THE HYPOTHESES OF COLOR VISION.¹

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TO the question "How do we see?" there are but two general replies, the eye must emit something, or something from without must enter the eye. For twenty centuries this was a debated question among philosophers who took sides with the leaders of their respective schools, and vigorously upheld their theories. A complete absence of experiment in this as in other branches of science was accompanied by an astonishingly great variety of arguments and extravagant hypotheses to support their adopted opinions. Colors were ranked among the bodies of which only the names were known. When philosophers were asked, for example, why such a body was red, they answered that it was in virtue of a quality which made it appear red.

It is far from obvious that white light is very complex in its nature; and failure to discover this resulted in the confusion of mind exhibited by writers on light and colors preceding Newton's decisive experiments.

In the following short sketch of the history of this interesting branch of science an attempt is made to outline briefly most of the hypotheses of both ancient and modern writers. An outline only is attempted because a full review would expand this paper into a volume.

For the present purposes the history of color vision is here divided into four periods: first, from Pythagoras to Newton (540 B. C.—1671 A. D.); second, from Newton to Thomas Young (1671–1801); third, from Young to Ewald Hering (1801–1874); fourth, from this last date to the present time.

FIRST PERIOD (540 B. C.—1671 A. D.).

Pythagoras and the Pythagoreans, the second school of Grecian philosophers, who flourished about 500 B. C. held the opinion that

¹ A Report made to the Physical Seminary, Cornell University, 1902.

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vision is caused by particles continually flying from the surfaces of bodies and entering the eye.

A century after these, Empedocles and Plato put forward the doctrine that the cause of vision is something emitted by the eye which meeting with something else that proceeds from the object is thereby reflected back again. In other words sight was considered a species of touch due to invisible feelers having their origin in the eye.

Aristotle (*De Anima*, Lib. 2, Cap. 6 : 350 B. C.) maintained that light is incorporeal. His ideas are best illustrated by a reference to the rainbow, in accounting for which very many theories of color production originated. He thought that the colors were due to imperfect reflection from raindrops, the image of the sun being distorted and color only exhibited. Aristotle also taught that black and white were the colors from which all others were derived, an idea which in modified form persisted to the time of Goethe. It was also supposed by some philosophers of this period that the rainbow was caused by the clouds communicating their color to the sunbeams.

Epicurus (300 B. C.) and after him Lucretius (75 B. C.) believed that we see by the intervention of light as we feel an object by means of a stick. Seneca, who flourished about 60 A. D., observed (*Nat. Quest.*, Lib. I, Cap. 7) that sunlight shining through an angular piece of glass gives the colors of the rainbow, which he explained as a species of false color such as is observed on the neck of a pigeon. His theory of the rainbow is interesting. "The rainbow must be circular of necessity just as waves spread in a circular manner from a disturbance in still water." Again, he says : "that the rainbow is the image of the sun reflected from a hollow moist cloud which distorts the image because of the nature and figure of the speculum. Since in water everything is seen larger, the image of the sun is large because it is reflected from a moist cloud which partakes of the nature both of glass and of water." The different colors are accounted for by supposing that they come partly from the sun, partly from the clouds, and form a mixture?

Heliodorus, a Stoic philosopher of Nero's time, adhered to the old theory of the emission of ocular beams, which he tried to strengthen by arguing from the shape of the eye.

Ptolemy, whose treatise on optics written about 150 A. D. is now lost, became the great authority on the subject to the time of Alhazen.

During the Dark Ages the Arabians were the scientific investigators. The treatises of two of them, Al Farabi and Ebu Haithem (about 1000 A. D.), are not now extant; but that of Alhazen, published about 1072, became the authority for the five succeeding centuries. His speculations on color do not however show any advance over those of European philosophers. He defines the colors of the rainbow to be three, but with Seneca supposes them to be produced by a mixture of sun's light with the blackness of the cloud from which it is reflected. In the same manner the colors of all bodies seen by reflection are tinged with the colors of the reflecting surface (*Optica*, p. 461). The colors due to refraction in a glass globe, he says, are not the same as those of the rainbow, because they are not of the same number and are not seen in the same way — by reflection — but by direct vision in the same manner as light itself.

Roger Bacon, who died in 1294 A. D., assented to the opinion of some of the ancients and of some of his contemporaries as well, that visual rays proceed from the eye. His great reason was that everything in nature is qualified to discharge its proper functions by its own powers in the same manner as the sun and other celestial bodies. He regarded the presence of light necessary for vision (*Opus Majus*, p. 289).

Johannes Baptista Porta, who published his work, "*Magia Naturalis*," in 1560 when but fifteen years old, performed experiments with the camera obscura, invented by himself at that time, which convinced him that vision was caused by the intromission of light into the eye. Light was considered by him to be colorless but capable of having color superinduced upon it from foreign causes. He also gives an account of the generation of each color of the rainbow from a mixture of light and the denser or rarer parts of the air. Later Porta expressed the opinion that the colors of the rainbow were produced by refraction in the whole body of rain or vapor and not in the separate drops (*De refractione*, p. 95).

Fletcher, of Breslau (1571), tried to account for the colors of the rainbow by means of two refractions in one drop and a reflection

from a second, but as is well known, Antonio De Dominis, Bishop of Spalatro (1611) arrived at the true explanation (*De radiis visus et lucis*).

