ON COLOUR SENSE

AN ADDRESS

DELIVERED TO THE

BIOLOGICAL SECTION OF THE BRITISH ASSOCIATION
AT EDINBURGH

ON AUGUST 4, 1892

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EDINBURGH
YOUNG J. PENTLAND
1892

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At the meeting of this Association held at Birmingham in 1886, I had the honour of delivering a lecture on the Sense of Hearing, in which I criticised the current theory of tone-sensation, and I propose on this occasion to discuss the current theories regarding our sense of colour.

I may premise that our conceptions of the outer world are entirely founded on the experience gathered from our sensory impressions. Through our organs of sensation, mechanical, chemical, and radiant energies impress our consciousness. The manner in which the physical agents stimulate the peripheral sense-organs, the nature of the movement transmitted through our nerves to the centres for sensation in the brain, the manner in which different qualities of sensation are there produced,—all these are problems of endless interest to the physiologist and psychologist.

Every physiologist has acknowledged the profound significance of Johannes Müller's law of the specific energies,—or, as we should rather say, the specific activities of the sense-organs. To those unfamiliar with it, I may explain it by saying, that if a motor nerve be stimulated, the obvious result is muscular movement; it matters not by what form of energy the nerve is stimulated: it may be by electricity or heat, by a mechanical pinch or a chemical stimulus, the specific result is muscular contraction. In like manner, when the nerve of sight is stimulated,—it may be by light falling on the retina, or by electricity, or mechanical pressure, or by cutting the nerve,—the invariable result is a luminous sensation, because the impression is transmitted to cells in the centre for vision in the brain, whose specific function is to produce a sense of light.

The same principle applies to the other sensory centres; when thrown into activity, they each produce a special kind of sensation. The sun's rays falling on the skin induce a sense of heat, but falling on the eye, they induce a sense of light. In both cases, the physical agent is the same; the difference of result arises from specific differences of function in the brain centres concerned in thermal and visual sense. We have no conception how it is that different kinds of sensation arise from molecular movements in the different groups of sensory cells; we are as ignorant of that as we are of the nature of consciousness itself.

The subject I propose to discuss on this occasion is not the cause of the different *kinds* of sensation proper to the different sense-organs, but the causes of some *qualities* of sensation producible through one and the same sense-organ.

The theory of tone-sensation proposed by Helmholtz is, that the ear contains an elaborate series of nerve terminals capable of responding to tones varying in pitch from 16 vibrations to upwards of 40,000 vibrations per second, and that at least one special fibre in the auditory nerve, and at least one special cell in the centre for hearing, is affected by each tone of perceptibly different pitch. Although the physical difference between high and low tones is simply a difference in frequency of the sound waves, that is not supposed by Helmholtz to be the cause of the different sensations of pitch. According to his theory, the function of frequency of vibration is simply to excite by sympathy different nerve terminals in the ear. The molecular movement in all the nerve fibres is supposed to be identical, and the different sensations of pitch are ascribed to a highly specialised condition of cells in the hearing centre, whereby each cell, so to speak, produces the sensation of a tone of definite pitch, which in no way depends on the frequency of incoming nerve impulses, but simply on the specific activity of the cell concerned.

In my lecture on the Sense of Hearing I pointed out in detail the great anatomical difficulties attending the theory in question. I endeavoured to show the physical defect of a theory which does not suppose that our sensations of harmony and discord must immediately depend upon the numerical ratios of nerve vibrations transmitted from the ear to the central organ, and I offered a new theory of hearing based upon the analogy of the telephone. According to that theory, there is probably no analysis of sound in the ear; the hair-cells at the peripheral ends of the auditory nerve are probably affected by every audible sound of whatever pitch. When stimulated by sound they probably produce nerve vibrations, simple or compound, whose frequency, amplitude, and wave-form correspond to those of the sound received. The nerve vibrations arriving in the cells of the auditory centre probably induce simple sensations of tones of different pitch, or compound sensations of harmonies or discords strictly dependent on the relative frequencies of the nerve vibrations coming in through the nerve.

I cannot now recapitulate the evidence derived from anatomical, experimental, and pathological observations that give support to my theory of hearing, but I may briefly say that it is opposed to the theory of specific activities, in so far as it has been applied to explain the different qualities of sound sensation. It is, however, in strict accord with the fundamental proposition stated by Fechner[1] in his great work on Psychophysics in these words: "The first, the fundamental hypothesis is, that the activities in our nervous system on which the sensations of light and sound functionally depend, are, not less than the light and sound themselves, to be regarded as dependent on vibratory movements." It is evident that, if we could only comprehend the nature of the molecular movement in the nerve that links the vibration of the physical agent to that in the sensory cell, we could advance towards a true theory of the physiological basis of different qualities of sensation

[1] *Elemente der Psychophysik*, 1860. 2nd edition, 1889, Part ii. p. 282.

in the different sense-organs. As yet no definite answer can be given to the question, what sort of molecular movement constitutes a nerve impulse, but in recent years our knowledge of the subject has been extended in a direction that opens up a new vista of possibilities.

