected from a surface. Reflectance, also called *albedo*, varies from 0 to 1 or, equivalently, from 0% to 100% where 0% is ideal black and 100% is ideal white. In practice, typical black paint is about 5% and typical white paint about 85%. (To keep things simple, we consider only ideal matte surfaces, for which a single reflectance value offers a complete description.)
***Luminance**, **illuminance**,* and ***reflectance**,* are physical quantities that can be measured by physical devices. There are also two subjective variables that must be discussed.
Lightness is the perceived reflectance of a surface. It represents the visual system's attempt to extract reflectance based on the luminances in the scene.
Brightness is the perceived intensity of light coming from the image itself, rather than any property of the portrayed scene. Brightness is sometimes defined as ***perceived luminance***. (Adelson 2000).

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[67] Anders Liljefors is former professor of architectural lighting at the Royal Technical University (KTH), Sweden and founder of the programme for lighting design at the Department of Lighting Science, Jönköping University, Sweden.

Adelson is talking here about light coming from images and scenes, because his article discusses mainly two-dimensional lightness illusions. But let us not be confused by that; his definitions apply just as well to spatial contexts.

The term *brightness* refers to the human experience of the intensity of light reflected or emitted by objects and surfaces. The sky, the moon or a candle flame has brightness, rather than lightness. But – as Adelson points out – also surfaces have brightness *in addition to* lightness, and their brightness depends on how much light they are perceived to reflect at a given moment. In a spatial or natural context, then, lightness refers to an object's particular perceived surface quality, to the surface's or object's overall ability to absorb and reflect light. Brightness refers to the experience of the amount of reflected or radiated light in relation to the overall, or global, scene.

Whiteness

A distinction must be made also between lightness and *whiteness*. Whiteness and *blackness* are parameters of colour in the NCS system and they are sometimes confused with the concepts of lightness and darkness. Unlike lightness and darkness, whiteness and blackness are discreet concepts, rather than expressions of the presence and lack of something. They are defined as relative visual similarity to the elementary colours black and white. The geometric model of the NCS colour space also includes the variables *hue* and *chromaticness*. Unlike all other systems (save the now obsolete Ostwald system) the NCS does not directly include lightness or brightness as one of its variables. Whiteness and blackness do contribute to the lightness and darkness (as well as to the chromaticness) of colours in the NCS system, but they have an indirect relation to lightness: in order to derive lightness from NCS whiteness and NCS blackness also hue must be taken into account: a yellow with five percent of whiteness is far lighter than a blue with the same percentage of whiteness. The reason is that yellow and blue are of different *lightness* to start with. The same goes for blackness in relation to the different hues. So what are whiteness and blackness, if not lightness and darkness? They are the visual constituents of a colour's impurity, its lack of vividness or distance from the ideal pure chromatic hue. As perceived phenomena they could be described as either mistiness or milkiness or fogginess in the case of whiteness, and shadiness in blackness or greyishness when both whiteness and blackness are present.

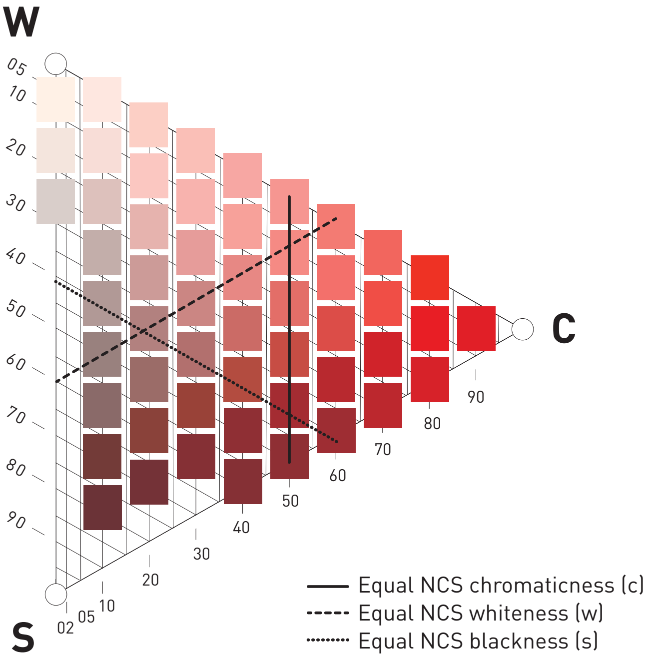

Figure 16. *Chromaticness, blackness and whiteness in the NCS system*

Brightness has an indirect, non-linear correlation with luminance; it is a perceived quantity that cannot be instrumentally measured. For example the full moon can be bright and luminous – almost dazzling – at night, but viewed in the very different global setting of daylight (this is sometimes possible) it will look only pale, a mere ghost of its nocturnal appearance, although its *measured luminance* will be the same as at night. The difference in the mode of appearance and the experience of brightness is, of course, due to adaptation and contrast – and this is exactly how brightness differs from both lightness and luminance.

One speaks of the sun, the moon or a lamp as being bright, but of a table or room as being brightly lit or illuminated (it is idiomatic in English, though, to speak of a room or a landscape filled with daylight as being bright). There are instances where the two modes of experience merge, as in self -luminous objects or surfaces in darkness being illuminated by cropped beams of light with for example theatrical profile projectors (which can lead to an illusion of self-luminance). Various types of image projection (slide-, overhead-, film-and data projection) also represent modes of appearance that can waver between the two types of experience.[68]

Lightness constancy

The great difference in appearance of the moon at night and in the daytime may also result from the fact that at night the moon is viewed in relative isolation. In most spatial contexts the lightness of objects is perceived as more or less unchanging despite changes and variations in illumination and juxtaposition. In other words, a piece of white paper is experienced (in all but the most extreme cases) as white in deep shadow, penumbra and bright sunlight. And a piece of coal will look black both outdoors and in the murky depths of the cellar – even though outdoors it will reflect hundreds of times more light (as radiant energy) than, say, the dimly lit white walls of the cellar. In other words, the ambient or incident light may vary, but the lightness estimation remains remarkably constant. This is called lightness constancy.

To help separate lightness and brightness from each other and from the concepts of luminance and illuminance, let us consider what our visual system is for? One of its most important tasks is to provide information about the typifying qualities of objects and surfaces. Among these qualities are texture, gloss and reflectance – all more or less permanent properties of objects and therefore fairly reliable indicators of the objects' physical properties. These can be measured. What we call colour and lightness are the brain's best estimate as to the chromatic and non-chromatic reflectance properties of a surface. Identifying lightnesses correctly helps us to identify and categorize things, places, etc., and lightnesses are important indicators of the "permanent" qualities of their surfaces and their materiality. Identifying brightnesses is also important, because we need this information to be able to separate the permanent property of *surface reflectance* (perceived as lightness) from the ever-changing property of *illuminance* or incident light, as well as to separate radiant objects from non-radiant objects (or light sources from illuminated things). The fact that the correlation of perceived lightness to measured reflectance is far better than the correlation of perceived brightness to measured luminance reveals something fundamental about the function and ecology of our visual system: it has evolved to inform us first and foremost about constancies.

In nature surfaces and objects are often illuminated unevenly. Tree branches and leaves or other obstructions can create complicated light-and-shadow patterns of illuminance. Objects are also rarely flat or their surfaces frontal in

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[68] The space and installation artist James Turrell (b. 1943) has in many of his works exploited the disorienting, often illusory, sensation created by confusing the modes of lightness and brightness.

relation to the light source or observer. This creates an uneven distribution of luminances even when the illuminance is even – as for instance in spherical objects that tend to display deep shadows and bright highlights at the same time. The same is true, of course, for any shape of three-dimensional object in normal directional light.

We are able to separate the forms of objects surrounding us from the ever-changing patterns of light and shadow. Furthermore we are able separate the patterns of illuminance from the patterns of luminance. In all but the most confusing cases we are able, without effort, to separate the colours of highlight, shadow and half-shadow in a spherical object from what we experience as the *'real colour'* or *´substance colour'* and the 'real *lightness'* of the object itself.[69] The same goes for a flat surface in dappled or uneven light. We do not say or think that a white wall lit in this way has different *lightnesses*, but that it is *lit* unevenly. In the language of perceptual science, it has different *brightnesses*. The confusion in the use of the terms lightness and brightness comes from their everyday use. Brightness is in most languages limited to describing phenomenally self-luminous objects and things, such as the sun, the sky, artificial light sources, but it can also describe ambient or incident light: a bright day, a bright room, etc. Brightness is also in everyday speech of many languages used to describe the vividness of colour (a bright pink dress, a bright blue flower), which confuses the issue even further. Since our capacity to apprehend the lightness of objects despite their varying brightness (or luminances) is very robust and requires no conscious effort (we are indeed mostly unaware of this separation), there has been little need to develop separate words or separate ways of using the word *brightness* to describe a) the variations of *illuminance* and b) variations of *luminance* of our surroundings. It is only when we pause to take a closer look at the nature of seeing, that this need arises.[70]

The human visual system has also a remarkable capacity for adaptation to intensities of light, both globally and locally.[71] If this were not so, we would

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[69] See also the section *The Real colour of object*s, pp. 92–100, in this article.