To account for the color he supposed that the red rays were those that had traversed the least space inside the drop and accordingly retained most of their native force, and striking the eye more vigorously gave it a stronger sensation. Similarly green and blue were produced by those rays, the force of which had been in some measure lessened in passing through a greater body of water. All the intermediate colors were composed of mixtures of these three primaries according to the hypothesis which generally prevailed at the time.

The theory of De Dominis was adopted and mathematically investigated by Descartes (1596-1650). But while sound in his investigations of the paths of the rays, he was much less happy in the way he accounted for the production of colors. "Light is neither a substance nor yet a mere property of bodies, but the motion of a subtle fluid communicated by the pressure of a luminous body. It is affected by two motions, a circular and a direct. When the circular is quicker than the direct the color is red; if the direct is quicker the color is blue; when the motions are equal the color is yellow. All the other colors are composed of these primaries." Descartes was, however, the first to state the real nature of black and white.

Malebranche (1638-1715) modified this theory of Descartes by the substitution of a medium filled with fluid vortices instead of perfectly elastic solid globules.

Following the example of other philosophers, Thomas Hobbes (1588-1679), an English writer, published a theory based upon experiments with a prism. The colored rays he considered to be due to modified light which he divided into two parts and named "first" and "second" light. The following extracts (*English Works*, vol. 1, p. 459; Molesworth Edition) will give an idea of his hypothesis. "Colour is light, but troubled light, namely such as is generated by perturbed motion as shall be made manifest by the red, yellow, blue and purple which are generated by the interposition of a diaphanous prism." "It is therefore evident that when

weak but first light passeth through a more resisting diaphanous body as glass, the beams which fall upon it transversely make redness: when the same first light is stronger the transparent beams make yellowness. When the second light is strong green is produced, but when weaker it generates purple.

"Whiteness is light, but light perturbed by the reflections of many beams of light coming to the eye together within a little space. Blackness is the privation of light."

Hobbes also considered that colors are formed from a mixture of white and black.

Perhaps the most extravagant opinion ever formed upon the subject of color vision was that of Dr. Hooke the contemporary and rival of Newton. Hooke reduced the primary colors from three to two. "Blue is an impression on the retina of an oblique and confused pulse of light whose weaker part precedes and whose stronger part follows; and red is a similar impression whose stronger part precedes and whose weaker follows. The fantasm of colour is caused by the sensation of the oblique or uneven pulse of light which is capable of no more varieties than two, which arise from the two sides of the oblique pulse though they be capable of infinite gradations, each of them beginning from white and ending, one of them in the deepest scarlet and the other in the deepest blue." (Priestley "On Vision, Light and Colours.")

De la Hire, who lived at this time, supposed difference in color to depend upon the degree with which the same light affects the optic nerve. For example, red blood appears blue through the veins because the light in passing through the skin loses its power and affects the nerve with less force. In common with many other writers he assigned the blue color of the sky to the sunlight reflected by the air, seen against a background of dark space.

Grimaldi (*De lumine, coloribus et iride*, 1666) made the discovery that when a circular beam of light passes through a prism it forms an oblong image. He did not infer the different refrangibilities of the colored rays, but looked upon it as showing that refraction produced color as well as reflection, which was the more general way according to the philosophers. Grimaldi's idea of color was that it was condensed light, red being more condensed than blue.

He concluded with Aristotle that light is no real substance ; not a substantial but an accidental quality.

Priestley (*On Vision, Light and Colours*, p. 240) thus sums up the theories of color production to the time of Newton :

“The Pythagoreans called colour the superficies of a body. Plato said that it was a flame issuing from them. According to Zeno it is the first configuration of matter, and Aristotle said it was that which moved bodies actually transparent. Descartes very sensibly argued that colour is a modification of light ; but he supposed that the difference of colour arises from the prevalence of the direct or rotatory motion of the particles of which it consists. Father Grimaldi, Deschales, and many others thought the differences of colour depended upon the condensation and rarefaction of light. Malebranche was of the opinion that differences in colour depend upon the quick or slow vibrations of a certain elastic medium filling the whole universe. Rohault imagined that the different colours were made by the rays of light entering the eye at different angles with respect to the optic axis ; and from the phenomena of the rainbow he pretended to calculate the precise angle that constituted each particular colour. Lastly Dr. Hooke, the rival of Newton, imagined that colour is caused by the sensation of the oblique or uneven pulse of light ; and this being capable of no more than two varieties, he concluded that there could be no more than two primary colours.”

Note.—Most of the hypotheses comprising the First Period will be found in Priestley's “*On Vision, Light and Colours*.”

SECOND PERIOD (1671–1802).

1671. Newton. “*New Theory of Light and Colours*.” *Philos. Trans.* (abridgment), Vol. I., p. 678. Reprinted in *Pop. Sci. Monthly*, Sept., 1902.

Newton performed his experiments on the decomposition of white light in 1666, but apparently did not publish the results until several years later. The following quotations from several of his papers will give his general views on color vision.

“The rays of light to speak properly are not coloured. In them is nothing else than a certain power and disposition to stir up a sensation of this or that colour.”