A nerve impulse travels at a rate not much more than 100 feet per second—an extremely slow speed compared with that of electricity in a wire. It has been thought to be of the nature of a chemical change sweeping along the nerve, but that hypothesis is opposed by the fact that the most delicate thermo-pile shows no production of heat, even when an impulse is caused to sweep repeatedly along the same nerve. Again, it is far easier to fatigue a muscle than a nerve. A living frog's nerve removed from the animal, and, therefore, deprived of all nutrition, can retain its excitability for nearly an hour, although subjected all the while to thirty or forty stimulations per second. An excised muscle, when similarly stimulated, is exhausted far sooner, because the mechanical energy entirely springs from chemical change in the muscular substance, and, therefore, the muscle is more easily fatigued than the nerve. The molecular commotion in the excited nerve produces a momentary electrical current; but that result is not peculiar to nerve; the same occurs in muscle when stimulated. Possibly, the molecular movement is of the nature of a mechanical vibration; at all events, we now know that a nerve can transmit hundreds, even thousands, of impulses, or let us simply say vibrations, per second. That fact is so important and significant in relation to the physiology of the sense-organs, that I show you an experiment to render it more intelligible. A frog's muscle has been hooked to a light lever to record its movement on a smoked cylinder. The nerve of the muscle has been laid on two electrodes connected with the secondary coil of an induction machine. In the primary circuit a vibrating reed has been introduced to serve as a key for making and breaking the circuit, and so stimulating the nerve with periodic induction shocks. If we make the reed long enough to vibrate ten times per second, ten impulses are sent through the nerve to the muscle and ten distinct contractions produced, as shown by the wavy line upon the cylinder. If we shorten the reed so that it will vibrate, say, fifty times per second, the muscle is thrown into a continuous contraction, and traces a smooth line on the cylinder; but if we listen to the muscle we can hear a tone having a pitch of fifty vibrations per second, from which we know that fifty nerve-impulses are entering the muscle, and inducing fifty shocks of chemical discharge in the muscular substance. If we take a reed that vibrates, say, 500 times per second, we hear, on listening to the muscle, a tone having the pitch of 500 vibrations. Observe, that we are not dealing with the transmission of electrical shocks along the nerve, but with the transmission of nerve-impulses. By stimulating the nerve with wires of a telephone it has been shown by D'Arsonval that a nerve can transmit upwards of 5000 vibrations per second, and that the wave-forms may be so perfect that the complex electrical waves produced in the telephone by the vowel sounds can be reproduced in the sound of a muscle after having been translated into nerve-vibrations and transmitted along a nerve. Such experiments go far in helping us towards a comprehension of the capabilities of nerves in transmitting nerve-vibrations of great frequency and complicated wave-form; but although they enable us reasonably to suppose that all the fibres of the auditory nerve can transmit nerve-vibrations, simple or complex, and with a frequency similar to that of all audible tones, we encounter superlative difficulty in applying such a theory to the sense of sight. In objective sound we have to deal with a comparatively simple wave motion, whose frequency of vibration is not difficult to grasp even at the highest limit of audible sound—about 40,000 vibrations per second. But in objective light the frequency of vibration is so enormous—amounting to hundreds of billions per second—that everyone feels the difficulty of forming any conception of the manner in which different frequencies of ether waves induce different qualities of colour sensation.

But before passing to colour sense, I wish to allude for a moment to the sense of smell. The terminals of the olfactory nerve in the nose are epithelial cells. It has been recently shown by Von Brunn[2] that in man and other mammals, the cells have at their free ends very delicate short hairs, resembling those long known in lower vertebrates. These hairs must be the terminal structures affected by substances that induce smell, and are therefore analogous to the hairs on the terminal cells in our organ of hearing. No one ever suggested that

[2] Von Brunn, *Archiv für Mikroskopische Anatomie*, 1892, Band 39, p. 633.

the hairs of the auditory cells can analyse sounds by responding to particular vibrations, and I think it quite as improbable that the hairs on any particular olfactory cell respond to the molecular vibrations of any particular substance. If we follow those who have had recourse to the doctrine of specific activities to explain the production of different smells, we must suppose that at least one special epithelial cell and nerve fibre are affected by each different smelling substance. Considering how great is the variety of smells, and that their number increases with the production of new substances, it would be a somewhat serious stretch of imagination to suppose that for each new smell of a substance yet to emerge from the retort of the chemist, there is in waiting a special nerve terminal in the nose. It seems to me far simpler to suppose that all the hairs of the olfactory cells are affected by every smelling substance, and that the different qualities of smell result from differences in the frequency and form of the vibrations initiated by the action of the chemical molecules on the olfactory cells, and transmitted to the brain. That hypothesis was, I believe, first suggested by Professor Ramsay[3] of Bristol in 1882, and it seems to me the only intelligible theory of smell yet offered. But it must be admitted that a theory of smell such as that advanced by Ramsay involves a more subtle conception of the molecular vibrations in nerve fibrils than is required in the case of hearing. It involves the conception that musk, camphor, and similar substances produce their characteristic qualities of smell by setting up nerve

3 Ramsay, *Nature*, 1882, vol. xxvi. p. 189.

vibrations, probably of different frequencies, and different complexities. We shall see what bearing this may have on the theory of colour sense, to which I now pass.

No impressions derived from external Nature yield so much joy to the mind as our sensations of colour. Pure tones and perfect harmonies produce delightful sensations, but they are outrivalled by the colour effects of a glorious sunset. Without our sense of colour all nature would appear dressed in bold black and white, or indifferent grey. We would recognise, as now, the beauty of shapely forms, but they would be as the cold engraving contrasted with the brilliant canvas of Titian. The beautiful tints we so readily associate with natural objects are all of them sensations produced in our brain. Paradox though it appear, all Nature is really in darkness. The radiant energy that streams from a sun is but a subtle wave-motion, which produces the common effects of heat on all bodies, dead or living. It does not dispel the darkness of Nature until it falls on a living eye, and produces the sense of light. Objective light is only a wave motion in an etherial medium; subjective light is a sensation produced by molecular vibration in our nerve apparatus.

The sensory mechanism concerned in sight consists of the retina, the optic nerve, and the centre for visual sensation in the occipital lobe of the brain. In the vertebrate eye the fibres of the optic nerve spread out in the inner part of the retina, and are connected with several layers of ganglionic cells placed external to them. The light has to stream through the fibres and ganglionic layers to reach the visual cells—that is, the nerve terminals placed in the outer part of the retina. They may be regarded as epithelial cells, whose peripheral ends are developed into peculiar rod and cone-shaped bodies, while their central ends are in physiological continuity with nerve fibrils. Each rod and cone consists of an inner and an outer segment. The outer segment is a pile of exceedingly thin transparent, doubly refractive discs, colourless in the cone, but coloured pink or purple in the rod. In man, the inner segment of both rod and cone is colourless and transparent. Its outer part appears to be a compact mass of fine fibrils that pass imperceptibly into the homogeneous-looking protoplasm in the shaft of the cell. Owing to the position of the rods and cones, the light first traverses their inner, then their outer segments, and its unabsorbed portion passes on to the adjacent layer of dark-brown pigment cells by which it is absorbed. It is not necessary for me to discuss the possible difference of function between the rods and cones. I may simply say that in the central part of the yellow spot of the retina, where vision is most acute, and from which we derive most of our impressions of form and colour, the only sensory terminals are the cones. A single cone can enable us to obtain a distinct visual impression. If two small pencils of light fall on the same cone the resulting sensory impression is single. To produce a double impression the luminous pencils must fall on at least two cones (Helmholtz). That shows how distinct must be the path pursued by the nerve impulse from a cone in the yellow spot of the retina to a sensory cell in the brain. The impulses must pursue discrete paths through the apparent labyrinth of nerve fibrils and ganglion cells in the retina to the fibres of the optic nerve. I now pass to the physical agent that stimulates the retina.