[70] In everyday speech we do not refer to two walls painted in the same colour in the manner: ”The wall in next room is the same white colour, although less bright”. Neither do we often say: ”The wall was of a uniform brown, although you could never see it as such, because of its varying brightness, due to the pattern of shadows falling on it”. We apprehend the reflectances as identical and uniform, despite the variations in luminance – even to the point of being unaware of the luminance variation. For further discussion about modes of attention see Merleau-Ponty (2002), pp 30–59, as well as the section *Identity colour and modes of attention* in this article and *Natural Experiences and Physical Abstractions*, pp 23–24 in this volume.

[71] The human visual system is capable of producing perceptions over an amazing luminance range of 1–10 000 000 000 000 (ten trillion) cd/m^2, representing at one end the absorption of one photon in a rod receptor (enough to create a tiny flash) and at the

either be blind in extreme levels of brightness and/or darkness or would probably need separate eyes or visual systems for seeing outdoors and indoors.[72] This adaptation leads to the fact that we do not register intensities of light as absolutes but in relation to spatial and temporal juxtaposition. This relativity cannot be measured. Illuminance on the other hand can be measured, the unit being lux (or lumen per square metre). Also luminance, the intensity of light radiating from a surface in relation to its area, can be measured in candelas per square meter (cd/m^2). Why is brightness then not the same thing as luminance? Again, we must take into consideration the effects of such factors as lightness constancy, *local* and *global adaptation* and *simultaneous contrast*. (For the last two see *Seeing and Perceiving*, p. 40 in this volume). A light meter is blind to these phenomena. Although it can provide information about physical quantities of light, it tells as very little about how we see and what we see in that light.

Brightness is the perceived intensity of light reflecting or radiating from a surface. And, as explained above, it cannot be measured with a light meter. The following illustration by Adelson may help to understand this and some of the other differences between measurable and perceived quantities:

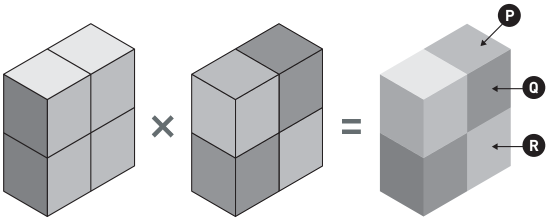

Figure 17. *Lightness and brightness. (From Adelson 2000)*

Patches p and q have the same reflectance, but different luminances. Patches q and r have different reflectances and different luminances; they share the same illuminance. Patches p and r happen to have the same luminance,

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other the impact of trillions of photons reflected from a sunlit sandy beach at midday. The capacity of the nervous system to carry signals is limited, however, which greatly reduces the scale of lightnesses or brightnesses perceptible at any one time. So, several adaptation mechanisms are needed to cope with the vast scale of input. (See also *Natural Experience and Physical Abstractions,* pp 22–23 in this volume).

[72] We do have separate systems for day vision and night vision, though. These are called photopic and scotopic vision, but the scotopic system, relying (as far as is known) entirely on the highly light sensitive and colour blind rod receptors, requires total or near darkness to operate fully.

> *because the lower reflectance of p is counterbalanced by its higher illuminance.*
>
> *Faces p and q appear to be painted with the same grey, and thus they have the same lightness. However, it is clear that p has more luminance than q in the image, and so the patches differ in brightness. Patches p and r differ in both lightness and brightness, despite having the same luminances.*
>
> (Adelson 2000)

Why is it important to make a distinction between lightness from brightness? The answer is that light and its effects on the visual quality of the environment, in urban and road planning, work environments, etc., are now described in the physically quantitative terms of radiant flux, illuminance and luminance, and lightness and brightness are none of these. Neither are they the same thing – and of the two, brightness is often confused with luminance. It would be very useful to develop methods and tools for assessing and separating these basic qualities of human visual experience.[73]

Attempts to systemize colour

The International Commission on Illumination (CIE) has ever since its foundation in 1913 played a central role in defining colour from physical and psychophysical premises. The advent of computerized colour management in the printed and electronic media has further reinforced the physical/psychophysical view of colour and light. Both colorimetry and computer colour management treat the mixing, augmenting and precise definition of colour as a matter of measuring amounts of light energy in so-called RGB-channels or as so-called *tristimulus values*. This of course makes huge sense for controlling colour on computer and TV-screens, where the colours really are produced with three types of phosphors. Problems start arising when the software tries to simulate such psychological percepts as *relationships* of hue, lightness, brightness and vividness. The first and biggest problem is that (contrary to common belief) there are no RGB-channels in the human brain on which to base the colour mechanisms of computers and colour measuring instruments.

The difficulties of mapping human colour vision into a Cartesian space have become more and more evident as neuroscience and psychology have revealed new facts about the non-linear aspects of the visual processes. As much as creators of colour systems would like it to be so, the variables of

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[73] Professor Anders Liljefors has suggested a method and a terminology for visual analysis of light in spaces. (Liljefors 2005). A further development of the method is under way and has been tested within the SYN-TES project in 2010–11. See Arnkil et al. 2011 and Matusiak et al. 2011.

human colour vision do not follow linear paths within a symmetrical space. All geometric representations of colour are therefore a compromise between clarity and accuracy. In colour spaces the compromise has to be made between two characteristics: symmetry and equal colour difference steps. This difficulty has led to ever-new mathematical-geometric representations of colour variables with acronyms such as HSV, HSB, HSL, LCh, CIE Yxy, CIELAB, CIELUV and CIECAM02.[74] The large number of colour models might give the impression that the difficulty lies in the complex nature of light, computers, digital reproduction or other physical challenges. It does not. The difficulty lies in finding a model that is sophisticated enough to truthfully simulate human colour vision.

Primary colour

> *The artificial results of mixing paints is doubtless what has led to the idea of 'primary colors', such as red, yellow, and blue. If any special set of colors deserves to be called primary, it is the set of red, blue, yellow, and green. – – (W)hat justification all four have as candidates for primaries has little to do with the three cones and much to do with the subsequent wiring in the retina and brain.*

– David Hubel (1995)

The idea that all colours are physically or physiologically reducible to a limited number of elementary or primary colours has intrigued artists, philosophers and colour scientists ever since ancient times. There is an air of transcendence to the notion of primary colours and even more so to the relatively recent idea that they are three in number. This idea is so deeply ingrained in the thinking and vocabulary of at least all those who are used to working with additive and subtracting colour mixing systems, that it seems almost blasphemous to doubt this principle. Yet, the deeper one delves into the paradox of the primaries, the more likely it appears that there might not be any one irreducible set of colours that are the origin of all other colours.

There are two separate aspirations in seeking the primaries in colour – and some of the confusions start with getting these aspirations mixed. One is purely technological: how to get the most hues, tints and shades from the least number of pigments, inks, lights or pixels. The other is more philosophical and cultural and is entwined with such usages and traditions as heraldry

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[74] Some colour systems, of which two of the most important are the Natural Colour System NCS and Munsell Color differ from these in that they do not attempt to describe any device-dependent properties of light or theories of the trichromacy of the human visual system. They merely attempt to map colour as *perceived* by humans without any claims about how or why we see colour.

and religious symbolism. It is also almost a truth carved in stone that the number of the primaries is three, and several pieces of weighty evidence are repeatedly put forward in defence of this theory in the text books: the three types of colour receptor in the human eye, the three primary lights that produce all imaginable colours, and so on. The development of the modern idea of three primaries is however very much tied with the development of colour technologies, including the technology painting. Artists have always endeavoured to limit the number of paints on their palettes, if only for economic reasons. However, the reason for the idea of primary colours in art is more philosophical than practical and springs from the above-mentioned aspiration towards strong symbols.[75]

Primaries and secondaries of the Itten 12-hue circle

The artist, pedagogue and writer Johannes Itten (1888–1967) confused the above aspiration or principles in his very famous and widely read opus *Kunst der Farbe* (1961, original German edition). Itten's 12-colour circle is based on the primaries red, yellow and blue that are given as the ground for mixing the secondaries orange, green and violet and thereafter all possible other hues and nuances. The 12-hue circle forms the backbone of much of Itten's theorising in this lavishly illustrated book, particularly the theory of colour harmony[76]. Itten defines the primaries as follows:

> *By way of introduction to colour design, let us develop the 12-hue colour circle form the primaries – yellow, red and blue. As we know, a person with normal vision can identify a red that is neither bluish nor yellowish; a yellow that is neither greenish nor reddish; and a blue that is neither greenish nor reddish – – The primary colours must be defined with the greatest possible accuracy. We place them in an equilateral triangle with yellow at the top, red at the lower right and blue at the lower left.* (Itten 1973, p 34)

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[75] The spiritual and symbolic significance of primary hues was emphasized in much of the transcendental abstract art of the early 20th century and is epitomized in the art of the Neo-plasticists, particularly in the works and writings of their ideological leader Piet Mondrian (1872–1944).

