THE COLOURS OF THE WORLD

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1. Introduction

From the standpoint of any individual who uses his eyes to see the environment, the retinal image should reveal the objects out in front of him in their proper qualities and relations. However, the retinal image is seriously defective as a direct representation of the environment because there are no objects in the image, but juxtaposed patches of colour. The image, like any other picture, is in two dimensions, the environment in three. The image of an object changes in size and shape as the observer views it from different distances and angles, while the object itself is unchanging. In colour, too, the image changes with the illumination, while the object retains its own colour. Interest in this problem dates from themid-1800s, particularly fromHelmholtz and Hering's unrelenting combat and the further developments of both positions. For example, G. E. Müller articulated many ideas on this topic.

2. Scientific background

Before the 1850s, the period that saw a revolution in the theory of colour vision, different traditions had sprung up producing incompatible results. The discovery in 1665 by I. Newton that light from the sun could be bent to varying degrees by a prism so as to produce a spectrum of colours ranging from red (least bent rays) to violet (most bent rays) (*degree of refrangibility*) provided the basis for the rejection of Aristotle's view that colours came from objects and led to its being replaced with the view that colour was a property of light. Thus, in various experiments with prisms and lenses, which separated and recombined light, Newtonfound that white light seemed to be produced by mixing light of different colours, at least four colours. Newton also assumed that mixing coloured pigments yielded the same results as mixing light of the same colours (Newton, 1671, 1704).

Fundamentally based on the Newtonian experimental work, further theories were developed above all in the German context. According to Kremer (1993), five traditions of colour mixing can be individualized. The first, referred to painters, dealt with pigments only and identified three primary colours, usually red, yellow, and blue, from the mixture of which all other colours derived (with white and black pigments added to vary saturation).

A second tradition used the colour wheel to mix coloured light. The device was a disc with different sectors painted in different colours. By spinning the wheel, mixed colours could be obtained, except white light.

The most valid representative of the third tradition,the Germanmathematician and physicist Christian Ernst Wünsch,became best known for his colour theory published in 1792 (Wünsch, 1792). Using prisms and lenses, he demonstrated that mixing pigments and mixing lights did not yield thesame results, thus liberating himself from the dictate of the Newtonian seven-colour theory. In addition, he produced white light using fewer "ingredients", that is, the combinations of four, three, or only two coloured lights, such as violet and greenish yellow, or red and blue. His assumption that all colours could be yielded on the basis of only three primary colours (*einfacheLichfarben*), red, yellow and violet, and this "was no longer a hypothesis, but a demonstrated statement" (Wünsch, 1792, p. 75), was criticized by Johann Wolfgang von Goethe, who wrote in *Xenien*, a collection of short satirical poems: “Yellow-red and green make yellow, green and violet-blue make blue! Pickle salad does make vinegar, so is really must be true” (Goethe & Schiller, 1796, Xenion 175).

The fourth tradition was more physiologically focused,being interested in the way the eye and the brain contributed to generate colour sensation rather than in thenature of light. The experiments concerned light of different colours entering different eyes (for example, by looking at a white field through a coloured glass usingdifferent colours for the left and the right eye). The results were uncertain:the two colours were often seen separately, with now one colourdominating and then the other. Mixed colours were rarely observed, and only under some circumstances.