When a beam of white light is dispersed by a prism or diffraction grating, the ether-waves are spread out in the order of their frequency of undulation. The undulations of radiant energy extend through a range of many octaves—as Hertz has recently shown—but those able to stimulate the retina are comprised within a range of rather less than one octave, extending from a frequency of about 395 billions per second at the extreme red to about 757 billions at the extreme violet end of the visible spectrum. The ultra-violet waves in the spectrum of sunlight extend through rather more than half an octave. Although mainly revealed by their chemical effects, they are not altogether invisible; their colour is bluish-grey. The only *optical*—that is, strictly *physical*—difference between the several ether-waves in the visible or invisible spectrum is frequency of undulation, or, otherwise expressed, a difference in wave-length. The *chromatic*—that is, the colour-producing—effects of the ether-waves depend on their power of exciting sensations of colour, which vary with their frequency of undulation.

Although the retina is extremely sensitive to differences in the frequency of ether-waves, it is not equally so for all parts of the spectrum. In the red and blue portions, the frequency varies considerably without producing marked difference of colour effect, but in the region of yellow and green, comparatively slight variations in frequency produce appreciable differences of colour sensation. One striking difference between the effect of ether-waves on the eye and sound waves on the ear, is the absence of anything corresponding to the octave of tone sensation. The ether-waves in the ultraviolet, which have twice the frequency of those of the red end of the spectrum, give rise to no sense of redness but merely that of a bluish-grey. Even within the octave, there are no harmonies or discords of colour sense corresponding to those of tone sensation.

Colours are commonly defined by three qualities or constants,—hue, purity, and brightness. Their hue depends upon the chromatic effect of frequency of undulation or wave length. Their purity or saturation depends on freedom from admixture with sensations produced by other colours or by white light. Their brightness or luminosity depends on the degree to which the sensory mechanism is stimulated. The loudness of sound depends on the amount of excitement produced in the auditory mechanism by the amplitude of sound waves; but a sound with small amplitude of undulation may seem loud when the nerve apparatus is unduly sensitive. The brightest colour of the spectrum is orange-yellow, but it does not follow that the amplitude or energy of the ether-waves is greater than in the region of dull red. There is no physical evidence of greater amplitude in the orange-yellow, and its greater luminosity is no doubt purely subjective, and arises from the greater commotion induced in the sensory mechanism.

The theory of colour sense long ago proposed by Sir Isaac Newton[4] is now commonly treated with what seems to me very undeserved neglect. Newton supposed that the rays of light induce vibrations in the retina which are transmitted by its nerve to the sensorium, and there induce different colour sensations according to the length of the incoming vibrations—the longest producing sensations of red and yellow, the shortest blue and violet, those of medium length a sense of green, and a mixture of them all giving a sense of whiteness. At the beginning of this century Thomas Young proposed a theory which seems to have been intended as a modification of that suggested by Newton rather than as a substitute for it. Young supposed that the ether-waves induce vibrations in the retina "whose frequency must depend on the constitution of its substance; but as it is almost impossible to conceive that each sensitive point of the retina contains an infinite number of particles, each capable of vibrating in unison with every possible undulation, it becomes necessary to suppose the number limited to three primary colours, red, yellow, and blue, and that each sensitive filament of the nerve may consist of three portions, one for each principal colour."[5] Soon afterwards he substituted green for yellow, and violet for blue, so that he came to regard red, green, and violet as the three fundamental colour sensations, by mixture of which in varying proportions all other colours, including white, are produced. Young believed that his

[4] See quotations from Newton in Reference 5.

[5] Thomas Young, "On the Theory of Light and Colours," *Phil. Trans. Lond.*, 1802, p. 12.

suggestion "simplified the theory of colours, and might therefore be adopted with advantage until found inconsistent with any of the phenomena."

Young's trichromic theory of colour sense was adopted by Clerk-Maxwell, and Von Helmholtz amplified the "three portions" supposed by Young to exist in "each sensitive filament of the nerve" into three distinct terminals in the retina, each having its own nerve fibre. He supposed that each terminal contains a different visual substance capable of being decomposed by light; that when the substance in the red nerve terminal undergoes chemical change its nerve fibre is stimulated, and the excitement travels to a cell in the brain by whose specific activity the sensation of red arises. In like manner, when the visual substances in the green and violet terminals are decomposed, nerve impulses travel through different fibres to different cells in the vision centre, by whose specific activities the sensations of green and violet arise. With Helmholtz there was no question as to difference in quality of sensation depending on difference in frequency of nerve vibration arriving in the sensorium; no such hypothesis was entertained by him either for tone or for colour sensation. With sight, as with hearing, he supposed that the function of frequency of undulation virtually stops at the nerve terminals in the eye and ear, and that the frequency of undulation of the physical agent has no correlative in the quality of motion passing from the receiving terminal to the sensory cell. He believes that the different frequencies of ether-waves simply excite chemical changes in different nerve terminals. He expressly states[6] that the molecular commotion in the nerve fibres for red, green, and violet is identical in kind, and that its different effects depend on the specific activities of the different cells to which it passes in the sensorium. It is evident that Helmholtz entirely dismissed the Newtonian theory of the production of different qualities of colour sense, and substituted for it the doctrine of his own great teacher, Johannes Müller.

