IV.—SOME NEW OBSERVATIONS IN SUPPORT OF THOMAS YOUNG'S THEORY OF LIGHT- AND COLOUR-VISION (II.).

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PART II.—COLOUR-VISION.

SECTION IV.—DISCUSSION OF SOME *A PRIORI* OBJECTIONS TO YOUNG'S THEORY.

IN the three preceding sections the way has been prepared for the consideration of Young's theory of colour-vision, firstly by the introduction of the conceptions of 'complete fading' and 'mutual inhibitions' of visual images, and secondly by the demonstration that the hypothesis of a special S-exciting process, which can find no place in that theory, is unnecessary and unfounded. Before describing any observations on colour I must consider here some objections to Young's theory of an *a priori* and general character. For I feel sure that to many persons these objections appear so weighty that unless something can be done to weaken the force of them they will not be able to consider the following sections without an adverse bias. These objections have been summed up by Prof. Cattell¹ in the dictum that Young's theory is 'pre-evolutionary' and 'pre-psychological'.

It is possible that these scientific-sounding epithets, pronounced in the tone of one who utters an oration over the grave of an unrepentant sinner, may seem to some minds to dispose finally of the theory in question. The characterisation of the theory as, 'pre-evolutionary,' is intended, I suppose, to express the opinion that it is not easy to picture the phylogenesis of the light- and colour-sense in terms of the theory. I believe that on the contrary it is possible to suggest a far more satisfactory view of the phylogenesis of the colour-sense in terms of Young's theory than in terms of Hering's, a view so much in harmony with all the relevant

¹ *Psychol. Rev.*, vol. i.

facts that the consideration of the problem becomes a support rather than a weakness to the theory.

Before presenting this view it is necessary to bring to the notice of those who have not specially concerned themselves with these matters of late years the present state of our knowledge with regard to vision under dim illumination. When Hering,¹ ten years ago, showed that at a sufficiently low intensity the solar spectrum appears colourless, as a mere band of grey of different degrees of brightness in different parts, this fact, taken in conjunction with the fact of the occasional occurrence of monochromatic or achromatic vision, seemed to give very strong support to his theory, because it seemed to prove that in the normal eye there is a special W-exciting apparatus which alone is functional in the monochromatic eye. There can now be no doubt about the existence of this separate W-exciting apparatus in the normal eye, and in the first section of this paper a new method of demonstrating its existence was discovered (obs. iv.).

But since Hering discovered the peculiar monotonous character of the low intensity spectrum and its similarity to that seen by the monochromatic eye, it has been shown, by experiments in colour-mixing, that the W sensation of the monochromatic eye cannot be regarded as produced by the physiological processes that determine the ordinary W sensation of the normal eye.² It has also been pointed out that the distribution of brightness in these spectra is very different to that in the spectrum of W light as seen by the normal eye.³ Prof. Ebbinghaus⁴ has proved also that the brightness of a W light formed by mixture of two complementary coloured lights cannot be wholly attributed to an independent W process.

Still more recently Herr. v. Kries⁵ has brought together evidence that makes it appear in the highest degree probable that the rods are the retinal elements of an independent W apparatus which functions alone in the normal eye when affected by light of low intensity only, and in the monochromatic eye. This view of the function of the rods had been suggested thirty years before to Max Schultze by his studies in comparative histology. This hypothesis of the independent W-exciting function of the rods must then be taken up into and incorporated with Young's theory, and

¹ Pfäfler's *Archiven*, Bd. 49.

² König u. Dieterici, *Zeitsch. f. P. u. P. d. S.*, Bd. iv., S. 827.

³ See Ebbinghaus, *Zeitsch. f. P. u. P. d. S.*, Bd. v.

⁴ *Ibid.*

⁵ *Zeitsch. f. P. u. P. d. S.*, Bd. ix.

when this is done the difficulty in representing the development of the visual processes in terms of this theory at once falls away.

It will be generally admitted that if we try to form a conception of the course of development of the colour-processes we must begin by assuming the vision of the lower animals, in which vision is but little developed, to be monochromatic, *i.e.*, we must assume the visual sensations to be of one kind only, varying only in intensity or brightness; and we must suppose this one kind of light sensation to be similar to our W or grey sensation or at least to stand to it in the relation of a direct ancestor. If we then seek the probable first step in the development of the colour-processes from this stage of simple grey-vision, we must, I think, assume that it consisted in a differentiation of the effects of the light of the warm and cold ends of the spectrum; the rays of the cold end would begin to set free, in addition to a W-exciting substance, a substance that by the excitement of a concurrently differentiated retino-cerebral apparatus would add the sensation of B to that of W; and in just the same way the rays of the warm end would begin to set free an additional X-substance that by the excitement of a second concurrently differentiated retino-cerebral apparatus would add the sensation of Y to that of W. If we then consider the state of a species in which the visual apparatus has achieved this degree of development we shall see that it would obviously be an advantageous arrangement that, when the retina was stimulated by W light, *i.e.*, by light containing rays of all wave-lengths, the two new colour-systems,¹ the Y and the B, both being excited in addition to the W system, should have the sensation-elements determined by them fused in consciousness to W. This compound W sensation-element would then add itself to and so re-enforce the sensation of W due to the excitement of the older W apparatus. For suppose that the Y and B sensations neutralised each other when the Y and B systems were excited together, this would leave a sensation of W but would involve a waste of the energy that, under the other arrangement, would go to re-enforce the W sensation. Or suppose the third possibility, namely, that Y and B when excited together fused to give a

¹ I use the word 'system' here and elsewhere in this paper, as also the word 'colour-system,' as a synonym for the phrase 'retino-cerebral apparatus' (or physiological mechanism). The word 'colour-system' as here used has therefore a meaning quite unconnected with the German phrase 'Farben-system,' and is only used because of the awkwardness of using 'apparatus' in the plural.

new kind of sensation. Then stimulation by mixed light would result in a sensation compounded of W and this new Y-B sensation; the ancient and primitive sensation of pure W or grey would have been lost, it could never again be experienced, and in place of the three perfectly distinct kinds of sensation Y and B and W yielded by the first arrangement, there would be possible only two, Y and B, and a mixture, bluish-yellow. To illustrate this by an example—it is obvious that a species or a variety endowed with the sensations of R and B and W would in this respect have an advantage over one endowed with R and B and P only.

Further, it is obvious that the original W apparatus would not be likely to undergo much further development if the Y and B systems developed in importance and in the intensity of the impression produced by them in consciousness, for they would yield when excited together a W sensation of correspondingly developed intensity.

It seems not unnatural to suppose that the developing differentiation of the colour-sensibility of the retina should have proceeded outwards from the centre, the region of acutest vision, and the one that is most used. In the peripheral zone of the human retina we have then the perpetuation of the primitive monochromatic stage of development of the eye, while the very rarely occurring monochromatic eyes are cases of reversion to, or arrested development in, this remote ancestral condition. In the same way the zone of the human retina, stimulation of which causes the sensations of Y and B and W only, remains in that stage of development in which only the first step of differentiation has been affected and the frequent cases of bichromatic vision, in which Y and B and W seem to be the only sensations that can be aroused by stimulation of the retina, are cases of reversion to or arrested development in this more recent ancestral condition.