[76] In his seminal book on colour Itten writes: ”Thus we have constructed a regular 12-hue color circle in which each hue has its unmistakable place. The sequence of the colors is that of the rainbow or natural spectrum. – – Unless our color names correspond to precise ideas, no useful discussion of colors is possible. I must see my twelve tones as precisely as a musician hears the twelve tones of his chromatic scale.” (Itten, 1973, p 34). Thereafter Itten treats his 12-hue circle much like a musician for deriving his abstract and geometric rules of colour harmony. (Itten 1973, pp 118-9).

From here Itten goes on to give precise instructions on how to carefully mix the secondaries and the intermediate colour between the secondaries and primaries, thus arriving at the 12 hues in a beautifully symmetrical and circular arrangement. As every art student, who has tried to follow Itten's instructions knows, it is impossible to create the desired circle from Itten's starting points. Itten's primaries will not yield the 12 hues as instructed and the student will always have to resort to bending the rules in order to achieve a balanced result. What Itten has defined here are in fact not the subtractive primaries of painting, but three of the so-called psychological primaries of vision and the brain, alluded to above by David Hubel and originally described by Ewald Hering in 1872.

Figure 18. *Johannes Itten's 12-hue circle from The Art of Colour, 1973 (Original German edition: Kunst der Farbe, 1961).*

Itten's colour circle (like those of many others) is an idealisation. It stands aloof from the real world as an abstracted symbol of ideas about colour. The three primaries, their derivatives and interrelations, as they are presented in his book, are a mixture of *perceptual* relations and *transcendentalism*. It is strange, though, that despite being an accomplished painter, Itten could not see the obvious disagreement between the transcendental and the technological – or perhaps he simply chose to ignore it.

Munsell's principal hues and Hering's elementary colours

The history of the Munsell system is somewhat similar to that of Itten's 12-hue circle. Like Itten, Munsell was at first an artist, trained in the Academie Julian in Paris, later becoming a pedagogue and colour researcher. His colour system, created around 1905, was based on his experience as a painter and on a strong desire for creating a system of colour harmony. These were coupled with a rigorously systematic inclination, which dictated that the arrangement of colours should be based on a decimal division. Therefore Munsell's circle has not three or four, but five *Principal Hues*: Yellow, Red, Blue, Green and Purple. Be careful to note, that Munsell does not call his five main hues *primaries*. He was well aware that they did not coincide with any existing theory of colour mixing[77]. One advantage of Munsell's arrangement of hues is that they yield more or less symmetrical relationships of complementary colours, as defined by additive mixing of coloured lights or cancellation of neural signals. This cancellation of hues was the starting point for the now more or less forgotten colour system of Wilhelm Ostwald (1853–1932).[78] Being a scientist (he was awarded a Nobel-prize in 1909 for his researches into physical chemistry and reaction kinetics) Ostwald based his colour system on the latest findings of colour physiology and psychology. Therefore he chose four primary hues: red, green, blue and yellow, following the principles of Hering. Fashioning his circle on the experiments of James Clerk Maxwell, Ostwald specified and placed these four primary hues opposite each other by empirically testing their cancellation on a Maxwell disc. This yielded a double-cone - shaped colour space that formed the basis for, among other things, various harmonic relationships of colour.

Ostwald's colour space bears a marked similarity to the NCS-system. Both are based on Hering's six elementary colours and the opponent process principle; both use blackness and whiteness as principal properties of colour perception and include them as main variables in their systems. Both systems are presented as symmetrical double-cone spaces. There are important differences though, regarding the four elementary or primary hues. Ostwald states that they must cancel optically and to emphasize this he placed them diametrically opposite on his circle. (Ostwald, 1969) This leads to the fact – which somewhat troubled the very systematic Nobel scientist – that the visual steps between the hues in the blue to green quadrant were far smaller that the steps

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[77] Another reason for having five principal hues in his colour circle was Munsell's endeavour to attain equal visual distance between the hues. A four-primary system (such as Ostwald's), where the primaries are equally spaced at right angles on the circle, will not yield equal distances between all the mixtures of the primaries.

[78] It is interesting to note that Ostwald's colour system and the accompanying tenets of harmony and composition of colours were in pride of place at the Bauhaus until they were swept aside after the arrival of Itten as the leader of the *Vorkurs*.

in for instance the yellow to red quadrant. The same problem is present in the CIELAB-space – and for the same reasons.[79]

There is an important difference to all of the above in the NCS system and its six elementary colours. This is why the NCS elementary colours are sometimes described as "psychological primaries". Their idea is in mapping the visual relationships within human colour vision. In other words, the elementary experiences of redness, greenness, yellowness and blueness describe, together with the experiences of blackness and whiteness, our experience of how colours resemble each other or how they are different. The six elementary colours are not colours in any physical sense any more than the cardinal compass points are real places in the world. Unlike almost all other colour systems the NCS does not make any claims, with or without its layout of the elementary colours, about the cause or origin of colours or about how to derive more colours from the elementary ones. This means that the percentages in the codes, such as the 30% of redness in Y30R, refer to relative visual similarity and not to any means of producing the colour.

How many are the primaries?

The notion that the primaries are three in number is relatively new and really gained momentum only after the invention of colour intaglio printing by Jacob Cristoph Le Blon around 1710. It was quickly discovered that three printing plates, inked with red, yellow and blue, were sufficient for producing an acceptable gamut of nuances in a full colour image. Minimizing costs and maximizing profits was the goal in the printing industry right from the beginning. This was the aim of Le Blon, also. So minimizing the number of plates or printing blocks would probably have made sense to anybody in the days when the plates were prepared by hand.[80]

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[79] To be accurate, Ostwald's primaries were yellow, red, ultramarine blue and "sea green", and since Ostwald's system was based on colour samples, their visual definition relied on the pigments available at the time. There might have been a similar reason for the contradiction between theory and practice in Itten's circle: to yield all the mixtures Itten was after, he should have used the modern colorants of the printing process, cyan, magenta and yellow. But magenta and cyan were not available as artists' pigments in Itten's time. It is only quite recently that near equivalents of them have become available.

[80] This did not mean, however, that only three or four plates or blocks were used forever from there on. In the effort for maximum quality and attractiveness they increased to as many as forty in some branches of the advertising and packaging industry in the late 19th Century. With the rapid development the printing process and the discovery of more and more vivid and lightfast synthetic colorants and pigments it is no longer necessary to engage so many printings, but in higher quality colour inkjet printing of today the former CMYK, or three colours plus black, have been replaced by five, six or even eleven inks.

As the inks developed the three-primary theory gained more and more acceptance and was reinforced by the discovery of the three primary lights, red green and blue, in the late 17th century and Thomas Young's trichromacy theory of colour vision (1802). With the theory of Thomas Young and the later neurological evidence of Hermann von Helmholtz the idea of the three primaries not only strengthened, but also shifted from a physical and material basis more and more towards a neurological and physiological one. It would be easy to assume from the evidence put forward by Young and Helmholtz that the matter of the primaries was at last settled. They were three – and for many of the physicists taking the theory of trichromatic vision as a starting point, they were specifically red, green and blue. The primacy of these RGB-primaries would probably still prevail were it not for Ewald Hering, who in 1872 hypothesized a rival theory involving not three but four unique hues, red, green, yellow and blue, that became the basis of his theory of opponent colour vision.

Today there is a wide scientific consensus that both the Young-Helmholtz theory of trichromatic vision and the Hering theory of opponent colour processes are fundamentally correct – they merely describe different stages of the coding of colour signals in the path from the retina to the brain.

Some of the differences in the way various colour systems define primary, elementary or unique hues are due to the fact they describe different stages of colour coding in the visual pathway. However this is not the only reason for the differences. There is also confusion about what one means by the words *primary*, *elementary*, *principal* etc. in connection with hue and colour. A widely used definition of primary colour states that it is a colour (substance) that yields secondaries, tertiaries and all other possible colours when mixed as pigments or other colorants. Another definition starts with perception, as does the NCS and as did Itten in his own way. A third definition starts from psychophysics and mixtures of coloured lights. This was the starting point of the CIE, when it started to build a system for mathematically designating colours of lights.

The International Commission on Illumination (CIE) began to develop a system for mapping all colours of lights visible to humans within a mathematical model in the 1920s. The fruit of this work was the 1931 Yxy -colour space that underlies all present-day spectrophotometric and colorimetric systems. Much of the logic of this system was based on trichromatic theory of colour vision as laid out by Young and Helmholtz in the previous century. This theory states that the colour-sensitive photoreceptors of the human eye, the cone receptors, are sensitive to three wavebands of light – short, medium and long – with overlapping sensitivities, particularly between the medium and long wavebands. The peak sensitivities of the cones have been measured to be at around 420–440 nm, 534–545 nm, and 564–580 nm respectively. The pioneering work of the CIE has dealt with producing mathematical functions for mapping colours of light, visible to the average human, in a way that allows their reliable scientific definition and comparison. Another starting point for the work was Hermann Grassmann's (1809–1877) three laws of additive colour mixture.[81] This simple psychophysical law laid the ground for the colour matching experiments involving three 'primary lights'. As Fred Billmayer and Max Saltzman say in their book *Principles of Color Technology*, there is nothing magical about these monochromatic lights. The CIE could have chosen any other set of colours, provided that they are sufficiently wide apart in the spectrum. (Billmayer & Saltzman 1981, p 40; Kuehni 1983, p 73).[82] In fact there is no set of three primary colours with which it is possible to mix all possible colours visible to the human eye. So, in order to derive a system for describing all colours as perceived by humans that was based on three primaries, negative values were assigned to some of the colours in the equation. This led to the designation of the three 'imaginary primaries' X, Y and Z. They became imaginary, because in the geometry of the CIE Yxy colour space, for mathematical reasons, they had to be placed outside the gamut of human colour vision.