The theory of Young and Helmholtz offers an explanation of so many facts, and has at the same time provoked so much criticism, that I must enter more fully into some of its details. On this theory, the sense of white or grey is supposed to result from a simultaneous and duly balanced stimulation of the red, green, and violet terminals. The red terminals are supposed to be excited chiefly by the longer waves in the region of the red, orange, and yellow, also by the shorter undulations extending as far as Fraunhofer's line F at the beginning of the blue. In like manner, the green terminals are excited chiefly by the waves of medium length, and to a less extent by the waves extending to about C in the red, and by the shorter waves extending to G in the violet. The violet terminals are stimulated most powerfully by the shorter undulations between F and G, but also by the longer ones reaching as far as D in the yellow; therefore, optically homogeneous light from any part of the spectrum, except its extreme ends, does not usually give rise to a pure colour sensation, all three primary sensations are present, and consequently the colour

[6] Von Helmholtz, *Handbuch der Physiologischen Optik*, 2nd edition, 1892, p. 350.

inclines towards white,—the more, the stronger the light.

The experimental facts in support of Young's theory are familiar to all who have studied Physics. Compound colour sensations may be produced by causing light of different wave lengths to fall simultaneously or in rapid succession on the same part of the retina. The commonest experimental device is to rapidly whirl discs with sectors of different colours, and observe the results of the mixed sensations; or to cause the images of coloured wafers or papers to fall simultaneously on the retina by Lambert's method; or to transmit light through glass of different colours, and cause the different rays to fall on the same surface; or to mix pure homogeneous light from different parts of the spectrum. For obvious reasons, the last method yields the most trustworthy results. We cannot, by any mixture of homogeneous light from different parts of the spectrum, obtain a pure red or green sensation, and, according to Helmholtz, the same holds true of violet. On the other hand, a mixture of homogeneous rays from the red and green parts produces orange or yellow, according to the proportions employed. A mixture of rays from the green and violet gives rise to intermediate tints of blue, and a mixture of red and violet light produces purple. Therefore, Young regarded red, green, and violet as primary sensations, and orange, yellow, and blue—just as much as purple—he regarded as secondary or compound sensations. Grassmann discovered that to obtain a sense of white or grey, it is not necessary to mingle rays from the red, green, and violet portions of the spectrum. He found that he could obtain a white sensation by mixing only *two* optically homogeneous rays from several parts of the right and left sides of the spectrum. The pairs of spectral colours which he found complementary to each other are, red and greenish-blue; orange and cyan-blue; yellow and ultramarine-blue; greenish-yellow and violet; the complement for pure green being found not in any homogeneous light, but in purple — a mixture of red and violet. The complementary colours may be arranged in a circle, with the complementaries in each pair placed opposite one another. Of course, the circle cannot be completed by the colours of the spectrum; purple must be added to fill in the gap between the red and violet. Helmholtz found no constant ratios between the wave lengths of homogeneous complementaries, and it is a striking fact that, while a mixture of the green and red, or of the green and violet, undulations gives rise to a sensation such as could be produced by rays of intermediate wave length, no such effect follows the mingling of rays from opposite sides of the spectrum. Pure green, with a wave length of 527 millionths of a millimeter, marks the division between the right and left sides. The mixture of blue from the one and yellow from the other side does not produce the intermediate green, but a sensation of white. A mixture of blue or violet and red produces not green, but its complementary—purple. On the trichromic theory, the sense of white produced by mingling any of these two colours is simply regarded as the result of a balanced stimulation of the red, green, and violet terminals.

But the anatomical form given by Helmholtz to Young's theory of primary colour sensations is beset with serious difficulties. It implies the existence of three sets of terminals in the retina, and these must all be found in the central part of the yellow spot where cones alone are present. Three sets of cones there would be necessary to respond to the red, green, and violet light, and a colourless pencil of light could not be seen uncoloured, unless it fall on three cones, which we know is not the case. Therefore, if there are three different terminals, they must, in the human retina at all events, be found in every single cone in the yellow spot. In a single cone there might be three sets of fibrils capable of stimulation in different degrees, but it seems impossible to suppose that the different vibrations started in one terminal could be kept discrete and transmitted to the brain through three different fibres in the optic nerve, even if the nerve contained a sufficient number of fibres, which we know is not the case.

The phenomena of colour-blindness also offer great difficulty. In several cases of apoplectic seizure it has happened that the centre for vision on both sides of the brain has been completely or partially paralysed by the extravasated blood. In such cases the sense of colour may be entirely lost either for a time or permanently, while the sense of light and form remain—although impaired. The loss of colour sense in some cases has been found complete in both eyes; in most of the recorded cases the loss of colour sense was limited to the right or left halves of both eyes; that is, if the lesion affected the vision centre on the right side of the brain, the right halves of both eyes were blind to all colours. That illustrates the well-known fact that a sense of light does not necessarily imply a sense of colour. The colour sense probably involves a more highly refined action of the sensory cell than the mere sense of light and form, and is on that account more liable to be lost when the nutrition of the sensory cell is interfered with. In the normal eye the peripheral zone of the retina is totally blind to colour. If you turn the right eye outwards, close the left, and then move a strip of coloured paper from the left to the right in front of the nose, the image of the paper will first fall on the peripheral zone of the retina, and its form will be seen, though indistinctly, but not its colour. It is difficult to say in that case whether the colour-blindness is due to the state of the retina or to that portion of the vision centre in the brain associated with it. The absence of cones from the peripheral part of the retina has been assigned as the cause, but it is much more probable that the portion of the vision centre associated with the periphery of the retina, being comparatively little used, is less highly developed for form sensation, and not at all for colour sense. It seems to me that the production of a sense of white or grey in the absence of all colour sense is not to be explained on the theory that it results from a balanced stimulation of red, green, and violet nerve terminals.