The fifth tradition dealt also with physiology, but at a more theoretical level. According to Descartes, Newton, and others, the eye worked via vibrations in the retina caused by light. Thefrequencies of the vibrations should correspond to the light of different colours. The combination of the different vibrations caused by a light beam incorporating multiple colours was supposed to happen in the brain. On this basis, Karl Scherffer, considered by his contemporaries one of the best mathematicians and physicists of the second half of the 18th century, asserted that different retinal elementsmight be associated with these different vibrations (Scherffer, 1761). Then, two works on colour vision appeared in 1777 and 1786 (Palmer, 1777, 1786). Their author, the English glass manufacturerGeorge Palmer, known also as Giros von Gentilly, using prims in his experiments, demonstrated that every ray of light contained different proportions of three colours, red, yellow, and blue:objects appeared coloured by the absorption of the rays relating to their colour and by their reflection of the other rays. White indicated the rejection of light, while black occurred when the three primary colours absorbed the rays of other colours, thus creating an intensity that exceeded the proportion of the colour. Furthermore, Palmer hypothesized the existence of three retinal elements, each of which was set in motion by only one type of ray. Accordingly, mixed light, such as purple, green and orange,stimulated more than one of the retinal elements, generating the sensation of a mixed colour, with equal stimulation of the three elements corresponding to white.

Palmer’s ideas on colour vision, which agreed with the viewpoint of an astronomer at Göttingen University, Tobias Mayer, who had constructed a three-dimensional colour mixture space based on red, yellow and blue as primaries (Mayer, 1758), were well known in the circles of Göttingen, just like its related thought that colour blindness was caused by a missing or a defect receptor type.Indeed, they were discussed and reviewed in 1781 in Lichtenberg’s Magazine, published by Georg Christoph Lichtenberg’s brother, Ludwig Christian Lichtenberg (Lichtenberg & Voigt, 1781).

3. Colour vision in the first half of 19th century: Young and Herbart

Palmer’s trichromatic theory of colour vision was resumed – although in an unaware way – by the physicist Thomas Young, who was a medical student at Göttingen University in 1795-96 and was acquainted with G.C. Lichtenberg, interested in physiological optics and colour vision. Basing himself on Newton’s theory, on 12th November 1801 he affirmed in *Hypothesis II* of his *Bakerian Lecture*:

> I use the word “undulation”, in preference to “vibration”, because “vibration” is generally understood as implying a motion which is continued alternately backwards and forwards, by a combination of the momentum of the body with an accelerating force, and which is naturally more or less permanent; but an “undulation” is supposed to consist of a vibratory motion, transmitted successively through different parts of a medium, without any tendency in each particle to continue its motion (Young, 1802, p. 16).

Young carried out an experiment that allowed light to pass through two pinholes set close together on a screen where he observed that the beams spread out, or diffracted, and overlapped. In areas where the light beams overlapped, bands of brightness alternated with bands of darkness. This phenomenon was called *interference* and Young compared it to waves in water, where the crests meet and combine to make bigger waves and troughs meet and cancel each other out. In 1817, he concluded that they propagate as transverse waves, not longitudinal waves as he originally proposed.

However, the undulatory theory of light instead of the Newtonian corpuscular opinion was the final point of previous research on the visual system and the starting point of research on chromatic vision. In the same year of the Lecture Young showed that astigmatism was due to irregular curvature of the cornea (Young, 1801) providing its first measurement; this discovery closed the investigations carried out in the 1790s on vision and, more precisely, on the process of focusing of the eye (accommodation), that was achieved by a change of shape in the lens of the eye, the lens being composed of muscle fibers (Young, 1793). Then, in 1800 he talked about a possible analogy between the propagation of the sound waves and of the light ones (Young, 1800). It was in this context that Young reread the Newtonian principle according to which colour sensation depended upon the wavelength of the light entering the eye. For him, "as it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect unison with every possible undulation, it becomes necessary to suppose the number limited, for instance, to the three principal colours, red, yellow, and blue" (Young, 1802, p. 21).

Consequently, he proposed a trichromatic theory of colour according to which colours result from the mixture of the three primary colours (red, yellow, and blue). As a result of learning from his friend, William Hyde Wollaston, that red light mixed with green light gave a yellow sensation, Young changed the primary colours to red, green, and violet, following their respective correspondence to a long wavelength (the first), intermediate wavelength (the second), or short wavelength (the third). In Young's opinion, such a trichromatism would not have been determined by light properties, but by physiological peculiarities of the human eye; more precisely, by the different tension degree of three types of receptors for daytime or photopic vision connected to primary colours. Therefore, any other colour would have resulted from the simultaneous stimulation of the three types of receptors (Young, 1802).