The history of the CIE-colour spaces (there are several) is one of transformations, technical compromises and abstractions. Therefore the so-called RGB-primaries, which are very much a child of this enterprise, should be treated with the same coolness as any other technological colour application. There may be a set of three primary lights that excite the colour sensitive cones maximally, but four or five would do it even better. The CIE 1931 Yxy colour space should therefore not be regarded as a model of how the human colour vision system functions. Neither should it be used as source for drawing conclusions about how many and what are the primary colours – or at least not outside the logic of the CIE system.

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[81] Grassmann's First Law: Any colour can be matched by a linear combination of three other colours, provided that none of those three could be matched by a combination of the other two. Second Law: A mixture of any two colours can be matched by linearly adding together the mixtures of any three other colours that individually match the two source colours. Third Law: Colour matching persists at all luminances. This law fails at very low light levels, where scotopic vision (rod-receptors) takes over from photopic vision (cone receptors).

[82] In this sense the primaries underlying the CIE 1931 Yxy space are somewhat like ordnance survey points in triangulation: one could start anywhere and still end up with an accurate measurement of the terrain.

David Hubel has proposed that the four unique hues or elementary colours of the opponent system, the psychological primaries, are the only set of colours that could qualify for the title of primary colours. The evidence in support of this is quite strong, but there is something in the intangible nature of the 'psychological primaries' that will probably make them, quite literally, difficult to grasp for most practitioners of colour. For those for whom colour is primarily a creative tool, the idea of *the primary*, *elementary* or *principal* in colours is so deeply entrenched in our experience of physically mixing colours, that shifting the concept to something that exists in the mind only is perhaps too radical. Therefore it makes sense to identify and acknowledge the various sets of primaries for their own worth, as practical solutions for the different technological applications or as theories of the psychophysics or the perceptual psychology of colours. But it is good to remember, that with the advancement of technology and with our deepening knowledge of perception and the physiology of colour vision they may still change, both in kind and number.

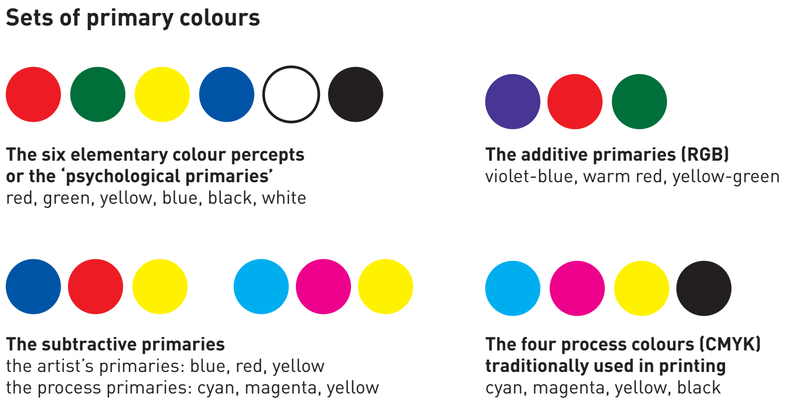

Figure 19. *Various sets of primary colours.*

Vividness of colour

There is one family of colour terms in colour science whose members are particularly hard to distinguish from each other: *saturation*, *colourfulness*, *purity*, *chroma*, and *chromaticness*. They all refer to the pureness, vividness or intensity of a colour. They are not, however, synonyms of each other, although they do all in their own way refer to the same phenomenon. There is also such a thing as *chromaticity*, which does not refer to vividness alone, but also to hue. Most of these terms have several meanings that vary across disciplines and some have received new meanings along the way. To avoid confusion I will here refer to the general concept of colour strength as *vividness* and will use the specific terms only when referring to their specific definitions.

Why so many different words for what at first sight seems the same thing? One reason is that chromatic intensity of colour can be defined in several ways. Another reason is that examining non-related colours (as aperture colours or isolated lights amid darkness) is very different from examining them in relation to each other. (Billmayer & Saltzman 1981, p 187). Yet another reason arises from the tradition of conceptualising the attributes colour as a three-dimensional space. There are many different ways of mapping colours in three-dimensional models. They all yield different mathematics for defining the attributes of colour, and the different terms for the vividness of a colour refer to different mathematical relationships of colours within the abstract models. But there is also a more fundamental reason for so many different terms and definitions of fullness or vibrancy of colour. The concept gains different meanings depending on whether the viewpoint is physical or perceptual.

Painters will know that colours can be made less vivid by at least four different means: by mixing a pure hue with white, which is called tinting, by mixing it with black, called shading, and by mixing the hue with grey, called toning. In addition, mixing a colour with one of an opposite hue, for example a red with a green or a yellow with a violet, will lessen the vividness of the colour, yielding darkish tones or shades of a more neutral appearance. This experience of controlling the vividness of colours by physically mixing pigments is a central starting point for much of the concepts and terminology concerning vividness.

Chroma

Chroma (from the Greek word *khroma,* colour) is given in the Concise Oxford Dictionary simply as “purity or intensity of colour”, but chroma is not a word that is in general use. The equivalent lay term in English is brightness, brilliance, depth, vividness, etc. Depending on the context, such words as muted, pale, pastel, garish, vibrant, dazzling etc. are also used to describe various degrees of chroma or chromatic strength. Chroma is an attribute of the Munsell colour system, which is why it is widely used among colour scientists and educators in the USA and other countries where the Munsell system has left its imprint on the colour language.

In the Munsell system colours of equal value (lightness) are placed on the same horizontal plane. As in most systems, the chroma of a hue in Munsell increases outwards on a straight horizontal axis starting from the achromatic centre, but unlike many other saturation-scales, the Munsell chroma-scale of any hue is one of constant value. In addition, the Munsell chroma scale has no maximum limit, only a definition of equal steps.

In *Principles of Color Technology* by Billmayer and Saltzman there is the following definition of chroma:

> *Perceived chroma (of a non-luminous related color). Attribute of a visual sensation according to which a non-luminous related color appears to exhibit more or less chromatic color, judged in proportion to the brightness of a white object color similarly illuminated. (Billmayer & Saltzman 1981).*

Billmayer and Saltzman point out that the term *perceived* chroma is used to distinguish it from Munsell chroma as well as the other uses of the word chroma. But what other uses are there? One instance is the L*C*h* colour space, where a colour may be expressed in terms of hue angle (h*) and *chroma* (C*). The third attribute here is Lightness (L*). Here the definition of chroma is very similar to Munsell's, except that L*C*h* does have limits for the maximum's of all three attributes.

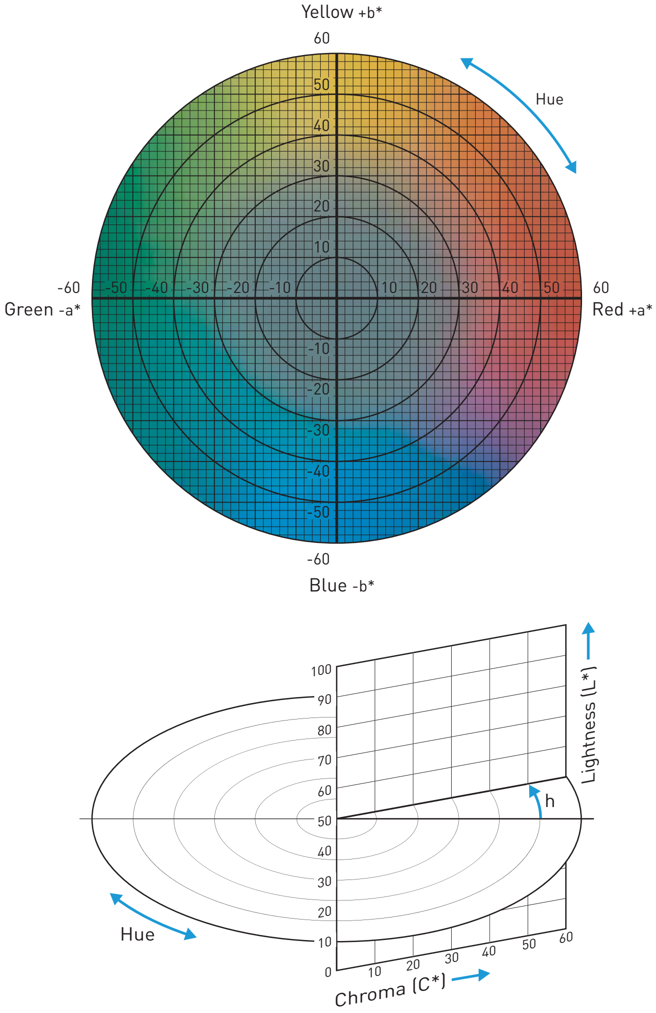

Figure 20. *The L*C*h* colour space is a cylindrical variation of the spherical CIELAB space. The hue angle (indicating hue) rotates counter-clockwise from +a (red = 0°). The chroma increases outwards from the central axis (grey scale = 0 chroma).*