“To the same degree of refrangibility ever belongs the same colour, and to the same colour ever belongs the same degree of refrangibility.”

“To explain colours I suppose that * * * the rays of light by impinging on the stiff refracting superficies, excite vibrations in the ether * * * of various bigness; the biggest, strongest or most potent rays, the largest vibrations; and others shorter according to their bigness, strength or power; and therefore the ends of the capillimenta of the optic nerve, which pave or face the retina, being such refracting superficies, when the rays impinge upon them, they must there excite these vibrations which * * * will run along the aqueous pores or crystalline pith of the capillimenta through the optic nerve into the sensorium; and there, I suppose, affect the sense with various colours according to their bigness and mixture; the biggest with the strongest colours, reds and yellows, the least with the weakest, blues and violets; the middle with green; and a confusion of all with white * * *.”

1686. Waller: *Phil. Trans.*, vol. 3, p. 274.

In this paper Waller describes the materials from which pigments of definite colors are made. He also briefly mentions experiments in which he mixed the simple red and yellow pigments with each of the simple blues, and concludes that these mixtures of primaries give most of the medium colors, namely, green, purple, etc.

1752. Euler: *Nova theoria lucis et colorum*. Lettres à une Princesse d'Allemagne, 1768. Nos. 23, 27 and 28.

Euler upheld the undulatory theory and strongly opposed the doctrine of light corpuscles. But he maintained that bodies became visible because the sun's rays fell upon them, throwing their particles into motion, generating in their turn rays which, affecting our eyes, rendered the bodies visible. The blue color of the sky he explained by supposing the dust suspended in the atmosphere to generate blue rays owing to their constituent particles being thrown into vibration by the sun's light.

1755. Abbé Nollet: *Leçons de Physique*, Tom. 5, Sec. 3. Quoted by J. D. Forbes: *Phil. Mag.*, S. 3, Vol. 34, p. 172, 1849.

This writer taught the Newtonian theory of light and colors, but maintained the primary qualities of orange, green and purple.

1758. Tobias Mayer: *Gottingische gelehrte anzeigen*, p. 147.
Quoted by Helmholtz: *Phil. Mag.*, S. 4, Vol. 4, p. 522,
1852.

The three colors, red, yellow and blue had been mixed as pigments in early times, and came to be regarded somewhat as primary colors. "Mayer was the first to give utterance to the view that the three primitive colours might correspond to three different kinds of light, red, yellow and blue, each of which furnished rays of all refrangibilities. According to this, at every point in the solar spectrum, red, yellow and blue rays are mixed together which do not differ in refrangibility and therefore cannot be separated by the prism."

1792. Chrétien Ernest Wünsch: *Versuche und Beobachtungen über die Farben des Lichtes*. Leipsic. Abstracted in *Annals de Chimie*, 64, p. 135, 1807.

Wünsch performed many experiments to prove that there were not seven primary colors as some supposed from the number of spectrum colors given by Newton, nor yet five as others believed. He was the first to select red, green and violet as primaries, a result to which he was led by his experiments on mixtures of the colored rays of the spectrum.

THIRD PERIOD (1801-1874).

1801. Thomas Young: "On Theory of Light and Colours." *Phil. Trans.*, Vol. 92, p. 12, 1802 (read in 1801). "Some Cases of the Productions of Colours." *Ibid.*, p. 387.

In the first paper Young selected red, yellow and blue as the three simple color sensations, with no other basis than current scientific opinion. Owing to the celebrated but misconstrued observations by Wollaston of the dark lines in the solar spectrum, Young modified his theory by selecting red, green and violet as primaries, quite independently, however, of Wünsch. This theory he further confirmed by experiments, after which it remained in obscurity until Maxwell and Helmholtz brought it to the attention of scientists and made it the basis of their investigations.

Young seems to have been the first to attribute a definite physiological significance to the three primary colors, the precise hues or

wave-lengths of which he had no means of determining. His general principles were modified and made definite by the experimental researches of Helmholtz, Maxwell, König and others. These do not all agree upon the hues selected as the primary colors, and Maxwell in particular selects a blue as the third of his triad of fundamentals.

"The referring of all colours," says Helmholtz, "to the three primitive ones has, in the case of the different observers, three different senses :

"1. That the different colours were such as permitted of the formation of all others from their combinations.

"2. Or, as supposed by Mayer and Brewster, that the primitive colours correspond to three different kinds of objective light.

"3. Or, as supposed by Young, that they correspond to three primitive modes of sensation experienced by the visual nerves, and from which the remaining sensations of colour are composed."

[Helmholtz: "On the Theory of Compound Colours." *Phil. Mag.*, S. 4, Vol. 4, 1852, p. 522. Also "Physiol. Optik."]

[Maxwell: "On Theory of Compound Colours, and the Relations of the Colours of the Spectrum." *Phil. Trans.*, p. 57, 1860.] See also A. M. Mayer: "History of Young's Discovery of his Theory of Colors." *Amer. Jour. of Science*, Ser. 3, Vol. 9, p. 251, 1875.

1802. William Hyde Wollaston: "A method of examining refractive and dispersive powers by prismatic reflection." *Phil. Trans.*, Vol. 92, p. 378.