Young's hypothesis, afterwards justified by the discovery of retinal cones, gave rise to many investigations that aimed at quantifying the constituents of colour mixtures. However, his model was – as Hermann von Helmholtz suggested – "nothing more than a further extension of Johannes Müller's law of special sensation" (Helmholtz, 1962, p. 134), according to which the quality of an experience was related to some specific quality of the energy in the nerves. In fact, in 1826 Müller stated the principle that the kind of sensation following stimulation of a sensory nerve did not depend on the mode of stimulation but upon the nature of the sense-organ (Müller, 1826). Thus, light, pressure, or mechanical stimulation acting on the retina and optic nerve invariably produced luminous impressions. This he termed the law of *specific nerve energies*, better clarified in his 1833-1840 *Handbuch der Physiologie des Menschen für Vorlesungen*. Therefore, the visual experience from light shining into the eye, or from a poke in the eye, arose from some special quality of the energy carried by optic nerve. "(S)ensation is not the conduction of a quality or state of external bodies to consciousness, but the conduction of a quality or state of our nerves to consciousness, excited by an external cause", wrote Müller in 1833 (Müller, 1833, Bd. I, p. 583). It was not by chance that Helmholtz observed: "the perception of each of the three fundamental colours arises from the excitation only one kind of sensitive fibres, while the two others are at rest or at any rate are but feebly excited" (Helmholtz, 1962, p. 280).

In this context, it is worth remembering Herbart's attempt to construct sensory space (Herbart, 1824-25). In attempting to rework Kant's idea that space and time were given in intuition in which things were shown to individuals as appearances.Herbart, referring to Locke and the associationists, assumedthat psychological space could be constructed from simple sensations empirically. Only a requirement of this construction was that it should possess all the characteristics of being immediately given (Herbart, 1825). To this purpose, three steps were significant: 1. the strength of associations between different perceptions should be distinguishable; 2) the associations between perceptions repeated in conjunction should be represented as flowing from one another with the strength of a mechanically determined necessity after achieving a particular temporal threshold of association; 3) once this degree of association between perceptions had been achieved, a function represented the path linking them. The function should be retained in memory. When activated by the proper cue, the sequence of steps represented in the functionrun through rapidly, approaching the limits of an immediate perception. After the appropriate learning period, this mechanism served to the foundation of the perception of visual space as immediately given.

The supposed existence of simple, pure sensations, likepure tones or principalcolours, can be considered the starting point for Herbart's psychophysics. In orderto be perceived, sensations needed a contrasting one with sensible difference between them. At the level of perception, there was a psychological process of comparison andmeasurement constantly reproduced. Consequently, staring at a patch of blue with immobile eyes would have led to the gradual disappearance of the colour (Herbart, 1825). Therefore, sensationswere forces (Herbart, 1824)which, resulting from the relation between an external agent and the physiological apparatus interacting with it, counterbalanced one another in varying degrees of intensity.

The new interpretation of sensibility foresaw a set of descriptive relations forming a mathematical calculus, which were called*Reihenformen*: their aim was to express the relationsbetween sensations in terms of their degree of intensity, quantity and quality. Such a logical calculus, which could be applied to each sensory modality, permitted to combine sensations of different modalities into acommon, unified experience. The same dynamical laws governed theconstruction of each modality of perception and the synthesis of perceptions into higher ordered unities, defined as*complexions*. In the case of a single colour, such as blue, it could vary continuously in intensityand saturation. Without working out the details quantitatively, Herbart assumed that such a manifold ofsensations could be represented as a linear series of sensations of increasing intensity.As for colour, he assumed that any colour in the visual spectrum could be constructed from three primarycolours, red, blue, yellow, each of them in the visual field was represented as a point on a colour surface, with one, blue for instance, at the centre of coordinates, and units ofred and yellow as the abscissas and ordinates.