I need scarcely say that colour-blindness has attracted a large share of attention, not only because of its scientific interest, but still more on account of its practical importance in relation to the correct observation of coloured signals. In 1855 the late Professor George Wilson[7] of this city called attention to the growing importance of the subject. Some years ago Professor Holmgren made an elaborate statistical inquiry regarding it at the instance of the Swedish Government, and lately it has been investigated by a committee of the Royal Society of London, who have just published their report.[8]

Although colour-blindness occasionally results from disease of the brain, retina, or optic nerve, it is usually congenital. Total colour-blindness is extremely rare, but partial colour-blindness is not uncommon. It occurs in about 4 per cent. of males, but in less than 1 per 1000 of females. Its most common form is termed red-green blindness, in which red and green sensations appear to be absent. So far as I can find, the first full and reliable account of the state of vision in red-green blindness is that given in 1859 by Mr Pole,[9] of London, from an examination of his own case, which appears to be a typical one. His vision is dichromic; his two-colour sensations are yellow and blue. The red, orange, and yellowish-green parts of the spectrum appear to him yellow of different shades. Greenish-blue and violet appear blue, and between the yellow and blue portions of the spectrum, as it appears to him, there is a colourless grey band in the position of the full green of the ordinary spectrum. This neutral band is seen in the spectrum in all cases of

[7] G. Wilson, *Researches on Colour Blindness*, Edinburgh, 1855.

[8] "Report of the Committee on Colour Vision," *Proc. Roy. Soc. Lond.*, July 1892.

[9] W. Pole, "On Colour Blindness," *Phil. Trans.*, 1859, vol. cxlix. p. 323.

dichromic vision. It may appear white or grey, according to the intensity of the light, and it apparently results from an equilibrium of the two sensations. No such band is seen in the spectrum by a normal eye. Mr Pole, in the account of his case given now three-and-thirty years ago, considered it impossible to explain his dichromic vision on the commonly received theory that his sense of red is alone defective, and that his sense of yellow is a compound of blue and green. He believed his green quite as defective as his red sensation, and that yellow and blue are as much entitled to be considered fundamental sensations as red and green. He suggested that in normal colour-vision there are at least four primary sensations—red and green, yellow and blue. Professor Hering is commonly accredited with the four-colour theory, but it was previously suggested by Pole.[10]

A year after Pole's paper appeared, Clerk-Maxwell[11] published his celebrated paper on the theory of compound colours, to which he appended an account of his observations on a case of what he believed to be red-blindness, but which we now know must have been red-green blindness. The spectrum appeared dichromic, its only colours being yellow and blue. His description of the case does not materially differ from that given by Pole; but Clerk-Maxwell believed in the trichromic theory of normal vision, and that red, green, and blue are the three primary sensations; con-

[10] See reference 9, p. 331.

[11] Clerk-Maxwell "On the Theory of Compound Colours," &c., *Phil. Trans.*, 1860, vol. cl. p. 57.

sequently, he supposed that the yellow sensation of a red-blind person is not yellow, but green.

It is evident that much depends on the question, Is the yellow sensation of a red-green blind person the same as that of normal vision? For many years it was impossible to give a definite answer to that question, but the answer can now be given, as we shall presently see. Colour-blindness is frequently hereditary, and two or three cases are known in which the defective colour-sense was limited to one eye, while in the other eye colour-vision was normal. In such a case, observed by Professor Hippel of Giessen, there was red-green blindness in one eye. Holmgren, who examined Hippel's case, has published an account of it.[12] With one eye all the colours of the spectrum were seen, but to the other eye the spectrum had only two colours, with a narrow grey band between them at the junction of the blue and yellow. The yellow seen by the eye with the red-green defect had a greenish tinge like that of a lemon, but in other respects the observations confirmed Pole's account of his own case.

Hippel's case seems to me important for another reason: by some it is believed that congenital colour-defect is due to the state of the brain. If there had been defective colour-sense on one side of the brain, it would not have implicated the whole of one eye, but the half of each eye. Its limitation to one eye, therefore, seems to me to suggest that the fault was in the eye rather than in the brain.

[12] F. Holmgren, "How do the Colour-Blind see the Different Colours?" *Proc. Roy. Soc. Lond.*, 1881, vol. xxxi. p. 302.

Another interesting fact in this relation is that in every normal eye, just behind the peripheral zone of total colour-blindness—to which I have already referred—there is a narrow zone in which red and green sensations are entirely wanting, while blue and yellow sensations are normal. Possibly the red-green defect is due to an imperfectly developed colour-sense in the portion of the vision centre connected with that zone of the retina, but Hippel's case seems to me to show that such defect might be due to the retina itself.

It has probably already struck you that red-green blindness is really blindness for red, green, and violet,—that Young's three primary sensations are absent, and the two remaining colours are those which he regarded as secondary compounds of his primaries.

That, however, is not all that is revealed by defective colour-sense. There is at least another well-known, though rare form, in which a sense of yellow, blue, and violet is absent, and the only colour sensations present are red and green. The defect is sometimes termed violet-blindness, but the term is somewhat misleading. It is much more in accordance with fact to term it yellow-blue blindness; indeed, we would define it precisely by terming it yellow-blue-violet blindness. Holmgren[13] has recorded a unilateral case of this defect analogous to Hippel's case of unilateral red-green defect; we therefore know definitely how the spectrum appears to such a person. In the case referred to all the colours of the spectrum were seen with the normal eye, but to the other eye the spectrum had only two colours—red

[13] Holmgren. See reference 12, p. 306.

and green. The red colour extended over the whole left side of the spectrum to a neutral band in the yellow-green, a little to the right of Fraunhofer's line *D*. All the right side of the spectrum was green as far as the beginning of the violet, where it "ended with a sharp limit (about the line *G*)."

If you turn to the Report of the Royal Society's Committee[14] on Colour Vision, you will find the spectrum as it appears to yellow—blue—violet—blind persons. The plate agrees with the description of Holmgren's case; but you will not find a representation of the spectrum as it appears to those who are red-green blind, and as described by Pole and others. In place of it you will find two dichromic spectra, one with a red and a blue half, said to be seen by a green-blind, the other with a green and a blue half, said to be seen by a red-blind person. We have copied them for your inspection, and you will observe that *yellow* does not appear in either of them. I do not for a moment pretend to criticise these spectra from any observations of my own. I am aware Holmgren and Donders maintained that red and green blindness may occur separately; but, on the other hand, Hering and Stilling have maintained that they are always associated, and George Berry, an eminent opthalmologist, has, from his own observations, assured me that such is the case.