If we try to picture the further evolution of the colour-sense, the process that would seem to be likely to give the best results, and therefore the one most likely to be effected by the factors that have controlled the origin and development of species, is a repetition of the process of differentiation such as gave rise to the B and Y systems, but occurring within either the B or the Y system. For reasons which we can hardly hope to determine this differentiation has proceeded in the Y system. The light of the two ends of the warm half of the spectrum must be supposed to have begun to set free, within the retinal elements of the Y apparatus, two different X-substances in addition to the Y X-substance, and with these two new X-substances, the R and the G, we must

assume the concurrent differentiation of the R and G retino-cerebral systems. Then just as it was obviously advantageous that Y and B sensation-elements, when excited together, should fuse to give W so obviously it would have been advantageous that R and G sensations when excited together should fuse to Y, else the primitive W and the original Y sensation would again be lost. As these two new colour-systems became developed in the retina from the fovea centralis outwards, the primitive Y apparatus would lose its importance and would probably undergo atrophy in this central region of most highly developed colour sensibility, just as the primitive W apparatus has become lost in the very centre, the fovea centralis itself. That the primitive W apparatus remains functional throughout the rest of those parts of the retina in which the colour-systems are developed is probably due to its having assumed the special function of vision under dim illumination, while no analogous functioning has justified the continued existence of the primitive Y system in the area of R and G sensibility.

This hypothetical sketch of the evolution of the colour-sense is such as is naturally suggested by the facts, and in the light of it it is not permissible to apply the epithet 'pre-evolutionary' to Young's theory, when that theory is supplemented by the theory of the separate W apparatus having its retinal endings in the rods. This view of the development brings Young's theory into harmony with the facts of colour-blindness and opens a road through what was perhaps the greatest obstacle in the way of its acceptance, namely, the fact that the dichromatic eye seems to see B and Y and W only.

The epithet 'pre-psychological' is meant, I suppose, to sum up the objections to Young's theory having their ground in the fact that W and Y cannot be analysed by introspection into a number of different colours, but appear to be simple sensations. In the case of W this seeming simplicity is an indisputable fact, but we have no particle of ground for accepting this fact as proof of the singleness of the underlying psycho-physical process.¹ If we put aside a vague feeling of the fitness of things, and the demands of this or that theory entertained by us, we have only analogy to help

¹ I use this term in the sense in which it is used by Prof. G. E. Müller, namely, to denote that part of the total physiological process which is the immediate correlate or determinant of consciousness and which, as I have argued in a previous paper (*MIND*, vol. vii.), probably consists in the passage of the impulse across the synapses from neuron to neuron in the highest levels of the cerebral cortex.

us in forming an opinion; and all analogy is against the supposition that a compound sensation, one resulting from the fusion of two psychical events having separate but contemporaneous underlying psycho-physical processes, must always be analysable, must always reveal its complex character to the reflecting mind. How many ears cannot analyse a clang into its component notes, or in fact distinguish a clang from a simple note! How many persons cannot differentiate the taste from the odour in the flavour of a familiar article of food! If the above rough sketch of the development of the colour-sense be approximately correct then it has been advantageous to species that the colour-processes, when excited all together and in equal degree, should by psychical fusion determine a sensation of W and that the R and G processes should in the same way yield Y, and it is surely absurd to suppose that Nature is incapable of bringing about such a result, merely because it is repugnant to our vague sense of the fitness of things. To do this is to invoke the aid of the historic anti-scientific principle that has perhaps done more than anything else to hinder the progress of science, and the influence of which, as the history of 'psychical research' shows, seems to have grown stronger with the advance of science, the principle, namely, that what we cannot understand cannot be true.

In the light of the above scheme of development it seems probable that the sensations of W and Y, although usually compound, give the impression of simplicity because they were originally evolved as simple sensations. I would further point out that if we accept as valid the inference from the feeling of simplicity to the simplicity of the underlying psycho-physical process then Hering's theory is in an equally difficult position with Young's theory. For we must then accept the same sort of feeling as our guide in determining which are the pure colours of the spectrum. If then we choose a pure R and a pure G light according to the dictum of consciousness, they cannot be made to yield by mixture a grey or W, but, as I shall show below (observation xlvii.), only various tones of R, Y and G.

Now Hering's theory demands that the light which excites the sensation of R only (in addition of course to W) and that which excites the sensation of G only, shall be complementary to one another; but of a complementary pair of R and G lights, one or other, the R or the G (or both), is always, according to the dictum of consciousness, a mixed or compound colour. Hering's theory is therefore equally 'pre-psychological' with Young's, and even more so, for to my

mind it is easier to believe that a sensation of W may be excited by three concurrent psycho-physical processes than that a sensation, clearly containing both R and B elements, or G and B elements, may be excited by one simple psycho-physical process.

SECTION V.—MONOCULAR STRUGGLE, OR THE MUTUAL INHIBITIONS OF IMAGES EXCITED BY SIMULTANEOUS STIMULATION OF COINCIDING RETINAL AREAS OF TWO OR MORE COLOUR-SYSTEMS.

The phenomenon of binocular struggle of different colours is familiar, and it is now pretty well agreed that when corresponding areas of the two retinæ are stimulated at the same time by lights of different wave-length, the colour-images may either appear alternately in consciousness, each in turn pure and unmixed with the other, or they may fuse to give the colour or neutral tone that usually results from their presentation to an area of one retina as an objective mixture.¹ Intensity of the coloured lights favours mutual exclusion, and dulness of the lights favours fusion in consciousness. The fact of fusion is obvious to most observers and is generally admitted, in spite of the curious passages in Helmholtz's *Physiologische Optik* (§ 777), in which the author while denying that binocular mixture of R and B can give sensation of P, yet admits that he may see the R and the B simultaneously at the same place. If now we consider the case of binocular struggle and fusion of R and B it is obvious that, whether we hold by Young's theory or by Hering's, we have to regard the struggle as due to the tendency to mutual inhibition of the cortical processes in corresponding areas of a R apparatus and a B apparatus; while fusion to form P we have to regard as a purely psychical fusion. By psychical fusion of R and B I mean that in a cortical area of one colour-apparatus there is going on a psycho-physical process which, when it occurs alone, determines a sensation of R, and in the corresponding cortical area of the other colour-apparatus is going on a psycho-physical process which, when it occurs alone, determines a sensation of B, but the two processes proceeding simultaneously each determines its proper sensation-element, which two elements fusing, by a purely psychical act, become the sensation of P. Of two colour-systems then, excited at the same time but separately in the two retinæ, each may assert

¹ See Rivers, *Proc. Camb. Phil. Soc.*, vol. viii., part v.

itself alone in consciousness, alternately with the other, or the two may affect consciousness at the same time and by psychical fusion give rise to a mixed or compound sensation.

Whether we hold by Young's theory or by Hering's we have to assume a separate retino-cerebral apparatus or system for each of the primary or simple colour-affections, R, G, B and W systems in the former case, R, Y, G, B, W and S in the latter case. We must further believe that each retina contains the peripheral endings of the nerve-fibres of its own set of four colour-systems that are distinct from the four systems of the other retina (or, according to Hering's theory, the six systems); for although it has been suggested that the central connexions of corresponding points of the two retinæ are anatomically identical this view is untenable. The view is naturally suggested by the fact that the fibres from corresponding halves of the two retinæ go to the same cerebral hemisphere. But this seems to be a false lead and is probably to be regarded as an arrangement of anatomical convenience merely, brought about in order that the centres for the left halves of both retinæ (i.e., for the right halves of the objective visual fields) may be in convenient proximity to the centres governing the movements of the right hand. Helmholtz¹ rejects the suggestion of the identity of the centres chiefly from a consideration of the influence of voluntary attention in effecting the predominance of one or other of two struggling fields, and his arguments and conclusion seem to be irrefutable.

