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1 Introduction

1.1 ROOTS OF THE DUPLICITY THEORY OF VISION: ANCIENT GREEKS

The duplicity theory is the most basic and comprehensive theory within vision research. Yet, there has been no attempt to describe its developmental history. In the present work, therefore, our aim has been to throw some light on this dark area in the history of science. As will be seen, the duplicity theory is not an old, static, antiquated theory dating back to Schultze's (1866) original formulation of the theory, as is generally held, but is a living body that expands and deepens as new knowledge of the rod and cone systems is obtained.

The beginning of the scientific study of vision may be traced back to the Ancient Greeks. However, due to an almost complete lack of knowledge about optics and sensory information processing at that time, the Greeks made two serious mistakes in their functional interpretation of the visual system. Thus, they generally held that (1) the crystalline lens of the eye was the most important organ of vision, being the actual sense organ, and (2) visual perception depended in a fundamental way on some sort of 'rays' that emanated *from* the lens *toward* the objects of the environment.

Both assumptions were accepted and adhered to in one form or other by many of the leading Ancient Greek philosophers and research workers. The most important among them, because of his strong and long-lasting influence on science in Western Europe, was Galen – also named Galenos (about AD 130–200). He presumed that visual perception depended on a 'pneuma' or 'visual spirit' that originated in the brain and circulated through the hollow optic nerve filling the crystalline lens in the eye. Thereby, it could confer the ability of perception to the lens.

The question of how the lens acquired information about the environment was answered, in accord with the generally held 'lantern' or 'emission' theory, by the assumption that the lens emitted some sort of 'rays' in the form of a cone that touched objects in the outer world. (The common observation that the eyes of animals may appear luminous like lanterns when seen in night vision supported the theory.)

The remaining question of how individuals obtained information about the environment from these 'rays' could be answered in accord with the 'likeness' principle. This principle presupposed that each object in the world could be characterized by a particular composition of the four basic elements ('earth', 'water', 'air' and 'fire'), which the Ancient Greeks believed formed the substance of the world, and that the 'water' element of the emitted outgoing 'rays' could gain knowledge about the 'water' elements of objects, the 'earth' element knowledge about the 'earth' elements, and so on, giving the individual complete knowledge of the perceived objects.

However, not all leading authorities accepted this generally held information theory. Aristotle (384–322 BC), for instance, rejected the 'lantern' theory on the well-known fact that humans do not see anything in complete darkness. In contrast to the 'lantern' theory he considered light to be an activity or a movement of an ether-like substance originating in luminous or illuminated bodies and transmitted through the transparent media of the environment to the eyes.

Democritus (460–370 BC) also rejected the 'lantern' theory and suggested that light consisted of particles that were transmitted *from* the objects *towards* the eye. More important, he advanced the seminal suggestion that the *perception* of an object and the 'real' object may differ considerably, since both the environment between the object and the body, and the sense organ itself, may change the messenger particles significantly. Colour, for instance, was not considered as part of 'real' objects, which he thought were composed of 'atoms'.

Such hypotheses and theories that deviated from the mainstream were, however, largely ignored or treated with ridicule until as late as the seventeenth century, when Kepler, Huygens, Hooke and Newton entered the stage. The two serious errors had then been dominating thinking for about two millennia (see Polyak (1948) for an excellent review of the ancient conception of the structure and function of the visual organ, and also Goethe's (1810) historical review).

Nevertheless, the Ancient Greeks, although led far astray in their thinking about visual information processing, may be seen as the originators of the scientific study of vision. Indeed, even the roots of the duplicity theory may be found in their research. Thus, the Ancient Greeks discovered that the ability to see by day and night differs markedly between animal species. Empedocles (fifth century BC) attempted to explain this difference by suggesting that it was due to differences in the relative amount of 'fire' and 'water' in the inner eye. A relatively small amount of 'fire' or 'water' produced poor night and day vision, respectively (Goethe, 1810, pp. 524–525, and p. 530). Similarly, Theophrastus (the successor of Aristotle at the Lyceum at Athens) suggested that nocturnal animals may see much better than humans by night due to more of the 'fire' element in their eyes. Interestingly, he also suggested that 'fire' from the sun may drastically reduce the amount of 'fire' in the eye and, thereby, reduce the ability to see by night (Hanssen, 2000).

1.2 FURTHER DEVELOPMENT OF THE DUPLICITY THEORY

Further progress in our understanding of the differences in visual processing in day and night vision had to wait for about 2000 years. Thus, the first modern breakthrough was accomplished by Schultze (1866). Based on comparative histological as well as psychophysical evidence, he suggested that (1) night and day vision were mediated, respectively, by rod and cone receptors in the retina, (2) the cones mediated both achromatic and chromatic sensations, while the rods mediated achromatic vision only, (3) the rod and cone systems functioned independently of each other, and (4) the cones provided for better spatial resolution. (For an evaluation of Schultze's duplicity theory, see Saugstad & Saugstad (1959).)