Chromaticness and chromaticity

Chromaticness is often given the same definition as *chromaticity*, i.e. the hue and saturation of a colour regarded independent of its brightness. The Collins English Dictionary still gives chromaticness as “the attribute of colour that involves both hue and saturation” (Collins 2000). Billmayer and Saltzman give chromaticness as follows: “Finally, when taken together, the hue and saturation of a perceived colour are called its chromaticness”. In their book *The Science of Color* The optical Society of America’s Committee on Colorimetry defined chromaticness as follows: “Chromaticness consists of hue and saturation, taken together, and is expressive of the quality of color sensation as distinguished from its intensity.” (Optical Society of America 1973, p. 66).

Chromaticness, defined in another way, is one of the variables of colour in the NCS system. Colours are judged according to their relative similarity with the six elementary colours yellow (Y), red (R), blue (B), green (G), black (S) and white (W), where the first four are called chromatic. Chromaticness is derived from the perceived proportion of a chromatic colour of a given hue (C) in relation to its whiteness plus blackness. The sum of all three is always 100%. Chromaticness (c) can also be given as the equation c = (y or b) + (r or g). In terms of whiteness and blackness, the equation is 100 – (w+s) = c. In the NCS literature chromaticness is defined as “... a scale between the achromatic greys and the most chromatic colour of a specific hue”. (Hård et al. 1996; see also Fridell Anter 2000, pp 26–27).

Saturation and purity

Saturation is a generic word that one nevertheless seldom comes across in casual speech about colour. It is widely used in professional language of art, design and science, though, and there it has got several parallel definitions. In Hermann von Helmholtz’s words saturation, or *Sättigung*, is the proportional mixture of "white" and pure monochromatic light of equal brightness. In the context of a colorimetric colour space the saturation of a colour can be understood as its proximity to its fully chromatic outer limit[83].

In the language of colorimetry saturation and chroma are separate concepts. According to Rolf Kuehni (Kuehni 1983, p 39) varying the brightness of a coloured lamp in total darkness is equivalent to varying its chromaticness. The brighter a red light shines, the higher its *chromaticness*. If one were to mix the red light of a lamp with the “white” light of another lamp of equal brightness (luminance) in varying proportions, one would create varying *saturations* of the red colour. Kuehni concludes: “Chromaticness is an absolute measure of chromatic content of a color regardless of its brightness, while saturation is a measure of the chromatic content of colors of equal brightness.” (Kuehni 1983, p 40).

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[83] The CIE 1931 Yxy colour space was designed so that it would include all possible colours visible to man, including monochromatic lights of the highest purity. David MacAdam defined the limits of chromaticity for surface colours in relation to the CIE Yxy space in 1935. These *Mac Adam limits* define the maximum purity of surface colours viewed under standard illuminant C. These limits vary in relation to the theoretical maximum outer limit of the CIE 1935 xy chromaticity diagram. The limits decrease in size as the luminance factor Y increases. (See Billmayer & Saltzman 1981, p 50).

There is also such a thing as NCS saturation. According to its definition, colours that lie on a straight line connecting NCS black and any other colour of the same hue display a constant relationship of whiteness and blackness and thus, according to this NCS definition, possess equal saturation. These colours also constitute what is called a ‘shadow series’, a term that we find similarly used also in the Ostwald system (Ostwald 1969). They display the perceived variation of a single coloured surface (or object) from fully lit to totally shaded, as in the perceived gradient of colour in a depiction of a round or cylindrical object in directional light. When viewing NCS colour samples of equal NCS saturation it is clear that the term saturation in NCS does not denote what is generically or in other colour systems called saturation, in stead they immediately suggest the perception of a natural and logical ‘shadow series’ of colours of varying vividness.

In colorimetric terminology there is something called *excitation purity* (or purity, for short). It refers to the capacity of light to stimulate, more or less, either a single or two cone receptors of adjacent hue sensitivity, thus producing a sensation of less or more pure chromatic colour. In terms of the CIE 1931 Yxy chromaticity diagram it can be understood as intensity of hue within the diagram. When a straight line is drawn radially from the illuminant white point E in the centre through the sample colour S and to the outer perimeter of the diagram C, the purity of the sample colour is the proportion of ES to EC. In the words of the OSA: “The chief response correlate of purity is saturation; the greater the purity, the greater the saturation. A certain minimum purity is required to evoke any consciousness of saturation.” (Optical Society of America 1973, p 107).

Colourfulness

Rather surprisingly, colour science uses also the word "colourfulness", which is given yet another meaning that is slightly different from those of the above. Billmayer and Saltzmann summarize the differences as follows:

For a given perceived color, colorfulness normally increases as the brightness increases, whereas such a colour exhibits approximately constant saturation as the brightness is changed. A given colour also exhibits approximately constant perceived chroma for all levels of brightness, but for a given brightness level the perceived chroma generally increases as the lightness of that colour increases, relative to the whiteness of white objects in the scene. (Billmayer & Saltzman 1981, p 187).

Discussion

From all of this one may gather that it is very easy indeed to be misunderstood when talking about the variables of colour. Perhaps the greatest stumbling block is using the terms without reference to their context and mode of appearance: related colours are a different kettle of fish from non-related colours; so are luminous colours in relation to non-luminous ones (lights in relation to surfaces). Of course, one could argue that in the real world colours are always related. Even a single lamp in darkness is related to the surrounding darkness and all colours are related to what has been seen before. The strength or vividness of their perceived colour, whatever name this attribute is given, seems a natural and easily understandable feature of the appearance of objects and surfaces in natural scenes. It is perhaps only when one tries to isolate visual features from their mode of appearance and from each other that things become complicated (even though the objective was perhaps the opposite). Different modes of appearance of colour (surface, film, volume, glow, lustre, etc.)[84] seem to require different definitions of colour strength: the intensity of redness in red wine is a very different thing from the redness of an apple or the vividness of a sunset. Their "colourfulness" is judged against different starting (and ending) points and along different scales. These differences in the modes of appearance are reflected in the geometry and mathematics of various colour systems and colour models, but their natural contexts are lost in the abstractions of the definitions.

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[84] For definitions of modes of appearance of colour see Katz 2002.

Vividness of colour in various applications

1) The vividness of a colour can be judged either with perceptual, physical or psychometric criteria.

2) If perceptual criteria are used, they usually apply to 'related' colours; if physical or psychometric criteria are used, they can refer also to 'unrelated' colours.

3) In related colours (surfaces, colour chips etc. viewed naturally) the scale is: neutral white, grey or black – fully vivid colour.

4) In non-related colours (a light surrounded by darkness, a surface colour viewed through an aperture) the scale can be: darkness (no light or colour) – maximally bright chromatic light (devoid of blackness or whiteness). This is called Chromaticness in CIE terms. Alternatively the scale is from neutral achromatic (white) light to fully chromatic light of the same luminance. This is called Saturation in the CIE.

5) In Munsell vividness is called Chroma and is always judged in proportion to a neutral grey of the same Value (lightness). The scale is: grey – full Chroma of equal Value.

6) In the NCS vividness is called Chromaticness and is judged in proportion to the sum of the colour's blackness and whiteness. The NCS includes a concept of *saturation* that is unique: colours that lie on a straight line connecting NCS black and any other colour of the same hue display a constant relationship of whiteness and blackness and thus, according to this NCS definition, possess equal saturation.

7) Excitation purity is a term related to the CIE 1931 xy chromaticity diagram. The colour of a light source's excitation purity is judged as the proportion of the distances measured along a line connecting the light's dominant wavelength on the outer perimeter of the diagram and the (theoretical) equal point in the centre. Excitation purity relates directly to the psychometric concept of tristimulus values of spectral sensitivity in the human visual system.

8) Chromaticity is the hue and saturation of a colour without regard to its brightness. In the CIE chromaticity model a very dark green and a very bright green could have the same chromaticity, i.e. they could have the same hue, but mixed with equal amounts of white, grey or black. The difference between colours of equal chromaticity and equal saturation, then, is that colours of equal saturation may vary in hue whereas those of equal chromaticity may not.