4. The trichromatic theory of colour vision: Hermann von Helmholtz

In the second volume of his famous treatise on optics Hermann von Helmholtz, one of the most important researchers in physiological optics, wrote:

> Colours are mainly important for us as properties of objects and as a means of identifying objects. In visual observation, we constantly aim to reach a judgement on the object colours and to eliminate differences of illumination. […] So, we clearly distinguish between a white sheet of paper in a weak illumination and a grey sheet in strong illumination […]. We have abundant opportunity to examine the same object colours in full sunlight, in the blue light from the clear sky, the weak white light of the clouded sky, and the reddish yellow light of the sinking sun or of candlelight. Not to mention the coloured reflexion from surrounding objects. […] Seeing the same object under these different illuminations, we learn to get a correct idea of the object colours in spite of differences of illumination. That is, we learn to judge how such an object would look in white light, and since our interest lies entirely in the constant object colour, we become unconscious of the sensations on which our judgement rests (Helmholtz, 1867, p. 408).

As for the term *unconscious*, in the first half of the nineteenth century philosophers and physiologists had begun to hypothesize that even representations and ideas could be unconscious.

According to Herbart, for instance, “one of the older representations can be suppressed entirely from consciousness for a while by a new one that is much weaker. However, its striving is not to be regarded as ineffective […] rather, it works with its whole might against the representations found in consciousness” (Herbart, 1816, pp. 106-107). On Lotze’s account, even conscious thoughts, including voluntary acts of will, incorporated the physical actions of a substance that took place outside the field of consciousness (Lotze, 1852, §109, pp. 125-126). In Helmholtzian terms:

> The mental operations through which we come to the judgment that a particular object in a particular state in a particular place outside us is present, are in general not conscious operations, but unconscious. In their results, they are similar to an inference, insofar as we achieve from the observed effect on our senses the representation of a cause of this effect, whereas, in fact, we can only perceive directly the nerve stimulations, that is, the effects, never the external objects (Helmholtz, 1867, p. 430)

Therefore, unconscious inferences were judgments that external objects bearing certain properties were present and were the causes of sensations. The theme of colour vision thus fell within Helmholtz’s more general arguments against nativism, and his commitment to analyse sensation and perception using the techniques of natural science (Lenoir, 1993).

Anyway, Helmholtz’s interest in colour began in the early winter 1852-53, when he was preparing a lecture on Wolfgang von Goethe as a scientist (Barnouw, 1987). The lecture, entitled *ÜberGoethesnaturwissenschaftlicheArbeiten* (Helmholtz, 1853), was delivered on 18 January 1853 before the German Society of Königsberg. His analyse concerned Goethian views on botany and comparative anatomy, on the one hand, and optics and the theory of colour, on the other. However, the appreciation of Goethe’swork expressed in the first part of the lecture changed in tone when he turned to examine Goethe’s optical theories (Goethe, 1810).During the previous two years, Helmholtz had done much work on optics and colour research, also reviewing the work of many others on the topic. In addition, every winter semester spent at the University of Königsberg he lectured on colour as part of his physiology course. Among the criticized authors, there was the English physicist David Brewster.In the 1820s and 1830s Brewster was responsible for a theory according to which each portion of the spectrum was composed of threetypes of light,i.e., the primary colours of red, yellow, and blue, which in turn could generate white. This contrary to Newton’s experiment with the prism, which had showed that there were seven spectral colours decomposable from white light.With the help of some of his colleagues in Königsberg, such as the physicist Ludwig Moser who was working on the effects of colour intensity, the so-called Purkinje effect, Helmholtz refused Brewster’s triple-spectrum theory, thus defending the Newtonian observations (Helmholtz, 1852a, 1852b).