In this paper Wollaston records his discovery of the principal "Fraunhofer" lines, the nature of which he was far from suspecting. He supposed that they divided the spectrum into four parts and formed the boundaries of the four corresponding colors, red, yellowish-green, blue and violet, the color of each division being quite uniform. He says that "we may distinguish, upon the whole, six species of rays into which a sunbeam is divisible by refraction." These are the four visible ones mentioned and in addition the invisible ultra-violet and infra-red. Wollaston evidently considered his four colors to be simple objective colored light.

This paper was important since it led Young to revise his theory.

1810. Goethe: "Farbenlehre." English translation, "Theory of Colours." Eastlake.

The hypothesis of Goethe is merely the absurd doctrine of the ancients that color is a mixture of light and darkness developed to a very high degree. "Light and darkness," Goethe says in the introduction to his work, "or light and its absence are necessary to the production of color." He bases his views on observations made by looking at a broad field of light (*e. g.*, a window) through a prism, and draws the general conclusion that next to the light a color appears which is called yellow; another appears next to the darkness which we call blue. When these are mixed in equal proportions the resulting color is green. All these colors produce new tints by being mixed with darkness.

Goethe's writings on color are remarkable for the abuse and denunciation which he heaped upon the experiments and color theory of Newton. To some of the propositions of Newton he applied such terms as "incredibly impudent," "mere twaddle," "ludicrous explanation," and others of a similar character.

1816. Schopenhauer: "Ueber das Sehen und die Farben." Abstract in *Encyc. Brit.*, Vol. 21, p. 450.

"The distinction of white and black with their mean point in the gray is referred to the activity or inactivity of the total retina in the graduated presence or absence of full light. The eye is endowed with polarity by which its activity is divided into two parts qualitatively distinct. It is this circumstance that gives rise to phenomena of colour. All colours are complementary. Each pair makes up the whole activity of the retina and so is equivalent to white; and the two particular activities are so connected that when the first is exhausted the other spontaneously succeeds. Such pairs are infinite in number. But there are three pairs which stand out prominently and admit of easy expression for the ratio in which each contributes to the total action. Red and green (each equal to $\frac{1}{2}$); orange and blue (2 : 1); yellow and violet (3 : 1).

1831. Brewster: On a New Analysis of Solar Light. *Trans. Roy. Soc. Edin.*, Vol. 12, p. 123, 1834. (Read in 1831.)

Awarded the Keith Biennial Prize in 1834 by Roy. Soc. of Edin.

The theory of Brewster is an elaboration of that of Mayer based on observations of an *impure* spectrum. The main points of the theory are as follows :

1. Red, yellow and blue light exist at every point of the solar spectrum.
2. As certain proportions of red, yellow and blue lights constitute white, the color of every point of the spectrum may be considered as consisting of the predominating color at any point mixed with white light.
3. By absorbing the excess of any color at any point, white light appears at that point which cannot be decomposed by any number of refractions.

The great reputation of Brewster induced most physicists for more than twenty years to adopt this view, Airy, Melloni, Draper, and Helmholtz alone dissenting. This theory persists to the present time, and as Rood remarks, is almost universally believed by artists.

Helmholtz investigated the experiments which misled Brewster, and showed that he had employed a spectrum mixed with stray white light.

1834. Thomas Exley. "Physical Optics," p. 28.

The following condensed extract will give a general idea of the views of this writer :

"The atoms of light have equal velocities, but unequal momenta and spheres of repulsion ; hence they ought to produce different effects or sensations on the delicate organ of vision. Probably those ethereal atoms which penetrate deepest into the sensitive part of the eye to produce their greatest effect give the red color, and those which pierce to the least depth produce violet, and those intermediate in proportion. Therefore the atoms which have the greatest absolute force and the least sphere of repulsion will cause a red color, and others according to one or other or to the proportion of both these circumstances will produce the same or other colors."

1867. W. Zenker. "Versuch einer Theorie der Farben perception." Archiv für Mikroskopische Anatomie (Schultze), Bd. 3, p. 248.

The retinal layer from which the rods and cones project acts as light reflector, according to the author. The layer of rods and

cones is supposed to have a greater refractive index than the layer above. Part of the light entering the eye is absorbed, and part reflected, the latter being the portion of the radiant energy which excites the sensation of color. The elements of the retina may be considered as systems of surfaces upon which the incident light-waves fall perpendicularly, and from which they are reflected in the same manner. These result in systems of standing waves with nodes at fixed distances from the reflecting layer, the distances depending upon the wave-lengths. The point of maximum disturbance will therefore be different for waves of different refrangibilities. The rods and cones, he says, are like piles of plates, each plate having a thickness equal to three standing waves of red, four of blue, and five of violet. The loops of the standing red waves will therefore always affect different plates from those acted upon by blue and violet, and hence these sensations will always be excited by the proper wave-lengths. This theory accordingly makes color perception a function of space not of time.

FOURTH PERIOD (1874-).

1874. Ewald Hering. A series of six papers in: Sitzungs. der Kaiserl. Akad. der Wissen. zu Wien. (Math.-Naturwiss. Classe). Fifth paper: Grundzüge einer Theorie des Lichtsinnes. 69 (3), p. 179, 1874. Sixth paper: 70 (3), p. 169.