But the following observation affords additional evidence in the same sense.

Observation XXV.—I fixated a bright W light (the window against a bright sky) for thirty seconds with the right eye only, and then covered both eyes carefully with several folds of black velvet. The vivid after-image faded completely after five minutes. I then admitted diffused daylight to the closed lid of the left eye for about two seconds, taking great care to admit none to the lid of the right eye. The after-image revived at once and died away again after about five seconds. It reappeared in this way at every repetition of the admission of light to the closed left eye during the following ninety seconds, and after that time could not be thus revived, even by admission of strong light to the left eye. I then admitted feeble light to the lid of the right eye for one or two seconds, when the after-image at once reappeared and persisted, after covering the eye again, for about five to ten seconds. It

¹ *Phys. Optik*, § 771.

FIG. 15.—(For description see next page.)

could be revived in this way during the following four minutes.

This observation, which I have repeated many times, seems to afford additional proof of the separateness of the cortical areas of the two eyes. For I have shown in section i. that the complete fading of after-images, while they are still revivable, is due to a failure of the nervous impulses excited in the retina to propagate themselves through the cortical areas in which consciousness is immediately determined. The effect of momentary stimulation of the retina by dim equally diffused light, in bringing back to consciousness after-images that have completely faded, can only be due to its raising the excitability of the visual cortical area, so that the feeble impulses coming from the retina are enabled to pass once more through these highest levels. Now, if the cortical areas of the two retinæ were identical, when the after-image is formed on one retina only, the admission of dim light to either eye should be equally effective in reviving the faded after-image. But we find that, though it has a perceptible effect of this sort in both cases, that effect is very much slighter in degree, and ceases to be effective much more rapidly in the case of the eye in which there is no after-image. The slight effect of stimulating this eye shows that there is some close and sympathetic connexion between the cortical areas of the two retinæ, although they are not identical.

The separateness of the retino-cerebral system of neurons connected with either eye may be inferred with a high degree of probability from phylogenetic considerations. Man and some of the quadrumana are the only vertebrates whose right and left visual fields overlap to any considerable extent. Their ancestors have had a pair of eyes which were incapable of being simultaneously affected by light from the same

FIG 15.—Diagram representing the two retinæ and the cortical centres connected with them. The upper four circles represent the cortical levels of the R, G, B and W systems connected with the left retina, the lower four the cortical levels of the R, G, B and W systems connected with the right retina. The broken line bisecting all the circles represents the purely anatomical separation of each centre into two halves which lie in opposite hemispheres of the brain. The continuous lines on the left side represent the sympathetic relation between corresponding points of the two systems of similar function connected with the right and left retinæ respectively. The dotted lines represent the antagonism between any point of any one colour-system of the one eye and the corresponding points of the other two colour-systems of the other eye. The broken lines represent the feebler antagonism between any point of any one colour-system of one eye and the corresponding points of the other two colour-systems of the same eye. The arrows radiating from the centre of each circle represent the antagonism between any point of the cortical level of any one of the systems and every other point of the same.

object. Either eye was therefore a separate organ complete in itself and incapable of being directly affected by the excitement of the other eye; and our eyes are the descendants of such a pair of separate and complete organs. And Dr. Gaskell has shown how in the course of evolution all other parts and organs may change and disappear like the baseless fabric of a dream while the central nervous system stands fast.

We may then represent the retino-cerebral systems demanded by Young's theory diagrammatically as in figure 15. For each of the four primary or simple visual sensations there are two complete retino-cerebral systems, one for each eye. Although the cortical area of each of these systems consists anatomically of two halves lying in opposite hemispheres, yet it seems to be functionally one and indivisible; this purely anatomical division of the cortical areas I have represented in the diagram by the vertical broken line bisecting each one. To represent the sympathetic relation between points of the cortical area of each system of one eye and the corresponding points of the system of similar function of the other eye I have drawn the continuous lines. Whether these lines represent actual nerve-fibres, *i.e.*, whether the sympathetic activity is brought about through the medium of nervous impulses, or whether it is purely psychically determined, we have, I think, no means of deciding. For the latter possibility we have now an analogy, perhaps a somewhat distant one, in the Marconi system of telegraphy.

Again, the cortical area of each colour-system of one eye must be represented as so related to the cortical area of each of the other two colour-systems of the other eye, corresponding point to corresponding point, that activity of the one tends to inhibit activity of these other two, although it does not necessarily and always do so. This relation is represented by the dotted lines in the figure. Now when the simultaneous excitement of two of these systems results in binocular colour-mixture, this is due to psychical fusion, and the interesting question arises, as in the preceding case—When inhibition of the activity of the one by that of the other occurs, as in binocular struggle, is this also primarily an inhibition of one psychical event by the other, with perhaps a consequent inhibition of the underlying psycho-physical process, or is the inhibition effected through the medium of nerve-fibres, the psycho-physical process being primarily, the psychical only secondarily, inhibited? The latter view seems to be more in harmony with the facts described in sections i. and ii. But it is perhaps not possible to decide

in favour of either, and to do so is not a matter of vital importance to the present discussion. The essential fact is the tendency to mutual inhibition.

Those who accept Hering's theory¹ must represent the retino-cerebral systems by a similar scheme with the difference that they must assume six instead of four colour-systems for each eye, and with the complication that the six systems fall into three pairs. They must assume each pair to be marked by the peculiarity that its two systems can never be simultaneously excited by external stimuli, because the retinal processes, which are the specific stimuli to the two systems, are mutually exclusive in character. Thus they must assume that the corresponding parts of the G and R systems of one eye can never be excited simultaneously, because the retinal processes excited by R light are antagonised by the action of G light, and where R and G light of equivalent intensities fall together upon an area of one retina, i.e. upon coinciding retinal areas of the R and G systems, neither of them is excited, but only the W system.

But now a difficulty presents itself for the theory of 'Gegenfarben'—What happens when R light falls on part of one retina and G light upon a corresponding part of the

¹ In dealing with this point I find it impossible to criticise the theory of 'Gegenfarben' as put forward by Hering himself, because I cannot discover that he has assumed any definite or consistent attitude towards the problem of the central connexions. The criticism of this paragraph applies therefore to Müller's improved and logical form of the theory. In the paper 'Zur Erklärung der Farben-blindheit' etc. (*Lotos.*, Bd. i.) Hering writes (p. 4) that he assumes six distinct psycho-physical processes, corresponding to the six primary sensations and that all these always proceed simultaneously but with different intensities in what he calls the 'Seh-substanz'; that a R light can increase the intensity of the R, Y and B psycho-physical processes but never that of the G. If we may infer from this that Hering regards the assimilation and dissimilation of the R-G retinal substance as incapable of proceeding simultaneously in the same area, then his theory is in this respect essentially similar to Müller's, and the criticism of this page applies equally to both. But if the dissimilation and assimilation of the R-G substance be assumed to proceed side by side, an assumption to which there can be no *a priori* objection, and which seems to be made by Hering in other connexions, where is the mutually destructive action of the effects of R and G light, resulting in neutralisation, to be conceived as occurring? Hering tells us it is not in the 'Seh-substanz,' but that there the R and G psycho-physical processes may and perpetually do take place simultaneously. If it be suggested that the antagonism is between the R and G psychical processes, this can only be accepted in the sense of Young's theory, in the sense namely that the R and G psychical processes destroy each the specific character of the other and so result in a third kind of sensation, Y or W. For it is impossible that the two psychical processes should abolish each other; that would be to equal the feat of the two Kilkenny cats that devoured each other so that none was left.