In his habilitation essay as ordinary professor Helmholtz reviewed earlier interpretations of colours, concluding that coloured lights or pigments could be mixed by adding or subtracting, that is by illuminating rays of light on the same retinal spot or by combining different pigments.

Starting from this perspective and in line with Young, Helmholtz realized that the correspondence between the various wavelengths of light and colour perception was achieved within organism; it was not the rays of light that were coloured and produced that various colour perception. Therefore, he proposed the existence of three types (violet, green, and red) of retinal nerve fibers or receptors. Each fiber class was differentially sensitive to wavelengths of light ranging from approximately 400 nm to 700 nm, with the violet-coding fiber maximally sensitive to the short wavelengths, the green-coding fibers maximally sensitive to the middle wavelengths, and the red-coding fibers maximally sensitive to the long wavelengths. Consequently, three mechanisms were sufficient to account for colour perception.

Within the tri-receptor model, different colour sensations were the outcome of the relative strengths, which with the three fiber types were activated by physical light. Since these fibers were believed to have a direct connection to the brain, stimulation of one or a combination of these fibers generated the various psychological experiences of colour. In particular, equal activation of all three fiber types produced the sensation of whiteness. The blackness sensation occurred when none of the fiberswere stimulated by light.

However, Helmholtz went beyond Young's theory in the introduction of three variables to characterise a colour, hue, saturation, and brightness, whereas Young showed that any hue could be produced by mixing no more than two coloured lights: every colour in the spectrum could be replicated by a mixture of just two of the *primaries*, red, green, and blue. In this way, Helmholtz was the first to demonstrate that the colours, which Newton had seen in his spectrum,were different from colours applied to a white base using pigments. The spectral colours shone more intensely and possessed greater saturation. They were mixed additively, whereas pigments were mixed subtractively. In each case, a different set of rules governed their combination.

5. The four-colour theory: Ewald Hering

If Helmholtz's theory was guided by the physics of light, Ewald Hering was strongly influenced by the phenomenological experience of colour and thus, more concerned with their introspective aspects (Baumann, 1992; Sinatra, 1996; Turner, 1993). Persuaded that uncoloured sensations did not derive from coloured ones, he started from the Helmholtzian trichromatic theory, observing that it could not account for why certain pairs of colours were not perceived together at the same place and at the same time, e.g. reddish greens or yellowish blues (Hering, 1878, pp. 9-23): when the different hues were arranged in a circle, there was a great number of bichromatic mixtures, but none of them could be described as yellow-blue or red-green. Similarly, the theory could not explain the phenomenon of *afterimages*, i.e., negative-coloured images seen after extended viewing of a coloured object (e.g., red after green, or yellow after blue).

Arguing (Hering, 1888) that this mutual exclusivity between yellow-blue and between red-green originated in neuro-physiologically based chemical processes of the visual system (Massof, 1985), Hering interpreted this perceptual constraint as evidence for an antagonistic relation between the chemical processes mediating yellow and blue, and red and green, which he called *Urfarben*, that is, primordial colours, remembering Goethe's *Urphänomen* and his *Urpflanze*, his primordial plant.Consequently, he postulated two chromatic opponent processes (red-green and blue-yellow) (*Gegenfarben*), each of them having an excitatory and inhibitory component, referred as assimilation (anabolism) and dissimilation (catabolism). This require (J. P. C. Southall, Trans. and Ed.). New York, NY: Dover Publication d that each opponent process received inputs from more than one class of cone, and that some were excitatory, others inhibitory. The antagonistic processes struggled to maintain a state of equilibrium in the visual system, although under normal viewing conditions there was usually an imbalance. The vast array of chromatic perceptions, therefore, arose from the degree of imbalance within the opponent processes.