9) In the world of computers and digital media the usual tool for determining colours is an RGB-based application that treats colours within parameters HSV, HSL, HSB (hue, saturation, value, etc.). In these colour spaces the Saturation is derived from calculations of brightnesses of red, green and blue phosphors. Thus Saturation in HSV-type systems is closely related CIE excitation purity, with the exception that it is judged in relation to either blackness (0 output in all RGB channels) or whiteness (maximum output in all RGB channels).

The real colours of objects

> *To see is not so much about looking at waves of light, but about looking at external objects mediated by these waves; the task of the eye is to enlighten us, not so much about the intensity or quality of the light reaching us from some object at a given moment, but about the object itself.*

– Ewald Hering

The difficulty of judging accurately the colours of objects, surfaces and materials becomes evident with changes in the ambient light, the viewing angle and distance as well as the contrast effect of adjacent colours. A house that looks neutral grey in direct sunlight may look bluish under an overcast sky and yellowish at sunset. The effects of distance, partly brought on by the physical effects of scattering and filtering of light by moisture and dust particles in the intervening air, are most dramatic in the bluish cast of distant mountains.

Despite these sometimes dramatic and often aesthetically pleasing transformations of colour, our vision is primarily wired to keep colours stable. This property or capability is called colour constancy and is probably common to most living creatures with colour vision. Colour constancy is reliable only up to a degree. It breaks down entirely under extreme conditions of lighting, such as very low levels of illuminance or strong chromatic distortion of lighting; and under an illuminant of poor colour rendering capacity (with discontinuous or distorted spectral distribution) object colours are often perceived as changed from ‘normal’. However, if one considers the enormous variations in both the intensity and the spectral distribution of both the incident and the reflected light of surfaces under various lighting conditions, it should not be possible to recognize the colours of any objects in the different illuminations of our daily lives.

The wavelength composition of ambient and reflected light changes continually around us. If our colour sense were attuned more to the spectral distributions of the light reflected from objects than to the colours of objects themselves, we would be at a loss in the street, at the fruit counter, everywhere. But fortunately we have the inexplicable ability to see the ‘real’ colour of the object – or as Helmholtz would say, to ‘discount the illuminant’. It is still not known, after about 150 years of investigation, how this is achieved and neither is it entirely clear how robust or accurate this ability is. The answer depends on the scale of accuracy that is used and context in which it is used.[85]

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[85] Obviously, a minute change in colour nuance that is evident in highly demanding colour discernment tasks can and will go entirely unnoticed in everyday situations.

Despite colour constancy, determining the exact colour even of nearby objects in so-called standard or normal conditions becomes a puzzle on closer reflection. Let us return to the case of the apples in *Seeing and Perceiving* (p. 36). Looking at one of the green apples on a white table in neutral daylight, which part of this round object as viewed from this angle should be considered as containing the 'real' colour of the object? (See also figure 21, p. 98). A naturalist painter would carefully record the shadows, half-shadows, cast shadows and highlights. The round object would be translated into either gradients of greens varying between slightly differing tints, shades and hues or perhaps, in a more Cézannesque tradition, into a pattern of flat areas of varying greens. The question is, which of these greens or which point in the continuums of the gradients represents the 'local' colour of the object? One will find several answers to this question in painting manuals, but very few of them venture to actually challenge the whole validity of this question.

It is somehow in our nature to treat material objects and surfaces as having, among all the other permanent properties, the unchanging property of object colour. Some philosophers will say that there is no such thing as object colour, that the world is in fact colourless; colours are an illusion and are at the most 'projected' on the world by the subject's brain or mind. Others say that colour is a property of, for example, the objects surface, a molecular structure that lends that surface a propensity to absorb and reflect light according to a particular profile. In between these two extremes there are various schools of thought that have attempted either a synthesis of these seemingly irresolvable theories or have tried to forge a path in completely new directions. Most of the theories of the third kind could be classified as relational. They emphasize the relative nature of perceived colour without completely abandoning the idea of colour as a property of 'the world outside'.

The question of whether the world is coloured at all in the sense of permanent properties, is of course a deeply philosophical one. Even more so is the question of whether we are able to gather any permanent truths about the world through our senses.[86] Leaving these huge epistemological questions aside, let us look at the problem of identifying colours from a more pragmatic viewpoint.

It is necessary sometimes to communicate very precise information about the colour of materials, objects or surfaces. For this purpose various methods and tools have been developed. First, there is measurement. The sample can be

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Thus for exacting colour perception tasks, such as the monitoring of printing jobs, even the *colour temperature* of the ambient light is specified in the viewing standard. In everyday visual tasks a change of up to ±1000 K will have no effect (after adaptation) on the perceived colours.

[86] For an overview of the ontological and epistemological problems concerning colour see Arstila 2005; see also *Natural Experiences and Physical Abstractions* in this volume.

measured either trichromatically with a colorimeter or, for an even more precise result, with a spectrophotometer. Both methods can instantly reveal colour differences that are hard to detect with the naked eye. Another possibility is to use a visual colour matching system such as Munsell or the NCS. In the case of measurement, the meter is placed over the target, a calibrated light flashes to illuminate the target according to very exact preconditions, and the reflected light is analyzed into components of spectral energy emission by the meter's microprocessor.[87]. The result is either a series of three numbers indicating the proportions of short, medium and long-wave radiation as detected by the human eye (colorimeter) or a series of some 40 or more numbers (depending on the precision required) indicating the presence of radiation at specific wavelength intervals, weighed against a theory of the spectral sensitivity of the human eye (spectrophotometer). In the case of visual colour matching the target is compared to a sample from a colour system's standardised collection. This too is ideally done under standardised viewing and lighting conditions.

These kinds of colour measurement provide highly accurate information about whether a colour is the same or different than a sample or another target. But does it tell us what is the 'real colour of the object'? If by colour we mean what humans see in the real world here and now and in context with other colours, the answer must be no. Measuring data are abstract series of numbers that have no connection to the *experience of colours in context*. Colour sample matching is a step closer to real *experience*, but it still misses out on the contextual issues in perception. As mentioned earlier, colorimetric and spectrophotometric measurement, as well the underlying CIE-system, were in fact never developed for precise colour identification, but for the purpose of attaining highly precise information about colour differences. Visual colour systems, such as the Munsell and NCS systems, on the other hand, were developed for the very purpose of providing a reliable system for identifying, comparing and communicating colours of objects and surfaces in the real world. Visual colour systems, with their collections of systemized and standardized colour samples, are no doubt the best way to go about this task.[88]

It was mentioned in the section on *vividness of colour* (p. 84–91) that colours can be examined either as non-related or related phenomena. An example of

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[87] This may seem like a fairly straightforward physics and maths task, but there are many hitches and obstacles to be avoided before anything near a 'correct' reading is obtained. Just consider the difference in appearance and reflectance pattern of a piece of red fabric and polished red metal. The same kinds of difficulty are involved in visual colour matching.

[88] Painting or high-quality colour photography can render the contextuality and hence the general impression or "atmosphere" of spaces and environments much better than any colour notation system, but this happens inevitably at the expense of accuracy in real colour, as explained in the above example of the green apple.

non-related colour is colour viewed through a reduction screen[89]. An even more extreme example of non-related colour would be a patch under the measuring head of a spectrophotometer: no ambient light is allowed to interfere and the measuring distance and angle are held constant. The 'viewer' is reduced to an abstract set of numerical data representing the 'standard observer'. Related colours, on the other hand, are the ones we normally experience in everyday situations. The problem with identifying and recording the latter is their very relatedness. Perceiving and experiencing the colour of a wall from a distance of, say, twenty meters is quite different from measuring it flush against the surface with the help of a colour sample. Our experiences of the world and its colours happen together with, in relation to and as a result of light, shadow, distance movement, space, the entire array of stimuli and our actions and reactions to them. Colour is always related to all of the above and to the individual's intentionality and mode of attention. (For a full treatment of the problems of identifying colours using a visual system such as the NCS see Fridell Anter 2000, p. 28-39).

In our everyday experience the world is not only coloured, but there is a permanence or constancy to the colours of objects and surfaces. This is in stark contradiction with the view of some philosophers that colours are an illusion and that the world, properly speaking, is indeed colourless. This view is just as baffling as is simplistic the physicalist view, that the colours of objects are the same thing as their spectral reflectances. In a third approach, which can be called relational, colours are real properties of the world, but they depend on relationships with the totality – on the surrounding colours, the illumination, viewing angle, distance and the observer. Both in the physicalist and in most of the relationist approaches, colours exist independent of the observer – the only difference being that in the physicalist view the 'real' colour can be determined by, for example, measuring and in the relationist view the real colour is what one sees in the particular conditions for the appearance of that colour.[90] Thus colour becomes very much contextual. There are many views among the relationists about the possibility or impossibility to measure or otherwise accurately determine the 'real' colour of objects, be it contextual or something else. Below is a short overview of some of the approaches.

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[89] At its simplest a reduction screen is a piece of grey or black paper with a hole in the middle through which colours can be viewed in isolation. In the more sophisticated set up there is a grey screen with an aperture placed in a neutral grey, evenly lit chamber that the observer sees as filling his entire field of vision. The chamber forms a kind of *Ganzfeld* in which the aperture colour floats, robbing it entirely of its contextuality.