Of the various methods of testing colour-vision, that suggested by Seebeck is most commonly employed. The individual is mainly tested with regard to his sense of green and red. He is shown skeins of wool, one pale

[14] See reference 8, Plate I., No. 4.

green, another pink or purple, and a third bright red, and is asked to select from a heap of coloured wools laid on a white cloth, the colours that appear to him to match those of the several tests. We have arranged such test skeins for your inspection, and have placed beneath each of them the colours which a red-green blind person usually selects as having hues similar to those of the test. It is startling enough to find brown, orange, green, and grey confused with bright red; pale red, orange, yellow and grey confused with green; blue, violet, and green confused with pink. But these "confusions" have all their explanation in the fact that the red-green blind have only two colour sensations—yellow and blue, with a grey band in what should have been the green part of his spectrum.

We have now to show you another and more striking method of ascertaining what fundamental sensations are absent in the colour-blind. It is the method of testing them by what Chevreul long ago termed *simultaneous contrast.* If, in a semi-darkened room, we throw a beam of coloured light on a white screen, and interpose an opaque object in its path, the shadow shows the complementary colour. If the light be red, the shadow appears green-blue; if it be green, the shadow appears purple or red, according to the nature of the green light employed. If the light be yellow, the shadow is blue; if it be blue, the shadow is yellow. We must remember that the part of the screen on which the shadow falls is not entirely dark; a little diffuse light falls on the retina from the shadowed part, so that the retina and vision centre are slightly stimulated where the image of the shadow falls. We use an oxyhydrogen lantern, and transmit the light through plates of coloured glass carefully selected.

The experiment is rendered still more striking, though at the same time a little more complicated, by using two oxyhydrogen lamps, and throwing their light on the same portion of the screen. If a plate of coloured —say ruby—glass be held before one of the lamps, and an opaque object, such as the head of a T square, be placed in the path of both lights, the shadow cast by the white light falls on a surface illuminated by red light from the other lamp, and shows a deep red, far more saturated than the surrounding surface of the screen, where the red and white lights fall. The shadow cast by the red light shows the complementary bluish green, and the contrast of the two is exceedingly striking. When we use a plate of pure green glass, the shadow showing the inducing colour is a saturated green, the other shows the complementary purple. With yellow glass one shadow is deep yellow, the other pale blue. With blue glass one shadow is saturated blue, the other pale yellow. With pink glass the *complementary green is deeper* than the shadow showing the inducing pink, and is on that account very striking.

These experiments which we have shown you point to some subtle physiological relation between complementary colours. A colour-sensation produced in one part of the vision centre forces, so to speak, the neighbouring part, which is relatively quiescent, to produce the complementary colour subjectively. I say *vision-centre* rather than *retina*, because, if one eye is illuminated with coloured light while the other eye is feebly illuminated with white light, the complementary colour appears in the centre belonging to that eye. The sense of white appears to be a mysterious unity;—if you *objectively* call up one part of the sensation, you call up its counterpart *subjectively*. If a colour and its complementary counterpart be both displayed objectively at the same time, the action and reaction of effect afford a sensation far more agreeable than is producible by the objective display of only one of them. The agreeableness of the contrast of complementary colours, no doubt, springs from this harmony of effect. There is no harmony of colour effect analogous to that of music, but there is harmony of a different kind, and that harmony is formed by the contrast of complementary colours.

Now, I imagine many of you have already anticipated the question, What information can simultaneous contrast give regarding the fundamental sensations of the colour-blind? From an extended series of observations, Dr Stilling of Cassel has ascertained that if a person cannot distinguish between red and green, no complementary colour appears in the shadow when the inducing light is red or green; but if the inducing light is yellow or blue, the proper complementary appears. If a person was found blind to red, the complementary green never appeared; if he was blind to green, the complementary red did not appear; when the inducing light appeared colourless, the shadow was also colourless. Stilling, therefore, concluded that either the sensations of red and green, or of blue or yellow, were wanting at the same time, or that all colour-sense was absent.[15] It is difficult to see how these results are to be harmonised with the conclusions arrived at by the committee of the Royal Society.

Facts such as these are regarded by some as lending support to the theory of colour-sense proposed by Professor Hering of Prague.[16] He supposes that the diversity of our visual perceptions arise from six fundamental sensations, constituting three pairs—white and black, red and green, yellow and blue. The three pairs of sensations are supposed to arise from chemical changes in three visual substances, not confined to the retina, but contained also in the optic nerve and vision-centre.[17] He imagines that a sense of white results from *decomposition*, induced in a special visual substance by all visible rays, and that the *restitution* of the same substance produces a sense of black. The sensations of the red and green pair are supposed to arise—the one from decomposition, the other from restitution, of a second substance; while yellow and blue are supposed to result from decomposition and restitution of a third substance. From our knowledge of photo-chemical processes, we can readily suppose that light induces chemical change in the visual apparatus, but that the wave lengths in the red and yellow parts of the spectrum induce *decomposition*, while the wave lengths in the green and blue induce *restitution* of substance, it is

15 J. Stilling, "The Present Aspect of the Colour Question," *Archives of Ophthalmology*, 1879, viii. p. 164.

16 E. Hering, "Zur Lehre vom Lichtsinne," 2nd ed., Vienna, 1878.

17 Hering, *Ibid.* p. 75.

difficult to believe. How such a visual mechanism could work it would be difficult to comprehend; for example, if we look at a bright red light for a few moments and then close our eyes, the sensation remains for a time, but changes from red to green, and then slowly fades away. According to Hering's theory, the green after-sensation results from the restitution of a substance decomposed by the red light. But if we reverse the experiment by looking at a bright *green* light and then closing our eyes, the after-sensation changes to *red*. The theory in question would require us to suppose that the green light builds up a visual substance, which spontaneously decomposes when the eyes are closed, and so produces the red after-image. I confess that such a hypothesis seems to me incredible. Another remarkable feature of Hering's theory is, that colours termed *complementary* ought to be termed "*antagonistic*,"[18] because they are capable of producing a colourless sensation when mingled in due proportion. If the complementary colours yellow and blue could produce black when they are mixed, they might be termed "antagonistic;" but since their combined effect is a sense of white, and since the addition of them to white light increases its luminosity, it seems very difficult to comprehend on what ground the term *antagonistic* should be substituted for *complementary*. I confess I am quite unable to follow Hering when he supposes that three pairs of mutually antagonistic chemical processes are produced in the retina when white light falls upon it,—that these processes are all continued on through the optic nerve into the vision

[18] Hering, *Ibid.* p. 121.

centre, and there give rise to our different light and colour sensations.