other? There can be no mutual exclusion of the two retinal processes, the R system is excited in one eye and the G system in the other. How then is the resulting sensation of W or gray to be accounted for in terms of this theory? So far as I know Hering has not dealt with this difficulty further than by refusing to assign definitely his hypothetical assimilation and dissimilation processes to the retina. It will be generally admitted that if Hering, in order to meet this difficulty, locates the assimilation and dissimilation processes elsewhere than in the retina, his theory loses at once its attractive plausibility. Müller¹ attempts to meet the difficulty by the dictum that if the two retinal processes concerned are incompatible with one another then the nervous impulses set up by them, when separately at work, must also be incompatible, so that in the case of binocular mixture of two complementary colours, *e.g.* of R and G, to give a W sensation the nervous impulses started in the two retinæ neutralise one another in the brain. This suggested escape from the difficulty seems to involve the assumption that the cortical centres, or some part of the cerebral paths of the fibres from the two retinæ are identical. But even if the evidence which refutes this view were lacking, the further assumption that, while nervous impulses exciting the sensations of R and B may proceed simultaneously in the brain, those exciting R and G cannot thus proceed, because the chemical processes by which they are initiated are opposed in character, this further assumption is one that has but slight foundation; for Müller's extremely complex argument in 'proof' of this assumption² involves the further assumption of an intimate knowledge of the physics of the nervous impulse and the acceptance as established facts of views that to most readers will seem to be merely interesting hypotheses.

We see then that for the explanation of binocular mixture of complementary colours giving sensation of W, while Young's theory requires only its one fundamental postulate of psychical fusion, Hering's theory requires two additional assumptions complicating the fundamental one of mutually opposed retinal processes; and of these two complicating assumptions the one, that of the identity of cerebral paths, is rendered untenable by the considerations adduced by Helmholtz and by the facts described above in observation xxv., while the other has no foundation, but is purely hypothetical and invented to meet the requirements of the case.

¹ *Zeitsch. f. P. u. P. d. S.*, Bd. xiv., § 82.

² *Ibid.*, § 80.

An alternative open to the holders of the theory of 'Gegenfarben' is to assume that there are only three retino-cerebral systems connected with either retina, and that a pair of complementary sensations are excited by two different kinds of activity throughout the same system. A third possible view is that the nerve fibres connected with either retina, together with their central prolongations (i.e., the central neurons), are of one sort only, but that each is capable of being excited throughout its length to six different kinds of activity, corresponding to the W, S, Y, B, R and G sensations respectively. But these difficult assumptions would not render easier the explanation of the W sensation resulting from binocular mixture of colours in face of the fact that we must assume separate central paths for the two retinæ.¹

Returning now to the consideration of our scheme of colour systems the following question presents itself—How is it that, while simultaneous excitement of corresponding areas of the B system of one eye and the R system of the other may result, according to the conditions, in fusion of the sensations to P or to alternate exclusion of one by the other, in the case of simultaneous excitement of corresponding areas of the R and B systems of one eye fusion of the sensations to P seems to occur in every case?

In considering this question it is well to bear in mind the fact, so forcibly insisted upon by Lotze, that what needs explanation is not the fact of fusion in consciousness of the effects of simultaneous visual stimuli, but the absence of fusion in any case, as in all cases in which they do not fall upon the same or corresponding points. When R and B lights affect the same area of one retina their effects fuse in consciousness not because they have the same 'local sign' but because they are not held apart through having different 'local signs'. In the case of R and B lights falling upon the same area of one retina, the 'local signs' of the two affections of consciousness are presumably identical, but in the case of R and B lights falling on corresponding areas of the right and left retinæ respectively the 'local signs' cannot be identical and as Lotze pointed out,² not even quite similar, owing to the necessity for convergence of the eyes in vision

¹ Müller argues in favour of the assumption of three separate kinds of material substratum for the psycho-physical processes, one for each of the pairs W and S, Y and B, G and R; but he inclines to the view that each retinal element is connected with one fibre of the optic nerve only, and is the seat of the six different chemical changes that initiate six different kinds of impulse in the nerve fibre (§§ 28, 29, 30).

² *Medicin. Psychol.*, § 30.

of near objects. This would seem to account sufficiently for the fact, insisted upon by Helmholtz, that the result in consciousness of binocular mixture of R and B differs appreciably from the result of their monocular mixture, in that in the former case the fusion is less complete and attention may more easily be directed to one or other and cause it to predominate in consciousness.

Another factor is probably of greater importance in determining the less tendency to fusion of binocularly than of monocularly mixed colours, namely the effects of use.

It is obvious that in the ordinary course of life the simultaneous excitement of corresponding areas of the R system of one eye and the B system of the other must be of extremely rare occurrence, while the simultaneous excitement of the R and B systems of one eye is of frequent occurrence, namely, whenever we see a P object. It seems therefore probable that the difference in the result of simultaneous stimulation of two colour-systems in the same and in opposite eyes is largely due to the effects of use, and since there exists antagonism and a tendency to mutual exclusion of the activities excited in corresponding cortical areas of two colour-systems of the right and left eye respectively, it must be held that a similar antagonism may exist between corresponding areas of the colour-systems of one eye and may be expected to manifest itself under suitable conditions.

Fechner¹ has pointed out this possibility and he states that Plateau and he himself have proved it to occur. But I cannot find any record of observations on the subject by either of these authors. Most other writers seem to have ignored the possibility. Helmholtz mentions merely that one colour may under suitable conditions appear to be seen through another in monocular vision.

In the paper by Mr. Breese² referred to in section i. the author describes perfectly clearly a case of monocular struggle, when patches of R and G light were thrown upon the same area of one retina, but he does not seem to have realised the great theoretical significance of his observation. His method of mixing the two colours was to fixate a square of R on a grey ground with one eye (the other being covered) and then to bring the vertical edge of a glass prism across the centre of the pupil so that the R rays enter by one half of the pupil only. A G square was then so disposed that rays from it entering the prism were

¹ *Abh. d. sachs. Ges. d. Wissensch.*, 1861, Bd. v.

² "Monograph Supplement" to *Psych. Rev.*, May, 1899.

refracted and sent to the same area of the retina as the R rays, through the other half of the pupil. He then observed a distinct struggle with alternate predominance of R and G. It is to be noted that the two coloured fields were crossed by diagonal lines in opposite directions and also that Breese had been using these same two patches of R and G in a long series of observations in stereoscopy, and it seems possible that thereby a very definite physical disposition of the cortex had been built up for the apperception of each of the two patches and that these favoured the occurrence of struggle in his case. Nevertheless, on repeating the observation I was able to see the struggle of R and G perfectly clearly. It is noteworthy that, although under these conditions Y is the predominant colour of the combined patches, yet one has the impression of seeing the one colour through the other just as is often the case in binocular colour-mixture. Breese notes this fact, and it is interesting in connexion with Helmholtz's discussion of binocular colour-mixture. For Helmholtz advances this fact, that one colour seems to be seen through the other, as a proof that the binocular mixture does not occur, but that as he says one merely sees the two colours occupying the same area at the same time. It is obvious of course that it is not that the colours do not fuse to give a sensation of Y, but that the psychical factor, the knowledge that there are two objective patches of colour superposed, and also the lack of exact coincidence of the two patches, cause the appreciable difference between the Y so produced, whether by monocular or binocular mixture, and a simple patch of Y.