In addition, Hering proposed a third, achromatic channel: it was a white-black chemical process and viewed as the oldest of the three systems, partly because it was the most stable. This inference was based on the reciprocal relation observed between black and white under conditions of spatial and temporal contrast, but not on mutual exclusivity, since there was a continuous transition from white to black passing through the various shades of grey. Moreover, against the generally accepted opinion that black was the absence of retinal stimulation, Hering argued that there was a considerable degree of brightness remaining with the total exclusion of light from the eye. He called this "mean grey" or "middle grey". True black, he maintained, occurred only under conditions of simultaneous or successive contrast; black demanded external stimulation, not its absence.

Hence, if the intensity of a white annular light increased around a centre stimulus, dissimilation of the affected areas of the visual field would increase and at the same time this activity would induce assimilation into the surrounding areas of the visual field. If this surround induced more assimilation into the centre such that it cancelled or inhibited the dissimilation already present in that visual area, the centre would appear black. Under conditions of temporal contrast, a white inducing stimulus would generate dissimilation in the visual area excited by it. After termination of the white stimulus, the process of assimilation would dominate over dissimilation in an attempt to restore the system to a state of equilibrium. Before equilibrium would be reached, a black afterimage would be perceived.

6.The developments of Helmholtz – Hering controversy

One of Helmholtz's friends,the Dutch physiologist andophthalmologist FranciscusCornelisDonders, had no doubts about the trichromatic theory, while he was taking knowledge of Hering's theory of four fundamental colours. Thus, he looked for their physiological correlation in the visual cortex of the brain. In 1881 a chemical model emerged, according to which there were molecules in the cortex generating white on complete dissociation, and the four main colours and the mixed colours between them on partial dissociation (Donders, 1881). As the three fundamental processes in the retina had multiple connections with the terminal chemical processes in the visual cortex, the primarycolours of the trichromatic theory did not need to be identical to the main colours of the chemical-physical system.

On the contrary, Georg Elias Müller was an adherent of Hering's theory:they knew each other well. In a letter of April 1928 to Edwin Boring in answer to a question about his early formative years, Müller the former wrote: "With quick determination I now turn myself energetically toward natural science, and bury myself in Helmholtz's *PhysiologischeOptik* and the like" (Boring*et al.*, 1935, p. 345). This "burial" led to his involvement in a third field of interest, the psychology of vision. In fact, best-known for his research on memory, Müller also developed a theory that attempted to go beyond the empirism*versus* nativism debate by improving on Hering's idea of colour vision. Indeed, Hering's concept of middle grey was improved by Müller, who was one of the first researchers to distinguish between retinal and cortical activities in the visual field. In 1896-1897 he published *ZurPsychophysik der Gesichtsempfindungen*, in which he adopted Hering's theory of the three reversible photochemical substances (he held that the processes were chemical rather than metabolic, as Hering had thought) and added his concept of cortical grey as the zero-point from which all colour sensations diverge (Müller, 1896-97).He suggested the presence of three reversible or antagonistic chemical reactions in the retina: white-black, red-green, and blue-yellow. If light produced a white reaction in the retina, an opposing reaction neutralized the white reaction and the retina returned to a state of equilibrium. The reverse occurred during a black reaction. Similar reciprocal processes were assumed to exist for the red-green and blue-yellow pairs.

According to Müller, in the cortex existed an endogenous white process and an endogenous black process that were also antagonistic with each other and dominated over the weaker chromatic excitations. The active retinal processes determined which of the cortical processes were in an excited state. If a white reaction dominated the retina, the white-black balance was disturbed, causing the white excitation in the cortex to increase and signal the perception of whiteness. Similarly, if a black reaction prevailed in the retina, it increased the black excitation in the cortex to signal the sensation of blackness. Lastly, if the black and white reactions in the retina were in equilibrium, *Augengrau*, subjective gray,was perceived.

Ten years after his retirement, namely in 1930, Müller published 1300 pages of supplementary volumes to the *ZeitschriftfürPsychologie* (Müller, 1930). The volumes, characterized by Judd (1951, p. 836) as the best articulated of the two-stage colour theories, are still almost unknown by the scientific community. There is still much work to be done.

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