Papers collected under the title: Zur Lehre vom Lichtsinnes. Vienna, 1878.

The hypothesis of Hering, the great rival of the Young-Helmholtz theory, is based upon the idea of visual substances. Hering assumes six psychophysical processes corresponding to six primary sensations which may be arranged in complementary pairs, black-white, blue-yellow, green-red. Three photochemical substances are supposed to exist in the retina, one corresponding to each of the pairs of sensations. The sensations of white, yellow and red are caused by the dissimilation of the corresponding visual substances, and the sensations of black, blue and green are caused by the assimilation of the same substances. These substances are not present in equal amounts. All the rays of the visible spectrum have a dis-

simulating action on the black-white substance, but different rays in different degrees. Mixed light appears colorless when it acts on the blue-yellow or red-green substance with equal dissimilative and assimilative power. The effects are not complementary merely but antagonistic. For example, fundamental red and green do not produce white by their combination, but merely destroy each other's effect and leave visible the white which is already there. This is not strictly true of the white-black antagonism, for their actions do not destroy each other but give rise to a series of grays. Each visual sensation is really a mixture of all six fundamental sensations. The one of the six which has relatively the greatest weight gives the character and name to the mixed sensation.

1876. Kühne. Papers in: "Verhandlungen des Naturhistorisch-Medicinischen Vereins zu Heidelberg," 1877-79.

Following close upon the discovery (1876) by Boll of the "Visual purple," Kühne constructed a theory of vision. He supposes that the waves of light give rise in the retina to different compounds according to their length, and thus produce the different color sensations.

1877. Augustin Charpentier. "De la vision avec les diverses parties de la rétine." *Archives de Physiol.*, 4, p. 894; also, "Sur la distinction entre les sensations lumineuses et les sensations chromatiques," *Compt. Rend.*, 86, 1878, pp. 1272 and 1341. Theory further developed in numerous other short papers in *Compt. Rend.*, *e. g.*, 2 Semes, 1885, p. 275. Also see *Nineteenth Century*, August, 1893, Vol. 34, p. 258 in art. "Recent Science" by Kropotkin.

This theory distinguishes in optical phenomena: first, a luminous sensation; second, a chromatic sensation; third, a visual sensation, or a sensation of form. Charpentier supposes a double process—chemical and thermal—of colored light upon two different pigments of the retina. The photochemical effect of light decomposes the visual purple and generates in the optic nerve one sort of vibrations totally independent of the color, and varying in amplitude with the intensity. Another pigment is supposed to be located between the rods and the cones which absorbs light and heat. This absorption generates in the nerve another set of thermal or thermo-electric un-

dulations which always begin a little later than the former, the interval being greater for violet than for red.

Two waves are thus moving along the optic nerve with corresponding phases at different intervals. Their various combinations provoke a variety of sensations which we interpret as so many colors.

1881. W. Preyer: "Ueber den Farben- und Temperatursinn mit besonderer Rücksicht auf Farbenblindheit," Pflüger's Archiv, Bd. 25, p. 31.

In every color sensation Preyer distinguishes three parts: quantity or intensity; quality or tone; temperature. The intensity depends upon the force with which the retina is acted upon by the ether waves, the quality upon their amplitude. He also makes an æsthetic division of colors into two classes, warm and cold. The warm colors are from red to yellow green, the cold from this latter to violet. The color process is developed from an earlier existing temperature sense, and indeed the color sense may be considered a special case of the thermal sense limited to the retina. In this hypothesis, each retinal nerve fiber sensitive to color impressions terminates in two "cones," one of which is excited by warm colors and the other by cold, the deciding factor being the wave-length. The rods give sensations only of white, gray, and black, the cones the color sensations.

1882. E. Landolt: "Théorie de la perception des couleurs," Arch. d'Ophthalm., II., p. 79.

1883. H. R. Droop: "Colour Sensations," Phil. Mag., S. 5, 15, p. 373.

This very indefinite theory of color vision is based upon two cases of color blindness described by Holmgren. One of the persons saw only red and bluish green in the spectrum and was blind to blue and yellow; the other saw yellow and blue, but was blind to red and green. As these were cases of monocular color-blindness their observations were accurately described. From these data he outlines a theory comprising five fundamental sensations, the complementary pairs red-green, yellow-blue, and the sensation of white. No suggestion is given as to what are the retinal processes by which the colors are perceived.

1884. A. Angelucci: "Una nuova teoria sulla visione," comunic. preventiva presentata All' Acad. Med. de Roma, 14 July, 1884. Also in: *Rec. d'Ophthalm.*, p. 34, 1886.

1884. F. C. Donders: "Noch einmal die Farbensysteme," *Graefe's Archiv für Ophthalmologie*, Bd. 30 (1), p. 15.

The theory of Donders comprises features of both the Young-Helmholtz and Hering theories, and at the same time introduces some new ideas of the possible mechanism of color perception; the most prominent being that of successive partial dissociation of the complex color molecules of a single visual substance, which gives rise to the four simple color sensations, red, yellow, green and blue. It is thus a four-color theory, but he supplemented this by a three color theory (red, green, violet) under certain conditions in order to obtain for his theory the advantages which a three-color theory has.