The conditions most favourable to the observation of monocular struggle may be expected to be (1) steady and prolonged fixation; (2) relaxation of the ocular muscles (for these conditions are conducive to complete fading); (3) fairly bright colours; (4) sharply bounded patches of simple and definite shape, different for the two colours; for, as was pointed out in section i., a homogeneous and definitely bounded patch of colour tends to come and go in consciousness as a unit, more or less independently of other parts of a complex image. I therefore repeated Breese's observation with certain modifications described below and found that in this way I secured more satisfactory results.

Observation XXVI.—I cut a vertical slit, 30 mm. by 15 mm., in a sheet of cardboard and, at a horizontal distance of 15 cm. from it, a second hole in the form of a cross of the same dimensions as the former. This I fitted into an aperture in the shutter of the dark room and covered the one hole with

R paper and the other with G; so that there appeared a bright R patch and a bright G cross on a dark ground. I then fixed a glass prism with edge vertical and at a few inches in front of the R patch and turned towards the G cross, and brought one eye as close as possible to this edge of the prism in such a position that this edge fell across the centre of the pupil. By a little management of the prism I could then throw the image of the G cross reflected from its anterior surface on to the same area of the retina as the image of the R patch so that I saw a R patch with a Y cross upon it, as in figure 16. Slight movements of the head from side to side then cause the R or G to predominate, and at a middle position of the head they fuse to Y. On fixating steadily with relaxed accommodation and a + glass before the eye to preserve the definition of the patches there occurred at moments complete fading of the R patch, leaving

FIG. 16.

the cross a pure G, and at other moments the whole cross disappeared, leaving the R patch only; or some part, a vertical or horizontal limb, of the cross would disappear leaving the rest of the cross Y upon the R patch.

On using R and B in place of R and G both struggle and fusion to P occurred very readily.

A second method by which I have observed monocular struggle is the following:—

Observation XXVII.—In a large sheet of cardboard I cut two holes, each 30 mm. by 15 mm., the long axis of the one being vertical and of the other horizontal. Over one I pasted a sheet of R gelatine and over the other a sheet of G gelatine, and over both a sheet of white paper with closely set parallel black lines. On setting up the cardboard in a frame against a strong lamp the light comes through both paper and gelatine, and the holes appear as in figure 17, the one a bright R and the other a bright G, and both crossed by the

parallel lines diagonally. I then set a thin sheet of plane glass perpendicular to the cardboard along the line *a b*. On looking obliquely through the glass with one eye, the direct image of the one patch and the reflected image of the other could then be combined in the usual way, i.e., thrown so as to fall across each other upon the retina. There then appears a short-armed cross of which the centre is a square area in which the retina is affected by the rays from both the R and the G patches. In this area the diagonal lines of the two images cross one another at right angles, those of the reflected image being reversed.

A rivalry of the two sets of lines in this area is then very obvious if the brightness of the R and G patches be made about equal. It resembles closely the rivalry of lines that occurs on combining binocularly the cross-lined squares of figure x., plate viii., in Helmholtz's *Physiologische Optik*.

FIG. 17.

The lines of one or other set may be present alone at one moment, and then patches of lines of the other set may appear suddenly in parts of the area, or the one set may give way suddenly and completely to the other. The only difference between this rivalry and the binocular rivalry is that in this case the two sets of lines combine, i.e., appear simultaneously in consciousness, more readily, whereas, as we have seen, this can only be effected to a slight extent, in the case of the binocularly combined lines, by a great effort of attention. When the lines of the R patch appear alone they are G and the spaces between them are R, and conversely with the lines of the G patch; but when both sets of lines are visible in one area the spaces between them are Y.

On repeating this observation, using daylight from 'the bright sky instead of lamplight, the spaces appear W when both sets of lines are visible; otherwise the phenomena are exactly similar to the above described. The rivalry is in this case so striking that a lay person, who knew nothing of the subject or of the purpose of the experiment, on looking at the combined image at once remarked upon the curious play of lines and colours.

But the cross lines, although they assist, are not essential for the production of rivalry of the colours, as is shown by the following observation.

Observation XXVIII.—I laid a strip of crimson paper, 30 mm. by 15 mm., vertically upon a sheet of black paper and below it a similar strip of G paper horizontally, as in figure 18.

FIG. 18.

Then by means of a glass plate standing vertical to the paper along the line *a b* I combined the direct image of the one, with the reflected image of the other coloured strip so that they formed a cross. Then on steadily fixating with relaxed accommodation and with a + glass before the eye to preserve definition there appeared a lively struggle or alternation of the images in consciousness. At times both the R and G images were complete and the common square centre appeared a bright grey, at times the R or G image disappeared entirely leaving the other one alone and pure. This too I have repeated with other pairs of colours.

A third method by which one may observe the struggle between colour-systems of one eye excited simultaneously in corresponding areas is simply to fixate steadily a patch of light of not too low intensity for a considerable period. Since

every kind of light (except light of low intensity) stimulates all three colour-systems as well as the W-system, and since the tendency to complete fading of any image excited by continued stimulation of any one of the systems becomes greater the longer the image has remained present to consciousness, it may be expected that on prolonged fixation of any light one or other of the colour components of the image may fade completely, leaving the others still in consciousness. Such a case is described above in section i. (observation iv). In that case the R component of a R light faded leaving the W component only as a pure sensation.

Observation XXIX.—For me the simplest variety of this method of observing monocular struggle, is to fixate steadily the window-pane against an evenly bright white sky, such as is common in this country in bright wintry weather. After a period of fixation of a few seconds, a period which varies inversely as the brightness of the sky, each pane becomes suddenly a very bright G of low saturation. The G rapidly turns to B and then, after perhaps thirty seconds, patches of dull purple begin to appear and the panes show for some seconds all the familiar appearances of rivalry of R and B, such as are seen when the sky is looked at with a R glass before one eye and a B one before the other. After about fifteen seconds the B yields to the R and pure bright R alone remains and persists for two or three minutes, becoming gradually duller and losing saturation until only a dull grey remains.

A similar sequence of colours I have observed many times, using also sunlight transmitted by plates of milk-glass and ground-glass, or reflected by sheets of W paper. It never fails to occur if only the W light be bright enough. The only variation is in the initial stage in which B is sometimes present mixed with G, or alone. Thus, if I fixate the brightly glowing mantle of a Welsbach incandescent gas-lamp, a W light tinged with Y, it becomes, after a few seconds, a bright B which may persist from thirty to sixty seconds and then as rapidly becomes a pure bright R.

Fechner¹ has described a somewhat similar sequence of colours on fixation of bright W light, but he described the first colour to appear as Y. This difference is easily explicable, as I shall show later. He suggests that the phenomenon is due to the different rates of advance of fatigue in the different colour systems. In this I agree with him, but I would assign the fatigue, that is here concerned, not to the

¹ Pogg, *Analen.*, Bd. 1.

retina, as probably Fechner conceived it, but to the cortical levels of the different colour-systems.

Hering has described how, after fixating a bright patch of colour for some thirty seconds or more, and then diminishing its intensity, as by casting a shadow upon a fixated patch of coloured paper, or turning down the lamp which illuminates it, the original colour disappears and gives place to its complementary colour. When the fixation is further continued the complementary colour slowly loses saturation, until it passes back through a neutral tone to the original colour. Hering claims that all this can be accounted for in terms of his theory. However that may be, I have to describe a phenomenon similar to this but more striking and not easily to be reconciled with Hering's theory. The observation consists in the application of the method of simple prolonged fixation to patches of coloured light of good saturation and medium brightness.