In 1881, Professor Preyer contributed an important paper on Colour Sense[19] in which he supported Young's theory of primary colour sensations, but assuming their number to be four instead of three. Believing with Schultze that the cones are the only terminals in the retina concerned in colour sense, Preyer supposes there are four sets of cones containing different photo-chemical substances which are severally affected by undulations in the red, yellow, green, and blue parts of the spectrum. But since it has been calculated that the cones are thrice as numerous as the fibres of the optic nerve, Preyer has endeavoured to bring the Helmholtz amplification of Young's theory within the range of anatomical possibility by supposing that the four sets of cones are arranged in pairs, each pair being connected with one nerve fibre. This hypothesis, however, could not meet the case, even if cones were the only visual terminals. The rods are far more numerous than the cones; therefore, although it is probable that in the yellow spot each nerve fibre is connected with only one or two cones,—elsewhere in the retina each fibre must be connected with several terminals, the number increasing more and more towards the periphery of the retina, where the power of perceiving a double impression is far less than at the yellow spot. Preyer supposes that the pairs of cones are in two sets mingled together; the pairs of one set being for the reception of red and green stimulation, the other for

[19] W. Preyer. Über den Farben und Temperatur Sinn mit besonderer Rücksicht auf Farbenblindheit. Archiv für Physiologie, 1881, vol. xxv. p. 31.

yellow and blue. The part of Preyer's theory that appears to me attractive is that the photo-chemical changes induced in the several terminals cause vibrations to be transmitted through the nerve whose frequency must be far less than that of the undulations of the ether, and their wave-length consequently far greater, but " the ratios of the wave-lengths of the ether and nerve vibrations probably remaining almost unchanged."[20] If Preyer had only gone a step further and supposed that different colour sensations are producible in the same cells by different frequencies of vibrations entering the sensorium through the same nerve fibres, I would gladly have assented to a theory which would have been essentially a return to that of Newton; but my learned friend still strives to account for different colour sensations on the doctrine of specific activities, and to support the idea that different visual substances are located in different optic terminals. He supposes that when the cones of the red-green pair are simultaneously stimulated, vibrations of different frequencies are transmitted to a ganglion cell in the retina, and thence to a fibre of the optic nerve, but *not simultaneously.* He does not entertain the idea that the two sets of vibrations are compounded, and so transmitted by the fibre; on the contrary, he believes that " one and the same nerve fibre cannot be stimulated in a double manner at the same moment,"[21] and therefore, to explain the transmission of vibrations of two frequencies by the same fibre, he supposes that there must be a rapidly alternating transmission of the two sets of vibrations. I feel unable

[20] Preyer, *Ibid.* p. 98.

[21] Preyer, *Ibid.* p. 96.

to assent to that idea, for it appears to me that if an undulatory theory is applicable to nerve action, we must believe that simple pendular vibrations of different frequencies can be compounded. Nor do I feel able to assent to Professor Preyer's theory of the production of two qualities of sensation—say red and green—by vibrations transmitted through the same fibre. Reduced to the simplest expression, his theory is, that the fibre eventually ends in two sensory cells of specifically different activities, one producing a red, the other a green sensation ; that these two cells are affected sympathetically by vibrations of different frequencies,—the red cell by vibrations of the frequency transmitted by the red cone, the green by those of the frequency transmitted from the green cone. It seems to me far simpler to suppose that the vibrations produced by chemical change in visual substances in the retina may be transmitted either as simple or compound vibrations simultaneously by the same nerve fibres, and produce different sensations in the same cells, according to frequency and complexity of the incoming vibrations.

It seems to me that the difficulty of this question is much increased by attempting to show that different cones are concerned in the reception of different colour impressions. In support of such a view, the fact is adduced, that, in birds and some reptiles, each cone contains an oil globule of a red or orange colour in some cones, and of a yellow or greenish-yellow in others. The coloured spheroid is placed in the outer part of the inner segment immediately internal to the outer segment, and must exercise a selective absorption on the light passing to the outer segment. The presence of these coloured spheroids is remarkable, but we know as little regarding their physiological significance as we do regarding that of the yellow pigment in the internal layers of the retina at the yellow spot in our own eyes, through which all the light must pass ere it can reach the inner segments of the cones in that portion of the retina. All the cones in the human eye, as in that of all mammals, are colourless, and it involves serious difficulty if we suppose that different cones are affected by red, green, yellow, and blue light. The image of a coloured star small enough to fall on only one cone, can be seen of a fixed and definite colour, that does not alter when the position of the eye is changed, and the image shifted from one cone to another in the yellow spot. That fact, alone, seems to me sufficient to show the necessity for supposing that each cone is capable of stimulation by all visible undulations of light, and of transmitting such nerve vibrations as are capable of inducing all the colour sensations.

It further appears to me that the difficulty of the case is increased by attempting to show that cones are the only optic terminals concerned in colour impressions, while the rods minister only to a sense of light. It is true that cones are relatively few in number, or may indeed be absent from the retina of nocturnal animals, such as night-flying owls and bats, but that cannot be regarded as proof that the rods are not concerned in colour sense. Rods are much more numerous than cones everywhere in the human retina, save at the yellow spot. Throughout the greater part of the retina the cones occur singly, surrounded by numerous rods. Yet when the image of a coloured star, small enough for the area of a single cone, is made to fall on lateral parts of the retina, its colour does not disappear, and reappear when the eye is moved, as would inevitably happen if the rods were not terminals concerned, as well as the cones, in colour sense.

It must be admitted that the production of nerve impulses within the terminals of the retina is almost as obscure as ever. It is still the old question, Does light stimulate the optic terminals by inducing vibration or by setting up chemical change? Whichever view we adopt, it seems to me necessary to suppose that all the processes for the production of nerve-impulses can take place in one and the same terminal, and can be transmitted to the brain through the same nerve-fibre.

I referred to the sense of smell, because it seems to me we cannot in that case escape from the conclusion, that the different sensations arise from different molecular stimulations of the same olfactory terminals.