1884. C. A. Olliver. "A Correlation Theory of Colour Perception." *Phila. Med. Times*, 14, p. 715, 1883-4.

"Each and every healthy optic-nerve filament transmits to the color-center of the brain for recognition, nerve energies equal to as many special sensations as its peripheral tip is capable of perceiving. Color perception takes place through each and every optic nerve filament." Instead of separate nerves for several independent fundamental color sensations with the retina as the distinguishing factor, the "color-center" of the brain perceives color according to the specific energy transmitted.

1886. Roechlin.

The theory of this writer is that yellow and blue are the only two simple colors of the spectrum, the third being always found fused with yellow or blue to form reds and violets. Roechlin asserts that purple may be produced by combining violet and yellow, as well as by the mixture of red and blue.

1886. S. W. Burnett. "The new Theory of Color-perception." *Amer. Jour. Ophthal.*, Vol. 3, p. 278.

In this theory the brain is made the differentiating organ, and the nerve fiber is supposed to undergo different changes according to the different colors striking the retina. The same nerve is the conducting apparatus for different colors, which set up corresponding undulations, and these are the sources of different color sensations.

1888. W. Wundt. "Die Empfindungen des Lichtes und der Farben." *Philos. Studien*, 4, p. 311.

Apart from every external light stimulation and from all equivalent internal stimuli such as pressure, the retina is in a constant condition of internal stimulation. To this corresponds the sensation black, which also in part accompanies the light stimuli giving rise to the sensation gray.

By means of every external retinal stimulation two different excitation processes are set free — a chromatic and an achromatic — which follow different laws. With weak stimulation the achromatic has the greater intensity, with moderate light excitation the chromatic is more intense, while with the most intensive stimulation the achromatic is again predominant. The achromatic excitation consists in a *uniform* photochemical process which reaches its maximum in the yellow. The chromatic consists in a *polyform* photochemical process which represents a periodic function of the wave-length. Antagonistic action occurs not between the color stimuli themselves, but between the photochemical processes, and results in leaving a colorless light stimulus.

1888. Chas. V. Burton. "Experiments on Colour-perception, and on a Photo-Voltaic Theory of Vision." *Cambridge Philos. Proc.*, Vol. 6, 1886-9, p. 308.

The author bases his theory upon experiments of Dewar and McKendrick (*Edin. Philo. Trans.*, XXVII., 141), who have shown that there is a considerable electromotive force between the anterior portions of the eye and a transverse section of the optic nerve. It was found that the current flowing was altered in amount only when light fell upon the retina. Yellow and green rays produced the greatest effect. The converse phenomenon is well known that an electric current applied to the optic nerve produces a sensation of light.

The theory suggested is that electric currents in the nerve fibers produce the sensation of light, and, if of sufficient intensity, of color also. The light of all wave-lengths falling upon the retina affects these currents in various degrees, which produce the phenomena of color. Persistence of vision is explained by a reverse current due to a polarizing electromotive force.

1888. A. Göller. "Die Analyse der Lichtwellen durch das Auge." Dubois-Reymond's *Archiv für Physiologie*, I. and II., p. 139. Reviewed by C. L. Franklin: *Am. Jour. Psych.*, Vol. 2, 1888-9, p. 155.

Göller explains the analysis by the eye of light waves into sensations of differently colored lights by rotatory polarization. "Monochromatic light, on entering the eye, passes through the transparent retina, and is reflected back from the pigment epithelium in a state of plane polarization. The outer members of the cones play the part of a plate of quartz — they shift the plane of polarization by a definite angle. A molecular motion of much slower period is then set up in the protoplasm of the inner members, and it is the sensitiveness of the nervous filament to the plane of this motion which constitutes the sensation of color. Two complementary colors are colors which have had their planes of polarization rotated, one ninety degrees more than the other, with a phase difference of a quarter wave-length, the amplitudes being the same. These conditions would be sufficient to cause their superimposed harmonic motions to produce the motion of circular polarization, and that would be indistinguishable from the motion produced by all the colors of white light acting together.

Two vibrations whose planes are at different angles would give an elliptic motion of such a kind that the direction of its major axis would give its tint, the excess of the major axis over the minor would give its saturation, and the minor axis would give the amount of white light mixed with it."

1889. Preobraschensky. "Hypothese des Farbensehens." *Jour. Russ. Phys.-chem.*, phys. part. 21, p. 248. Abstract: *Jour. de Phys.*, II., 9, 1890, p. 538.

In this article the author very seriously modifies the Young-Helmholtz theory. In place of three kinds of nerve elements he supposes two — one sensitive to waves from $.400\mu$ to $.600$, the other to those between the wave-lengths $.520$ and $.790$. The simple sensations correspond to the extreme vibrations. The gray sensation is produced by the simultaneous impression of the same intensity of two colors equally distant from the extremes. The perception of the intensity of light is the same in both theories.

1892. C. L. Franklin. "Eine neue Theorie der Lichtempfindungen." *Zeit. für Psych. und Physiol. der Sinnesorgane*, 4, p. 211.

"On Theories of Light-Sensation." *Mind*, N. S., 2, 1893, p. 473.