[90] This is a very simplified account of the many philosophical schools of thought on ontology and epistemology of colour. For a full treatment of this problem see Arstila 2005.

Inherent, identity and nominal colour

There is an increasing need in industry, commerce and design for measuring and designating colours accurately. Both physical and visual measuring tools and methods have been developed to answer these needs. While these tools have attained a remarkably high degree of accuracy, one challenge remains: relating the measuring data or the visual sample of a colour to the human experience of that colour in real life or in a specific context of real life. This is no easy task and therefore it is important to differentiate between methods and tools that actually try to measure or define the 'real' colour from those that – at first hearing – may seem to do so, but in actual fact make no such claim. In the following is a comparison of some of these approaches and their terminologies as well as a suggested new concept that in our view helps to clarify the differences.

One attempt to determine visually the 'real' colour of physical objects was made by Anders Hård. In connection with his work on developing the NCS system he put forward the interesting concept of *inherent colour*. In The Swedish Institute of Standards edition SIS 1993, 2.6 the terms *inherent colour*, *body colour* and *local colour* have been offered as translations of the Swedish word and concept "egenfärg", which translates more literally into English as (an object's) "own colour". The word *inherent* is given in the Concise Oxford Dictionary as "existing in or *in* something esp. as permanent or characteristic attribute..." This definition echoes in Hård's defintion of *inherent colour*: "... the colour that one imagines as belonging to a surface or a material, irrespective of the prevailing light and viewing conditions". (Hård & Svedmyr 1995, p 215; quoted in Fridell Anter 2000, p 25). Hård´s idea that the inherent colour exists, but is never as such perceived is very similar to the concept of the NCS elementary colours, which also exist, but cannot be seen or depicted.

Hård´s definition does, however, also include a method for operationally determining the inherent colour, which obscures the notion of an imagined 'real' colour: "... it can be operationally determined e.g. through comparison with a standardised colour sample." (Ibid.) Here Hård in effect refers to the standardised viewing conditions under which the NCS samples are perceived to correspond with their codes.[91] Hård suggests that the colour perceived under these conditions is equal to the 'real' colour. This, however, excludes the complexity of visual interrelations that are always present in real life situations.

In her doctoral thesis *What colour is the red house?* Karin Fridell Anter has used Hård's term *inherent colour* in a meaning different to the above. Inher-

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[91] The standardized viewing conditions are defined under the Swedish standard Svensk standard SS 19104, NCS-färgprover - Betraknings- och mätvillkor samt toleranser

ent Colour in Fridell Anter refers to a reference point or 'helper concept', as she says, to which perceived colour changes of surfaces are compared. She does, however, use the same method as Hård for determining inherent colours, and this is why she chose to use the same term. But unlike Hård, Fridell Anter makes no claims about the inherent colour representing any 'real' colour in the meaning discussed in this article. (Fridell Anter 2000, pp 59–64). Fridell Anter suggested already in her thesis that the term *nominal colour* would be more fitting as a description of the concept behind *inherent colour*, and the authors of this volume suggest that *nominal colour* should replace this term in all similar uses of the concept. (See *Light and Colour*, p. 50 in this volume). The Dictionary gives *nominal* as "in name only; theoretical – – minimal in comparison with real worth or what is expected..." (Collins 2003). It connotes face value, and as in the world of money and finance, nominal value can have a precise meaning without direct reference to anything real. This is exactly the relation of nominal colour to 'real' experienced colours.

On a very fundamental level there are at least two modes of perceiving colour. One entails the relative, relational and variable nature of colour, how it changes and how the appearance of objects changes in relation to environmental factors and time. It helps to place objects and spatial features in relation to distance, time of day and season. This faculty is involved in our ability to enjoy and evaluate our relation to our surroundings, to atmosphere and the changes of natural conditions. The other level has to do with the material qualities of objects irrespective of these conditions and changes.

As both Karin Fridell Anter and Monica Billger point out in their theses, we are able to change our mode of attention and thus extract several levels of perception from the same set of colour stimuli. (Fridell Anter 2000, pp. 36–38; Billger 1999, pp. 10–12). Maurice Merleau-Ponty's concepts of the 'reflective attitude' and 'living perception', as discussed in his *Phenomenology of Perception* (Merleau-Ponty 2002) are fundamental to the work of both Fridell Anter and Billger. (See also *Natural Experience and physical Abstractions*, pp. 23–24 in this volume).

A wall may be seen as 'overlaid', 'covered' or 'coloured' by shadows or colours reflected from nearby surfaces. For the purpose of separating and analyzing these layers or variations in perceived colour Monica Billger has introduced in her thesis *Colour in Enclosed Space*, the concept of *identity colour*. Billger writes:

> *The perceived colour is analyzed on two levels of reflective attention, one that can be called holistic and one that is more detailed. With the former attitude to the room we perceive* ***the identity colour****, and with the latter* ***the colour variations****.* ***Identity colour*** *is defined as the main colour impression of surfaces or parts of a room that are perceived as*

> *uniformly coloured.* ***Colour variations*** *are defined as the local appearances of the identity colour. These differences might depend on light distribution, reflections from other surfaces and contrast effects.* (Billger 1999, p 11).

By changing our mode of attention we are able to, as it were, separate the various layers or spatial attributes of perception. This shifting of attention between local and global or between object, light and shadow, is a part of the normal working methods of any visual artist. The difference between the reflective attentions of an artist or visual researcher and those of the 'man in the street' is one of level of consciousness. According to Billger the perceived colour of material is subject to a certain elasticity, due to the aforementioned spatial factors. This elasticity is an important subject in Billger's study, where a method to ascertain and record the influence of different spectral distributions of ambient light is at the centre of attention. Neither *nominal colour* nor *identity colour* claims to represent 'the real colour of the object'. The important difference between the two concepts is that *nominal colour* can be measured by comparison to a colour sample, whereas *identity colour* cannot be measured or operationally determined in any way, only perceived through holistic reflective attention.

Figure 21*. The three apples as 'seen' by a camera.* (Photo: Harald Arnkil)

Constancy colour

If we accept that the world is coloured in some way, but dismiss the view of colour physicalism that objects' colours are the same thing as their spectral reflectance properties, we must look somewhere else for the 'real' colour (if, indeed, there is such a thing as 'real' colour). Hård's definition of *inherent colour*, "… the colour that one imagines as belonging to a surface or a material, irrespective of the prevailing light and viewing conditions", is reminiscent of Helmholtz's idea of colour constancy as a mechanism or ability in humans to discount the illuminant. (See footnote 94 below). Let us return once more to the problem of determining the 'real' colour of the green apple. It was said that the faithful translation, from a given point in space, of the apple's colours onto a flat surface would leave us with several contenders for the 'real', colour of the apple. Indeed, a digital photograph and its millions of pixels would leave us with myriads of possibilities, but on closer inspection this analogy is false. Firstly, we do not fixate objects or scenes at any one time from one viewpoint, but two. We have stereovision; our two eyes provide us with two slightly different sets of proximal stimuli that are compared and synthesized in the brain. Secondly, we do not (voluntarily and naturally) view the world even from these two viewpoints statically. Either the object moves, or we move our eyes or bodies in relation to it.[92] This action is central to the process of extracting relevant information about the world – also its colour.

We perceive through our stereovision and our movement in relation to the green apple that the apple is round; that the shadows and highlights are transient qualities and that there is a 'permanent' colour to the apple that exists independent of the variations of highlights, reflections or shadows involved in the totality. The transient qualities of shadow, half-shadow, highlight, etc., are the object's primary visual spatial attributes that exist in relation to light and motion. If these are subtracted from the spatial equation, what is left is what could be called the *constancy colour*. But there is no way we can perform the subtraction without destroying the real experience of the object's colour. This *constancy colour* is *apprehended in* the totality by our experience of space and movement, but can never be perceived directly. *Constancy colour* cannot be measured and has precision only within the limits of ecological necessity, that is: for the efficient and reliable identification of objects, scenes and spaces in relation to the subject's ecology.[93]

Colours are to us what they are in their context. They belong to objects, surfaces, spaces and situations, in which contexts they gain their functional and emotional significances. We need constants in order to make sense of the world. To achieve this our mind-body has adapted to the stream of contingencies, the ever-changing illuminations and angles of view, by developing a preference for the features that are typical, recurrent and identity-giving. One of these is the colour of objects irrespective of *changes* in illuminant or *changes* in viewing angle and distance. There are numerous theories of how this is achieved, but all of them admit a certain level of flexibility (sometimes referred to as inaccuracy) in colour constancy.[94] Looked at in another way, this

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[92] For a more elaborate discussion of the significance of motion in perception see Gibson 1986 and Noë 2004. See also my article *Seeing and Perceiving*, p 34 in this volume.

[93] See also *Natural Experience and Physical Abstractions*, pp 24 and 25 figure 2 in this volume.