The theory that the human retina contains two basically different types of photoreceptor (rods and cones) that function independently of each other and operate under different conditions, giving rise to qualitatively different colour sensations, brought about a paradigm shift within vision research. Thus, the theory eventually became generally accepted and introduced a fundamentally new understanding of visual functioning. Schultze's theory also generated new fundamental questions with regards to differences and similarities as well as possible interactions between the information processing of the two receptor systems.

Obviously, answers to these questions presuppose knowledge of the characteristics of both the rod and cone mechanisms. Knowledge about basic characteristics of cones had long been accumulated within the Newton-Young-Maxwell-Helmholtz tradition (in the following referred to as the 'Newton tradition'), but little was known about rod functioning at the time Schultze (1866) published his important paper. The ignorance of the functioning of the rod receptor system is clearly revealed in Helmholtz's 'Handbuch' (1867, p. 214). Actually, at this developmental stage of research, he could find no conclusive evidence of *any* rod contribution to vision. No wonder, then, that the theory of Schultze did not gain immediate general acceptance.

In the following years, however, knowledge about basic rod functions developed rapidly within the Schultze-Boll-Kühne-Parinaud-König tradition (in the following termed the 'Schultze tradition') and strong evidence supporting and extending Schultze's theory emerged.

Early in the twentieth century, then, his theory had become generally accepted. Von Kries, a leading authority on vision, was its strongest defender and also coined the term 'Duplizitätstheorie' (duplicity theory; see von Kries, 1929). Perhaps his most important contribution, though, was his attempt to integrate the evidence accumulated within the Newton and Schultze traditions into a more comprehensive duplicity theory (von Kries, 1911).

Yet, the development of the duplicity theory was also profoundly influenced by a third research tradition (in the following termed the

'Goethe tradition') that started with Goethe, who believed that the phenomenological analysis of colour sensation in its own right would reveal the basic laws of colour vision (see Goethe, 1810). A great step forward within this tradition was taken when Hering pointed out that the phenomenological character of colour vision may also provide information with regard to the material processes underlying the phenomenological experiences. Indeed, on the basis of his phenomenological analysis of colour vision, Hering – in opposition to Newton, Helmholtz and Schultze – could conclude that the basic physiological colour-related processes had to *interact* and *oppose* each other somewhere in the visual pathway (see Hering, 1878).

Surprisingly, von Kries made no serious attempt to integrate the evidence provided by this third tradition into his theory. Thus, it was left to G. E. Müller (1896, 1897, 1923, 1930), who was deeply rooted in the Goethe tradition, to develop a duplicity theory that incorporated the evidence procured within all these three major research traditions.

Hence, the theory of G. E. Müller may be seen to represent the end of the first phase of the development of the duplicity theory. In order to review this first phase, we will describe the contribution of each of the three different research traditions and we start with the Newton tradition.

Part I The development of the basic ideas of the duplicity theory from Newton to G. E. Müller

2 The Newton tradition

2.1 NEWTON'S UNIVERSAL COLOUR THEORY

One major root of the duplicity theory as formulated by Schultze, von Kries and G. E. Müller is represented by the Newton tradition. Within this line of research a rudimentary understanding of the cone mechanisms developed, ending up with the formulation of the famous Young-Helmholtz trichromatic colour theory (Helmholtz, 1867). This theory profoundly influenced Schultze, von Kries and G. E. Müller in their attempt to construct their theories. In fact, the theory forms an integrated part of the duplicity theory and its development may therefore be seen to represent the starting point of the development of the duplicity theory.

Certainly, the development of the trichromatic theory was in many ways initiated by Newton's ingenious experiments and theories on light and colour. In fact, his contribution deserves to be ranked as *the first major paradigm shift within vision research in modern times*. Surprisingly, however, Newton's revolutionary ideas about light and colour are, today, not generally well known. In the following, therefore, we present his theories in some detail.

Newton's theories were first published 19 February 1672 as a letter in *Philosophical Transactions of the Royal Society of London* (1671/1672). His most important ideas about light and colour are stated below in his own words. They are given in his propositions 1, 2, 3, 7 and 13 (see also Cohen, 1978, pp. 53–57).

> 1. As the Rays of light differ in degrees of Refrangibility, so they also differ in their disposition to exhibit this or that particular colour. Colours are not *Qualifications of Light*, derived from Refractions,

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> or Reflections of natural Bodies (as 'tis generally believed,) but *Original and connate properties*, which in divers Rays are divers.
> 2. To the same degree of Refrangibility ever belongs the same colour, and to the same colour ever belongs the same degree of Refrangibility.
> 3. The species of colour, and degree of Refrangibility proper to any particular sort of Rays, is not mutable by Refraction, nor by Reflection from natural bodies, nor by any other cause, that I could yet observe.
> 7. But the most surprising, and wonderful composition was that of *Whiteness*. There is no one sort of Rays which alone can exhibit this. 'Tis ever compounded, and to its composition are requisite all the aforesaid primary Colours, mixed in a due proportion.
> 13. … the Colours of all natural Bodies have no other origin than this, that they are variously qualified to reflect one sort of light in greater plenty then another.