"In the earliest stage of its development the visual sense consisted only in the sensation of gray, *i. e.*, the whole black-gray-white series of sensations. There is a certain kind of molecule, called the 'gray-molecule' which is composed of an outer range of atoms somewhat loosely attached to a firmer inner core, and having different periods of vibration. The light waves of the entire spectrum in some measure, and particularly those of the middle part, have the power of tearing off this outer sheath of atoms which react chemically upon the retinal nerve ends, and bring about the sensation of gray. The color molecules are developed from the gray molecules in the following manner: The atoms of the outer range segregate themselves into three different groups at right angles to each other, and having three different average velocities. Light of the fundamental color tones (red, green and blue) tears off from a large number of molecules those atom-groups whose periods are synchronous with the vibrations of the light, and those special chemical substances are set free which excite the respective color sensations. Intermediate waves set free atoms of two kinds and so give rise to mixtures of colors. Certain mixtures of light set free all three kinds of nerve-exciting substance which results in the gray sensation."

1892. Edmund Hunt: "Color Vision." Glasgow.

In a critical essay Hunt discusses several of the existing theories of color vision, and the interpretations of their experiments made by various writers. In addition he presents a theory of his own. Rejecting the various three-color and four-color theories, he maintains that there are five pure or principal colors: red, yellow, green, blue and purple. No attempt is made to describe any retinal processes by which the pure colors and their mixtures are perceived. Black and white are not considered as sensations.

1893. J. B. Haycraft: "A new Hypothesis concerning Vision." *Proc. Roy Soc.*, 54, p. 272, 1893.

This paper briefly outlines an evolutionary theory in which color perception is a development of an earlier existing light-sense. To be concrete, the sensation of yellow has in the course of evolution been produced by pigments which stimulate the eye by the yellow, red and green spectral rays which they transmit. The red and green rays when mixed do not, however, give rise to red and green sensations, but simply intensify the yellow sensations. In a similar way combinations of other rays are treated.

1893. H. Ebbinghaus: "Theorie des Farbensehens." *Zeit. für Psych. u. Physiol. der Sinnes.*, 5, p. 145. Reviewed by C. L. Franklin. *Mind*, N. S., 3, p. 198, 1894.

This theory is a development of Hering's, with the distinctive idea—partial dissociation—of Donders. "The visual purple is identical with a photochemical substance of such a nature that its primary partial dissociation is the cause of the sensation of yellow, and its completed dissociation is the cause of the blue sensation. In the cones which contain no visual purple, that substance does in reality exist, but is concealed by the presence of a second visual substance which is successively green, red and white in color (*i. e.*, is always complementary in objective color to the visual purple in all its color changes) and which is the source of our sensations of red and green. There is a third colorless substance in rods and cones alike whose decomposition is the source of the normal white-gray sensations, and of the sensations of the totally color-blind as well as of those of the normal eye when temporarily color-blind owing to insufficient illumination, besides contributing to the brightness of all sensations of light."

1894. Oliver J. Lodge. "The Work of Hertz." *Nature*, Vol. 50, p. 137.

In this review of Hertz's work a brief outline of an electrical theory of vision is given as follows: "I therefore wish to guess that some part of the retina is an electrical organ, say like that of some fishes, maintaining an electromotive force which is prevented from stimulating the nerves solely by an intervening layer of badly conducting material, or of conducting material with gaps in it; but that when light falls upon the retina these gaps become more or less

conducting and the nerves are stimulated. This intervening layer acts as a coherer affected by Hertzian waves, or as selenium affected by ordinary light. The sensation of light is due to electrical stimulus; the sensation of black is due to the mechanical or tapping-back stimulus. Vision is persistent until this latter stimulus occurs. The energy of vision is supplied by the organism, the light only pulls a trigger."

1894. A. König. "Ueber den menschlichen Sehpurpur und seine Bedeutung für das Sehen." Sitz. Akad. Wiss. Berlin, Vol. II., p. 577.

In his papers König has developed the Young-Helmholtz theory along the line of assigning specific functions to the rods, cones, and visual purple. "He believes that the cones have nothing to do directly with the luminous sensation, but that they are catoptric instruments for the purpose of condensing light upon the walls of the pigment epithelium, where the photochemical processes take place which are the sources of the sensations of red, yellow and green. The blue sensation is furnished exclusively by the visual yellow of the rods, and the sensation of a faint light (and that of the totally color-blind) is also blue in quality and is due to the visual purple. Hence the fovea, where there is no visual purple, is blind to blue. The blue blindness of the fovea has not been confirmed by other observers."

1895. W. Nicati. "Théorie de la couleur." Archiv d'Ophthal., XI., p. 1. Reviewed by C. L. Franklin, Psychol. Rev., Vol. 3, 1896.

The author uses such words as protochroism, metachroism, pleochroism, for gray vision, partial color-blindness and normal vision respectively. There is no difference in rods and cones that will cause three-color sensations, but in the "bipolar cells" there is a separation of the terminations into three layers for the three sensations. The visual purple is chemically affected by light and generates electric currents which are conducted by threads of varying resistances. The strength of current which is conveyed by each thread determines the character of the color sensation. Suitable cells are provided near the threads which send down condenser

discharges to undo the effects of the first currents. For example, after red has been seen the discharge causes green.