[94] Helmholtz proposed that constancy of colours involved 'discounting the illuminant' by a process of 'unconscious inference'. This has been contested even in his own life-

flexibility is a natural part of the perception and the recognition of objects in varying contexts. We have adapted through evolution and through personal experience to this flexibility and are able to sense the constancy of colour in relation to these changes, to the totality. Perhaps it is not the *constancy colour* that is flexible (in the sense that *identity colour* is in Billger), but the correspondence of two levels: the colour we perceive through our reflective attitude and the apprehended, constant colour of living perception. We sense the one through the other within certain limits of flexibility.

Colours are manifested to us in the totality of space, objects, light and shadow, action and situation. Colours gain purpose and meaning through our ecology and intentionality, and their apparent constancy is subject to the constraints and flexibility of our ecology. We are attuned biologically to the recurring, typical and invariable aspects of our ecology, which give rise to the experience of the *constancy colours* in every moment. These colours are experienced as existing in the world. They are manifested with the same immediacy and naturalness as position or constant size.[95] They are not perceived directly, but sensed or apprehended, through *living perception*, in the totality of seeing. All the manifestations of colour that can be either perceived or experienced by various modes of attention are the result of our attention plus our intentionality interacting with the world. They are real in this context only. Therefore a contextual colour that is reduced to a set of numerical data, a spot in the aperture of a reduction screen or a reference to a sample in a visual colour system, is no longer that colour, but its mere abstraction, a ghost of the live experience.

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time. (See Evans 1948, p 170). Hering proposed that memory played a central role in constancy. Both views have been seriously challenged by the experiments and the subsequent Retinex-theory of Edwin Land. Today's constancy studies, continuing partly on the lines of Land and making use of the advances in computer science, involve computational theories of spatial perception. The aim of these theories is to arrive at a mathematical model of constancy that could describe 'automatic' nature of colour constancy.

[95] See *Seeing and Perceiving*, p. 37 in this volume.

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About the Authors

Harald Arnkil is an artist, educator and colour researcher. He was trained in fine art (painting) in the Finnish Academy of Fine Art, Helsinki, Finland, graduating in 1979. Since 1990 Arnkil has worked as Lecturer in Colour Studies at the Aalto University School of Arts, Design and Architecture. Besides teaching, he is presently pursuing doctoral studies and research in the field of colour.

Karin Fridell Anter, architect SAR/MSA and PhD architecture, is a researcher specializing in colour in the built environment. She is an associate professor at the Royal Institute of Technology and a researcher at University College of Arts, Crafts and Design, both in Stockholm. She has written several books on colour in architecture and numerous articles in Swedish and international journals. During 2010–11 she led the Nordic research project *SYN-TES: Human colour and light synthesis - Towards a coherent field of knowledge*.

C.L. Hardin is Professor of Philosophy Emeritus at Syracuse University, USA. He is the author of *Color for Philosophers: Unweaving the Rainbow* (1986) and co-editor of *Color Categories in Thought and Language* (1997). He takes colour to be a test case for theories about how the qualities of everyday experience manage to find a place in a quantitative universe consisting of matter and energy.

Ulf Klarén is a researcher, writer and lecturer on perception, colour and light. Until his retirement in 2011, he was Associate Professor and head of The Perception Studio at Konstfack, University College of Arts, Crafts and Design in Stockholm, Sweden. Ulf Klarén's publications include a textbook on colour and several scientific reports and contributions to anthologies. During 2010 - 2011 he was assistant project leader of the Nordic interdisciplinary research project *SYN-TES: Human colour and light synthesis –Towards a coherent field of knowledge*.

Further Reading

Arnkil, Harald (due in 2012). *Colours in the Visual World.* Aalto University School of Arts, Design and Architecture, Helsinki. Originally published in Finnish as *Värit havaintojen maailmassa*, this handbook for artists, designers and architects is due to appear in a revised English-language edition in October 2012. The emphasis is on contemporary theories of perception and their relation to the aesthetic and functional and application of colour in art, design and architecture. Each chapter ends with a set of study assignments.

Berns, Roy S. (2000). *Billmeyer and Saltzman's Principles of Color Technology*, 3rd Edition. Wiley-Interscience. This a completely revised third edition of Fred Billmeyer's and Max Saltzman's a classic work that originally appeared in 1967. It covers just about every imaginable aspect of colour technology, combining the clarity and ease of use of earlier editions with two decades of advancement in colour theory and technology. Roy Berns, a former student of Billmeyer and Saltzman is Professor of imaging science at Rochester Institute of Technology.

Billger, Monica (1999). *Colour in Enclosed Space: Observation of Colour Phenomena and Development of Methods for Identification of Colour Appearance in Rooms.* Doctoral dissertation, Department of Building Design – Theoretical and Applied Aesthetics, School of Architecture, Chalmers University of Technology, Göteborg, Sweden. Monica Billger's dissertation presents a new method for assessing the perceived differences of colour in interiors illuminated respectively by either daylight or different types of artificial lights. The effects of simultaneous contrast and reflections in space are examined and the book includes a discussion of what colour is as a physical property and as a perceptual quality.

Fridell Anter, Karin (2000), *What Colour is the Red House? – Perceived colour of painted facades.* Doctoral dissertation, Kungliga Tekniska Högskolan, Stockholm. Involving a thorough theoretical discussion of the problem, and analysing the results of over 3600 observations in the open air, this research investigates the way colours of painted facades change visually in relation to light, surroundings and distance. The results reveal clear and interesting patterns.

Gibson, James J. (1986). *The Ecological Approach to Visual Perception.* Lawrence Erlbaum Associates, New Jersey. Gibson revised his earlier theories on perception in this book, published just before his death. The texts are a radical departure from the pervasive theories of visual perception in the 1980s. They are still as fresh as when Gibson wrote them and many of his ideas are being followed up today.

Hardin, C. L. (1988), *Color for philosophers: unweaving the rainbow.* Extenden edition. Hackett Publishing Company, Indianapolis. A thorough examination of the physical and neurobiological facts behind colour phenomena and colour appearances.

Hardin wrote the book for philosophers. As he remarks, they are fond of referring to colour as an illustration about epistemological and ontological truths, without really knowing much about the physical and biological reality of colour. An entertaining lesson in scientific integrity for us all. The book won the 1986 Johnsonian Prize for Philosophy.

Katz, David (2002). ***The World of Colour.*** **Routledge, London.** Katz's classic work, first published in German as *Der Aufbau der Farbwelt* in 1910, offers a phenomenological overview of colour as it appears to us in everyday situations. Katz's division of colour phenomena into eight 'modes of appearance' are a corner stone of perceptual colour research.

Liljefors, A. (2005). ***Lighting – Visually and Physically.*** **Revised edition. KTH Lighting Laboratory, Stockholm.** Liljefors' little textbook for students of architecture and lighting design provides an important discussion and analysis of the differences between visual and physical approaches to light, and presents a number of concepts for visual analysis of light in its spatial context.

Merleau-Ponty M (1962/2002) ***The Phenomenology of Perception.*** **Routledge, London and New York.** Merleau-Ponty claims that perception is what gives us access to the world and that the perceived world establishes the development of the human and social world, which is implicitly present in all perceptions. In this perspective he discusses the role of the human senses. *The Phenomenology of Perception* is Merleau-Ponty's most famous work.

Noë, Alva (2004). ***Action in Perception.*** **MIT Press, Cambridge, MA and London, UK.** Alva Noë's philosophical essay builds on Gibson's theory of the ecology of perception. Noë extends the ideas further to include action of the perceiver as a central concept in the formation of visual perception. Furthermore, he challenges the traditional idea that our thoughts and perceptions happen in our brain only.

Valberg, A. (2005). ***Light Vision Color.*** **John Wiley & Sons, Chichester.** Arne Valberg in *Light Vision Color* takes an interdisciplinary approach to the visual system and combines fundamentals behind the visual sciences with recent developments from neuroscience, biophysics, psychophysics and sensory psychology. He deals with the basic perception of colour, light and space and discusses perceptual experience and relevant brain processes. He also explores photometry, contrast sensitivity and the relations between light, colour and colorimetry.

SYN-TES. This book is the result of a wider research project that involved other aspects of colour and light and their spatial interaction. Reports, articles and conference papers from the SYN-TES project (mostly in Swedish, but some in English) can be downloaded from www.konstfack.se/SYN-TES.

Index

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Are coloured shadows 'real colours'? What is the difference between lightness and brightness? Can colour experiences be measured? The texts in this book are the result of a sub-project of 'SYN-TES: Human colour and light synthesis – towards a coherent field of knowledge', a research project involving five Nordic universities and several Swedish companies and institutions. The project was carried out in Konstfack, Stockholm during 2010–11. Colour and light play an important role in the fields of art, design and communication. In the built environment they influence our experiences and feelings, our comfort or discomfort and our physiological wellbeing. A profound understanding of the interaction between colour, light and human beings calls for an interdisciplinary approach, involving several highly specialized fields of art science and technology. This book delves into the often confusing terminology of colour and light, aiming at clarifying their different usages and furthering understanding between researcher and practitioners.

SYN-TES
COLOUR AND LIGHT

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