Later, on the basis of very extensive experimental research, Newton formulated his universal colour theory, where he suggested that all colours in the universe, which are generated by light, are colours of either homogenous or compounded lights and that, when quantities and types of rays that excite the eye are given, then the colour of the light is known (Newton, 1730, pp.154–161). In his own words,

> And therefore if the reason of any Colour whatever be required, we have nothing else to do than to consider how the Rays in the Sun's Light have by Reflexions and Refractions, or other causes, been parted from one another, or mixed together; or otherwise to find out what sorts of Rays are in the Light by which that Colour is made, and in what Proportion (Newton, 1730, p. 160).

2.2 AN ALTERNATIVE TO NEWTON'S THEORIES OF LIGHT AND COLOUR

Newton's (1671/1672) paper represents one of the most important contributions in the history of science. In order to adequately appreciate this eminent contribution, it is necessary to pay due attention to the generally held view with regard to light and colour at the time the paper was published. Thus, the originality of Newton's paper is best apprehended by comparing his theories on light and colour with contemporary theories (Cohen, 1978, pp. 208–209). An illustrative example of the contemporary viewpoints is given by the colour theory of Hooke, a brilliant scientist on whom the Royal Society of London relied to evaluate Newton's paper (Cohen, 1978, pp. 110–115).

Despite the fact that Newton's discourse had been received with much applause at the Society's meeting, Hooke's referee report, delivered only a few days later, comparing the explanatory value of Newton's and his own colour theory, was severely critical. Hooke argued that his own colour theory could explain more simply not only his own experimental results but also those presented by Newton, and that it was useless in scientific theory construction to multiply entities without necessity in the way Newton had done. Thus, opposed to the basic assumption of Newton that 'white' sensation was linked to a complex physical stimulus, the available evidence seemed to Hooke to prove that 'white' light was nothing but primitive, simple, uniform and transverse pulses or waves propagated through a homogeneous, uniform and transparent medium (the ether). Whiteness and blackness were accordingly assumed to represent nothing but large and small quantities of this light. Chromatic, prismatic colours, on the other hand, were explained by the assumption that the uniform, simple motion of white light became blended or mixed with adventitious motions when it fell obliquely on a refracting medium. The part of the light refracted least was assumed to give the impression of red, the part refracted most blue, while all the intermediate colours in the spectrum were thought to be determined by intermixing of the red and blue light. Hence, all chromatic colours in the world, except red and blue, were assumed to be caused by compound pulses made of the red and blue primary pulses only. Finally, Hooke assumed that the adventitious motions could be destroyed by other motions when compounded lights were united anew. The original, simple white light could thereby be restored.

Today, it is of interest to note that Newton's more complex theory prevailed. Thus, Newton's most conspicuous and original hypotheses, that the light stimulus that generated the apparently simple sensation of white was compounded and determined by primary lights mixed in due proportion, and that the solar spectrum consisted of an innumerable number of different lights linked to different hue sensations, were later embraced by Young, Maxwell and Helmholtz.

On the other hand, faced with Thomas Young's famous double slit experiment, where he explained the interference pattern obtained by the wave concept of light, and the test experiment carried out by François Aragon in 1819, that came out strongly in favour of the wave model of Augustin Fresnel, the scientific community in the early 1800s abandoned Newton's corpuscular theory of light in favour of the wave theory (see Gribbin, 2003, pp. 403–410).

Newton knew that there had to be an intimate relation between light and waves, but did not consider the wave aspect to be an intrinsic part of his concept of light. Thus, he wrote, 'For, assuming the rays of light to be small bodies emitted every way from shining substances, those, when they impinge on any refracting or reflecting superficies, must as necessarily excite vibration in the æther, as stones do in water when thrown into it' (see Newton, 1675, p. 179, 193–194).

It should be noted, however, that Newton's corpuscular theory of light gained renewed interest in 1905, when Einstein explained the photoelectric effect by Planck's quantum principle and so was led to postulate the existence of 'quanta' of light.

At present, it is generally held that photons have both particle- and wave-like attributes. (For modern notions about elementary and force particles including the photon, see Greene, 2005, pp. 84–95,180–199, 344–360.)

It is of interest to note that a controversy concerning the nature of light similar to that between Newton and Hooke took place between Democritus and Aristotle. While Democritus held that objects could be seen through an empty space, Aristotle assumed that movement