1896. G. E. Müller. "Der psychophysischen Axiome und ihre Anwendung auf die Gesichtsempfindungen." *Zeit. für Psychol. u. Physiol. des Sinnes.*, Bd. 10, 1896, p. 1. Second paper; *ibid.*, p. 321. Also two other papers, Bd. 14, 1897. Reviewed by C. L. Franklin: "Professor Müller's Theory of the Light Sense." *Psychol. Rev.*, Vol. 6, 1899, p. 70.

The theory set forth in these lengthy papers is a modification of Hering's. Instead of the dissimilation and assimilation of visual substances as provided by Hering, Müller takes advantage of a conception of modern chemistry, namely the reversibility of chemical action under suitable conditions, which conditions, he assumes, are realized in the retinae of vertebrate animals. The chemical law of mass action is also used in treating of the intensity of the photochemical processes. The pairs of sensations are the same as in Hering's theory except that a slight difference is made in the white-black process. Müller makes use of the "self light" of the retina in modifying the antagonism which exists between the black and white sensations. These do not naturally counteract each other perfectly, and so Müller assumes that the "self light" produces the gray effects. No use is made of the visual purple as a substance for producing vision, but it is regarded as an aid in bringing about adaptation to faint light.

1897. J. von Kries. "Ueber Farbensysteme." *Zeitschrift f. Psych.*, XIII., p. 241. "Krit. Bemerk. zur Farbentheorie," *ibid.*, XIX., p. 175. 1898.

Von Kries in what has been termed a "reconstruction" of the Young-Helmholtz theory apparently inclines to the view "that there are two sorts of white — one physiological and brought about by a photochemical dissociation in the rods; the other psychical and due to a mental reconstitution of an even red-green-blue sensation into a sensation of indistinguishable quality from the first." In the latter case the red, green and blue sensations are occasioned by disturbances of the cones alone.

1897. W. Patten. "A Basis for a Theory of Color Vision." *Amer. Naturalist*, 32, p. 833. Abstract: *Science*, N. S., 7, 1898, p. 219.

"The theory is based on the structure of retinal cells in invertebrates. The structures in the eyes of invertebrates corresponding to the rods and cones of vertebrates are generally composed of groups of simple or compound wedges, containing systems of transverse fibrils accurately graded in length, according to their positions in the wedges. The fibrils are always arranged in planes at right angles to the rays of light. All the fibrils in these planes may be parallel to one another, or at varying angles, or they may radiate from the axis of each rod like the bristles on a test-tube cleaner, so that no two fibrils in the same plane are parallel. By assuming that the length and angular relations of a fibril determine the amount of its response to a wave of light of a given length and plane of vibration, it is possible to offer a logical explanation of many phenomena of color vision."

1898. Adolph Stöhr. "Zur Hypothese der Sehstoffe und Grundfarben." Leipzig und Wien: Deuticke, 1898. Reviewed by C. L. Franklin: *Psychol. Rev.*, Vol. 7, 1900, p. 415.

The author "assumes several visual substances, and also, in the end-apparatus of the optic nerve, ultra-microscopic visual elements or corpuscles which are excited, under proper conditions by the visual substances. It is further supposed that the direct action of light upon the visual corpuscles is already sufficient to set them into molecular vibration, and that the effect of the visual substance is simply to modify and to strengthen this vibration. The object of this duplex supposition is to combine in one a photo-chemical hypothesis and a photo-physical one. In the highest animals these substances are three in number, and they give rise to the elementary color sensations.

"The visual elements, corpuscles or threads as they are variously called consist of minute fibers each thickly strewn over its entire surface with projecting flat plates, four in a given plane, and composed of material of four different sorts fitted to respond to four different sorts of stimulus and to furnish three primary color sensations together with the sensation of white. The most characteristic part

of the theory is that these little plates are set into molecular vibration in the first instance by the direct action of light (all alike in this case, and attended by the white sensation), but in the second instance this vibration is added to by the synchronous molecular vibrations of the three photo-chemical substances, when severally produced by light of different periodicity. It is then neither the production nor the destruction of a photo-chemical substance that is effective in exciting the nerve terminals, but it is during its relatively brief period of existence that a given substance acts upon the particular color-plate with which it is in harmony."

The various theories outlined in this paper are shown in their mutual relationship to some extent in the accompanying figure. From Newton to Hering the development of color theory proceeded along one main line, the latter originating a new branch which rivals, and, in the opinion of many, completely overshadows the parent stem. By a combination of characteristic features of both Young-Helmholtz and Hering theories, Donders directed development along a third line. At present therefore color theorists are divided into three groups, the physicists conservatively holding to the main line, the psychologists and physiologists, while divided in their allegiance, for the most part accepting the hypothesis of Hering.

The chief theories are criticised from the psychological standpoint in the "Dictionary of Philosophy and Psychology" art. 'Color Vision.' Several are also treated at considerable length in Sir Michael Foster's "Text Book of Physiology," and in Calkins' "Introduction to Psychology," as well as in other works of a similar character. To these and to the critical reviews by Mrs. Franklin which are referred to in their place, as well as to Dr. J. W. Baird of the Department of Psychology, Cornell University, I am indebted for valuable information.

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