Observation XXX.—I laid a strip of R paper on a ground of medium grey in the full light of a strong reading-lamp and at a distance of 12 inches fixated with one eye, the other being covered, a spot on a square of W paper 2 mm. in width, laid on the centre of the R paper. I maintained full accommodation by a voluntary effort in spite of a tendency to relaxation that soon made itself felt. For about two minutes the R simply grew less saturated and then a veil of pale G seemed to shoot suddenly across the R, which seemed to remain visible through it, and then to retire as suddenly after about two seconds. This occurred several times in rapid succession, and then, after two minutes from the first appearance of this G veil, the R suddenly disappeared entirely and was replaced by a rich B-G, quite as saturated and vivid as the R itself when first fixated. The B-G persisted for about two seconds and then suddenly gave place to the pure R of undiminished saturation and brightness. This alternation of R and B-G occurred several times at short intervals. Then, while still fixating steadily, I relaxed my accommodation, whereupon the whole field of view faded completely, except the W square, which remained very dimly visible. Then this too faded completely and I experienced the sense of absolute darkness or blackness mentioned in observation iii. which I hold to be due to the condition of complete inactivity of the visual cortex, as distinct from the condition in which the 'Eigenlicht' is at work while there is no stimulation from outside. This absolute blackness endured only about two seconds and then the W square slowly emerged from the darkness into consciousness, followed by the R strip

and then by the rest of the field. This complete fading of the whole field recurred several times while I allowed my accommodation to remain relaxed. Then, by a voluntary effort, I restored full accommodation once more, when the complete fading ceased to occur and the alternation of R and B-G set in again and continued as long as I continued to fixate, the R predominating in the length of its periods, though the B-G was not inferior to it in vividness and saturation.

This observation I have repeated many times with slight variations of the conditions. Its novelty and theoretical importance will perhaps justify the description of a similar fixation, the results of which differed instructively from those described above.

Observation XXXI.—I laid a disc of R paper on a grey ground in strong lamplight. The R inclined a little to the orange side of pure R. I fixated as before with full accommodation. After two and a half minutes the first marked change of colour occurred, the R passed rapidly through Y to a pure bright G, the transition lasting only about one second or less. After two to three seconds the G gave place again to R. These changes from R to G continued to occur at intervals of ten to thirty seconds throughout the next twenty minutes. In the stage of transition a yellow phase was usually though not always perceptible. After twenty minutes there was perceptible some B mixed with the G and sometimes there was a glimpse of pure B, and then during a further period of fixation of about twenty minutes there occurred frequent changes of R to B-G, and usually there was perceptible a momentary grey phase during the transition.

The shortest period of fixation, after which I have observed this reversal of colour on simple fixation, was eighty seconds. For a long time I failed to observe any such change, save while accommodation was maintained, but I have once seen it during relaxation of accommodation. I have seen it equally well when using both eyes and in-bright daylight as well as in lamplight.

I have observed similar changes to the complementary or approximately complementary colours on simple fixation of patches of B, G and P, although in my case it occurs most readily, I think, with R. A striking way to make the observation is to place a R and a G strip side by side with only a narrow band of grey ground between them. Under such conditions I have seen the R strip become G, and at the same time the G strip become a reddish purple, so

that the two strips almost seemed to have exchanged places.

One interesting feature that sometimes occurs I have yet to describe. During fixation of a R strip the B-G sometimes shoots across it without entirely covering the strip, for the R is still visible in tiny spots, so that it appears to be seen through numerous minute holes in a B-G cover. This resembles closely the phenomenon of 'Glanz' sometimes observed during binocular colour-mixture.

Sometimes at the moment of reversal of the colour, I am conscious of a slight sense of muscular activity about the eyes, and it is possible that slight contractions of the pupil are the occasions of the reversal in many cases. For if the fixation be made with partially relaxed accommodation the reversal can then be brought about at will by increasing the degree of accommodation, and at the same time, of course, narrowing the pupil and so cutting off from the retina some of the rays from the coloured strip. But frequently I cannot detect any change of accommodation or sense of activity of the eye-muscles at the moment of reversal, and a change in the pupil can only be an assistant cause of the change of colour in any case.

The full explanation of this phenomenon of reversal of colour during prolonged fixation I must defer until after treating of after-images of coloured light. Here I will only point out that it is clearly a case of struggle between the different colour-systems of the one eye, simultaneously excited in coinciding areas of their retinal levels.

In the case of a compound colour such as P it is obvious that two kinds of struggle are theoretically possible on fixation, firstly, a struggle between the R and B, the R and B systems being equally stimulated by the P light, and secondly, a struggle between P and its complementary G. This latter kind of struggle occurs when a simple patch of P light, as a strip of P paper, is fixated for some minutes with accommodation maintained. The other kind of struggle, that between R and B, I have been able to observe only when accommodation is relaxed, and the R and B areas do not exactly coincide. The following observation illustrates the influence of the lack of coincidence of the retinal areas stimulated in the R and B systems.

Observation XXXII.—I cut a hole 15 mm. by 10 mm. in a piece of cardboard and fixed the cardboard over an aperture in the window-shutter of the dark room, and covered the hole with a piece of the P paper supplied by Rothe for the colour-wheel. On fixating this bright P patch, with accommodation main-

tained, struggle occurred between P and G, and with relaxed accommodation I could not observe any change of colour. I then fixed a glass prism vertically before the shutter in such a position that on looking into it I could see the P patch refracted through the prism. The patch then appeared as two overlapping patches of coloured light, the one R the other B, and P where they overlapped, as in figure 19. Each was fairly sharply bounded, for apparently rays of two wavelengths only are transmitted in any quantity by this paper. I fixated with one eye with relaxed accommodation and a + glass before the eye to preserve the definition of the images. There occurred then just such a struggle of R and B as results when R and B patches are made to overlap binocularly by fixation of two separate patches of R and B with both eyes and parallel visual axes. Sometimes the R faded completely leaving the B alone, sometimes the B leaving the R alone, sometimes the lateral strip of pure R or B faded leaving the

FIG. 19.

rest of the figure, and sometimes both lateral strips leaving only the middle strip of P.

The influence, favouring the struggle of R and B, of the lack of coincidence of the stimulated retinal areas of the R and B systems seems especially interesting. It is due largely, or perhaps wholly, to that tendency to cohesion of parts of a homogeneously stimulated area of any colour system which was illustrated by observation xv. We have here a factor of which it is impossible to say that it is physiological or psychical, or rather we seem to get a glimpse of the physiological mechanism underlying what may be properly accounted a psychical factor.

We seem to have in this method of prolonged fixation a means of distinguishing between the physiologically simple and the compound colours, namely by observing whether they are capable of analysis into two constituent colours or only capable of reversal to the complementary colour. It is

interesting then to apply this test to Y, which is claimed by Hering as a simple colour. Under this test Y behaves as a compound colour, showing a struggle of R and G.

Observation XXXIII.—If I fixate any patch of bright Y light, a square of ground-glass covered with Y gelatine and held up against the sun, or the flame of a lamp seen through a sheet of Y gelatine, it becomes after some seconds, and the more rapidly the brighter the light, a pure bright R, which persists a few seconds only and then passes back rapidly through Y to become a pure bright G which seems to persist indefinitely.

Y does not readily become B under the conditions under

FIG. 20.

which R, B, G and P become reversed to their complementary colours, and even when I fixate a strip of Y paper and after thirty seconds cast a shadow upon it, it becomes not B but R, and it is only after more prolonged fixation that diminishing the illumination will make it change to B. This lesser tendency of Y to give place to its complementary colour is, I think, due to the fact that in my case the B system is less vigorous and self-assertive than the G and R systems, a fact other indications of which I shall point out below.