From Lippmann's recent researches on *The Photography of Colour*,[22] it appears that all parts of the spectrum can now be photographed on films of albumino-bromide of silver, to which two aniline substances, azaline and cyanine, have been added. It seems, therefore, reasonable to suppose that a relatively small number of substances could enable all rays of the visible spectrum to affect the retina. Von Helmholtz believes that three visual substances would suffice, but if the primary

[22] G. Lippmann, "On the Photography of Colour," *Comptes Rendus*, 1892, tome 114, p. 961.

sensations are to be regarded as four—red, green, yellow, and blue—at least, four visual substances appear to be necessary, and I think we must assume that all of them would require to be found in the same visual cell in the retina, and that the nerve-impulses to which their decompositions give rise, are all transmitted through the same optic fibres to the brain cells, there to produce a sense of uncoloured or coloured light. Evidently such a hypothesis is not altogether novel, it is essentially a return to that long ago suggested by Newton, the only difference being that the light is supposed to induce photo-chemical change in the retina, as Von Helmholtz suggested, instead of mere mechanical vibration, as Newton supposed. But if, in the sense of smell, nerve undulations are induced by the mechanical vibrations of molecules acting on delicate hairs at the ends of cells, is it after all so very unreasonable to suppose that within each visual cell there are different kinds of molecules that vibrate in different modes when excited by ether waves? Four or five sets of such molecules in each terminal element in the retina would probably be sufficient to project successively or simultaneously special forms of undulations through the optic nerve to induce colour sensations differing according to the form and frequency of the incoming nerve undulation.

The photo-chemical hypothesis has much in its favour. We know how rapidly light can induce chemical change in photographic films, and we know that light induces chemical change in the vision purple in the outer segments of the rod-cells of the retina. The fact that the cones contain no vision purple is no argument against the theory, for the inner segment of both rod and cone is by many regarded as the true nerve terminal, and there is no vision purple in either of them. The visual substances in the cones, at .all events, are colourless, and the existence of them as substances capable of producing nerve-impulses by chemical decomposition is as yet only a speculation awaiting proof. The fatigue of the retina produced by bright light is best explained on a chemical theory, but it could also be explained on a mechanical theory; for we must remember that even if the nerve-impulses produced in the visual cells were merely a translation of the energy of light into vibration of nerve-molecules, the nerve-impulse has to pass through layers of ganglionic cells before reaching the fibres of the optic nerve, and in these cells it probably always induces chemical change.

The phenomena of partial colour-blindness could be explained on a photo-chemical theory by supposing that it results from absence of the substances required to produce the wave forms necessary for the defective colour-sensation; but the total colour-blindness at the anterior part of the retina is obviously a difficulty. How could we have a sense of light from that portion of retina if all the visual substances are absent? That is one of the reasons why Hering supposed that a special visual substance is present everywhere in the retina, which by decomposition gives rise to a sense of light as distinguished from colour. But, even on the hypothesis we are pursuing, it is not necessary to suppose that all visual substance is absent, for the colour-blindness in the front of the retina could be explained by supposing that colour perception has not been developed in the corresponding portion of the vision centre, and consequently all nerve impulses coming from that part of the retina produce scarcely anything more than a sense of light. But evidently the same reasoning would apply to the zone of the retina that is blind to red and green. The absence of these sensations might be due—not to any peculiarity in the retina, but to a peculiar molecular state of the corresponding part of the vision-centre, rendering it unable to produce red and green sensations, although suitably stimulated by the incoming nerve-impulses.

If the photo-chemical theory be entertained, it seems necessary to suppose that there is some singular relation between the pairs of substances, which respectively give rise to red and green, yellow and blue, seeing that both members of a pair frequently, if not always, fail together. It seems to me that the great difficulty arises when we consider the puzzling phenomena of contrast. If light of a particular wave-length decomposes a special substance, and gives rise to, say, a sense of red, why does the complementary bluish-green sensation appear in the remainder of the vision-centre. If the induced colour were a pure green, one might attempt to explain it by supposing that a sympathetic change had been induced in a substance closely related to that suffering decomposition by the objective light, but no such simple explanation is admissible; the complementary contrast of red is not green, but a mixture of green and blue. The inadmissibility of such an explanation becomes still more apparent if we take pure green as the inducing colour. The complementary contrast that appears is purple, which involves a blue or violet as well as a red sensation. It matters not what inducing colour we adopt, the induced contrast is always the complementary required to make a sense of white. George Wilson[23] long ago suggested that simultaneous contrast probably arises from a "polar manifestation of force;" indeed, he regarded it as a "true, though unrecognised, manifestation of polarity." It is enough to mention that interesting suggestion, but I must not pursue it, for we are dealing with a problem that has as yet baffled the wit of man.

I have placed before you a subject that involves physical and physiological considerations of extreme difficulty. I have endeavoured to show the nature of these difficulties, and although I have not attempted to solve them all, I have at all events sought to show reasons why we should refer our different colour sensations to differences in the nerve vibrations transmitted from the optic terminals, rather than to specifically different activities of cells in the vision-centre. Although I have no hesitation in adopting a tetrachromic in place of a trichromic theory of normal vision, I am unable to relinquish the essential part of Young's theory—that there is a relatively small number of primary colour sensations. To abandon that idea entirely, as Krenckel and Berry[24] have done, is to return to the Newtonian theory, the difficulties of which none knew better than

[23] G. Wilson, see reference 7, p. 179.

[24] G. Berry, Examination of Cases of Colour Blindness (*Edin. Med. Jour.*, Oct. 1879), and Critical Remarks on the Theories of Fundamental Colour Sensations, *London Ophthalmic Hospital Reports*, 1890–91.

Thomas Young. I have not found it an agreeable task to point out the shortcomings of some theories advanced by those for whom I have the deepest regard; but, in the progress of scientific thought, it is especially necessary to keep our minds free from the thraldom of established theory. Theories are but the leaves of the tree of science; they bud and expand, and in time they fade and fall, but they enable the tree to breathe and live. If this address has been full of speculation, I trust you will allow that the scientific use of the imagination is a necessary stimulus to thought, by which alone we can break a path through the dense thicket of the unknown which surrounds us.