One other observation seems to find its proper place here. Just as a patch of colour may be changed to its complementary colour by diminishing its brightness after a period of

fixation of thirty seconds or more, so it may be changed by adding W light to it.

Observation XXXIV.—I laid on a dark table a sheet of W paper and beside it a broad strip of G paper with a smaller strip of R paper upon it as in figure 20. With my right hand I held a sheet of plane glass vertical to the table along the line *a b*. In my left hand I held a large sheet of S paper which I laid over the W sheet. I then fixated the point *x* looking down upon the coloured slips obliquely through the glass plate. If I then withdrew at once the S paper so as to uncover the W paper, the W light from it reflected in the glass mixed with the R and G of the coloured slips and considerably reduced their saturation. But if I continued to fixate for thirty seconds or more while the W paper remained covered and then exposed it, the G and the R were both changed to their complementary colour, which of course was mixed with the reflected W light and therefore of lower saturation than the strips themselves; so that in place of a R strip lying upon a larger G strip, I saw a B-G strip lying upon a larger R strip. On continuing the fixation with the W paper exposed, the colours passed slowly back through a neutral tone to the original R and G mixed with W.

This reversal of colour may be very conveniently observed by the use of the apparatus for testing for colour-blindness devised by Hering and made by Rothe. If the two halves of the circle be made R and G respectively, and W light thrown in after fixating for thirty seconds, the R and G semi-circles became G and R respectively.

MONOCULAR STRUGGLE AS OBSERVED IN AFTER-IMAGES.

In section iii. I have advanced the view that, by the action of light upon the retina, substances (which I there called X-substances) are set free which, by a further chemical change capable of proceeding in the absence of light, but accelerated by the incidence of light-rays, excite the endings in the retina of the fibres of the optic nerve, and I suggested that after-images are due to the persistence in the retina of the action of the excess of these X-substances set free and not used up during the action of the light. In dealing with the after-images of W light I did not attempt further to define these X-substances.

Young's theory demands three such substances, R, G and B X-substances, and we have seen that it is necessary in the light of modern research to add a fourth, a W X-substance,

having its seat in the rods and in all probability of small importance in vision in ordinarily bright light, while the R, G and B X-substances must be assigned to the cones. After stimulation by bright W light, there must then be present and active in the retinal area affected all four X-substances.

Since monocular struggle of colours, involving, as it does, the complete fading of the parts of a compound image due to the activity of one or two of the three colour systems, can occur during the fixation of an unchanging patch of light, when all the sensation elements are reinforced by the activity of the ocular muscles, it is to be expected that it should occur much more readily in the case of after-images, if the view of their nature indicated above be the true one. After what has gone before it must be obvious to any one who will make the necessary observations that the familiar phenomena of '*farbiges Abklingen*' of after-images is simply a case of monocular struggle.

Fechner, who described the phenomena of '*farbiges Abklingen*' very carefully,¹ did not offer any satisfactory explanation of the successive appearance of the colours. At that time Hering's theory had not been proposed or doubtless Fechner would have applied his observations to the refutation of it.

Helmholtz accepts Fechner's account of the phenomena but does not throw any new light on the subject.

Unfortunately Fechner described the phenomena as resulting from what he called '*Blendung's Bilder*,' and his splendid enthusiasm led him to do very serious injury to his eyes by gazing at the sun in order to observe them. This name and this deplorable result, together with the warning given by Helmholtz in this connexion, have tended, I suppose, to make observers shy of the subject and to create the impression that there is something abnormal and quasi-pathological in the whole series of phenomena.²

Hering³ puts aside the whole subject with the remark that

¹ *Pogg. Analen.*, Bd. I.

² Fechner seems to have exposed his eyes to unnecessarily bright light. I have not found it necessary to fixate a brighter light than bright sunlight transmitted through ground-glass, and this only very rarely. Although I have many times fixated very bright lights for periods ranging up to ninety seconds and less bright lights for periods ranging up to fifty minutes, my eyes do not seem to have suffered appreciable injury from the work. In fact, a prolonged fixation produces now less discomfort about the eyes than when I began to work at this subject. The only ill-effects that have made themselves felt have been slight deep-seated headache, passing off in a few hours, and slight inflammation and thickening of the eyelids, passing away always during a few weeks' rest.

³ *Zur Lehre vom Lichtsinne.*

the colours that appear in the after-image of W light are of low saturation and due to feeble unnoticed coloration of the seemingly W light, while Müller has not yet attempted to deal with it.

Miss Washburn¹ has recently given an account of the '*farbiges Abklingen*' following fixation of patches of white cloud, and her descriptions agree in the main with Fechner's and with those given below, but for the purposes of this essay it is necessary to describe the phenomena anew and to point out some features not hitherto described, so far as I have been able to ascertain. For this purpose I have made series of observations on the after-images given by W light of different intensities, using as source of light sunlight and light from W clouds transmitted through plates of ground glass and milk-glass, as well as patches of sky and cloud and pieces of W and grey paper exposed to daylight of all degrees of brightness, and also the light of the incandescent gas-lamp transmitted through ground glass and milk-glass. In the case of all but the brightest lights it is advantageous to use a shaded disc as the source of light, else the after-image is complicated by the presence of a halo. Some of these observations are partially described in section III.

I there mentioned that in all cases of stimulation by W light, except in the case of the duldest light that will yield an after-image in the dark, there appears some coloration of the after-image, and that the colours are of low saturation in the after-image of dull W light, and are more saturated the brighter the light. The colours that I usually see in the after-image of dull W light are R and G. Sometimes in the first one to two seconds after the exclusion of the light it is impossible to make out any definite after-image although one may have an indefinable sense of something going on in the area of the retina affected. Sometimes a grey and sometimes a B of very low saturation, i.e., a bluish-grey, follows immediately. A few seconds after exclusion of the light a R of low saturation almost invariably appears, persists for a variable period according to the brightness of the light, and then enters upon a dull patchy struggle with G, in which the G, also of low saturation and brightness, soon gains the upper hand and then persists as long as the after-image is at all visible. With a still dimmer grey light or a fixation of shorter duration the after-image is merely a fuzzy grey patch that dies away in the course of a few seconds.

If the W light fixated be rather brighter, the colours

appear more saturated but run much the same course. The last stage is always in my case a dark G of fair saturation fading slowly away. The R preceding the G is rather less constant in its appearance and the B of the first few seconds, though frequently perceptible, is the least constant and often it is replaced by a violet tinge which quickly gives way to R or G.

If, in the above cases, a sharply bounded patch of light be fixated in place of the shaded or half-shaded disc, the play of dull colours in the after-image can usually be observed equally well, unless the fixation has been continued for a considerable time, in which case the halo is usually bright enough to inhibit the activity of all the colour systems, including the W system, in the area of the after-image for part or the whole of the duration of the after-image, so that the so-called negative after-image of W light appears, as described in section iii.

With still brighter W light the colours of the after-image gain in saturation and also in constancy of appearance and sequence, until when a W light, that is bright enough to be slightly dazzling, is fixated for a period not less than fifteen seconds the appearance and sequence of the colours is almost quite constant. Such a degree of brightness I obtained by reflecting sunlight from a flat mirror on to and through the sharply bounded disc of milk-glass. The milk-glass cuts off a very large proportion of the light so that the disc seen from the dark room is by no means very dazzlingly bright. With such a disc I made the following series of observations.

Observation XXXV.—In each case I fixated a dark spot near the centre of the disc, with both eyes at a distance of 18 inches, and then suddenly shut off the light by releasing the photographic shutter.

(a) Fixation for half a second. After-image—an evenly bright B of fair saturation which becomes less saturated and gives way after twenty seconds to a dark G that slowly fades away.

(b) Fixation for five seconds. After-image—during first one to two seconds I could distinguish nothing definitely, then emerging as out of a haze appeared a bright R disc which became momentarily Y several times as it struggled with G and then gave way after thirty seconds to dark pure G, which faded slowly away in about sixty seconds.

(c) Fixation for twenty seconds. After ten seconds' fixation the W disc became bright G of increasing saturation. After-image—a very bright yellowish-G disc with narrow R border. The Y-G begins at once to recede from the R border and

then comes and goes in patches on the now R disc. The patches of Y-G continually diminish in size and are confined more and more to the centre of the R disc, until after two minutes the R disc remains of pure very saturated R with a narrow B border. It remains thus for seventy seconds and then the R begins in turn to recede towards the centre, while the B border spreads inwards, until the whole appears as a pure B disc with small patches of R struggling with the B about its centre. Then the disc remains for about fifty seconds a pure saturated B which then gives way rapidly to pure dark G, and this fades slowly away in about one minute.

I have chosen this series for description because it proves, if any proof be needed, that the colours of the after-image of W light are not due to unperceived coloration of the W light, as Hering has suggested, for in this case the same W-light is followed immediately according to the period of fixation by B, R or G.

Of the three after-images described above the third is the most important, for it presents most of the features that appear very constantly in my own case after fixation, for not less than fifteen seconds, of bright W lights of all intensities except the very brightest that can be easily borne. The G of the first phase varies, according to conditions which I have not been able to determine, from a very pure saturated bright G to a bright golden Y. When the latter appears there is always visible a R border to the disc. Frequently a pure bright G disc develops a R edge and then the G becoming yellower retreats upon a R ground towards the point of fixation. This retreat of the colours towards the point of fixation is a very constant feature. Each of the primary colours appears in turn at the edge of the disc as a border to the colour in possession of the field, and then as the latter retreats towards the point of fixation the former appears as the ground upon which the latter struggles in patches before it disappears and leaves the former filling the field. During the struggle the retreating colour sometimes appears as a veil through which the other colour is seen. This feature, the retreating towards the point of fixation, is probably an indication of the fact that the colour systems are most vigorous and fully developed in the fovea centralis in the retina, and in the corresponding parts of their cortical levels.

Observation XXXVI.—One more example of the '*farbiges Abklingen*' when still brighter W light is used, namely, sunlight transmitted through ground-glass; this is a W light of dazzling brightness. I fixated a point on the ground-glass for twenty-five seconds. The after-image appeared at

once as a brilliant bluish-W disc. This persisted fifteen seconds and then became B-G with a G edge, and then the B retreated rapidly towards the point of fixation and disappeared, leaving a bright pure G disc; this, developing a R edge, persisted unchanged for about sixty seconds; then G began to retreat and appeared as Y-G patches struggling upon a R ground and becoming more and more Y until they disappeared leaving a pure R disc with a B edge. After persisting unchanged about twenty seconds the R struggled on B in just the same way and then disappeared leaving a disc of pure rich B. The B remained unchanged forty seconds and then struggled with and gave way to G, which then persisted to the end, fading slowly away.

The two observations last described illustrate a very constant feature of such after-images, namely, the tendency of the three primary colours to follow one another in a recurring cycle of the order G, R, B, G, R, B. In the one case the cycle passes from G to G in the other from B through G R B to G again, thus almost completing the double cycle. If the W light be only moderately bright R is usually the first colour to appear and is then succeeded by G which persists to the end. After brighter light G comes first and is succeeded by R then B and then G again. If the light be still a little brighter the G is usually mixed with R from the first, i.e., it appears Y and has a R edge; and if the light be very bright then the first phase of the after-image is W or bright B of very low saturation, i.e., a mixture of all three colours in which B slightly predominates. The B then soon passes through B-G to pure G which is then followed by the cycle of pure colours

An important feature of the after-images of bright W light is that, after the first short period in which two colours fuse to give Y, or, as is the case after the brightest lights, all three fuse to give W, the colours that in turn occupy the area of the after-image, alone and unchanging for considerable periods, are R, G and B only, and these are in every case of exactly the same colour-tone although varying in brightness or intensity in different cases and in different stages of one after-image. The R is a rich crimson R, decidedly less orange than the R of the solar spectrum, the B is a rich ultramarine B, and the G a pure G which I can only describe as having no inclination towards B or Y. They seem to agree as closely as possible with the colours which Herr König and Herr Dieterici have deduced as the desirable primary colours (*Grundempfindungen*) from their experiments in colour-mixing and which they describe as a R inclining somewhat

from the R of the spectrum toward P, a G of wave-length $505 \mu\mu$ and a B of wave length about $470 \mu\mu$.¹

They are the purest, richest, most saturated colours that I have ever experienced, and I believe that in this way, and this way only, one may experience absolutely simple, i.e., unmixed and fully saturated colour-sensations.

These are the only colours that fill the whole area of the after-image at any time after the first few seconds. In the periods of struggle small patches of mixed colour may appear for a few seconds, especially at the edges of patches of the retreating colour as they struggle upon the other coloured ground. The Y which frequently follows at once upon the W light always reveals its mixed character by resolving itself into G struggling upon a R ground, or more rarely into R struggling upon a G ground.

After what has gone before, the explanation of the principal features of '*farbiges Abklingen*' is obvious. During the action of W light on an area of the retina there are set free in it R, G, B and W X-substances. When the light ceases to reach the retina the excess of these substances remains and continues to excite the four sets of nerve endings, those of the R, G, B and W systems respectively. If the W light is feeble there is set free a relatively large amount of the W X-substance, for this system is especially adapted for stimulation by light of low intensity. In the after-image the W element therefore predominates, and if the W light be dull enough the W system alone may excite the after-image. Brighter W light sets free larger amounts of the R, G and B X-substances, both absolutely and relatively to the amount of W X-substance. With the increased intensity of the colour-processes, corresponding to the larger amounts of X-substances remaining after the light is shut off, the antagonism between the colour-processes becomes more acute, and the duration of the after-image is greater. Hence, with increasing brightness of the W light fixated, we see colours of increasing purity, and each of the three primary colours predominates in turn. In the period immediately following the shutting off of the light the colour-systems tend to function together, probably because the intensity of their excitement is unfavourable to 'complete fading'. But the increasing fatigue of the cortical levels and the diminishing intensity of the retinal processes favour the occurrence of 'complete fading' until one or other colour-system is enabled to predominate over the others. While, then, the cortical area of

¹ *Zeitsch. f. P. u. P. d. S.*, Bd. iv., S. 343.

this one system, say the G system, remains active, the activity of the corresponding cortical areas of the R and B systems are inhibited by the activity of the G system. They remain at rest, and recovering more or less from their fatigue, while the fatigue of the cortex of the G system is increasing, one of them, usually the R system, soon triumphs over and inhibits the activity of the cortex of the G system. The R cortex then functions alone for a space until the B cortex, being still further recovered from its fatigue, triumphs in turn over the R. The B cortex yields in turn to the G which has now enjoyed the longest period of rest. *Hence the regularly recurring cycle of colours—each colour-system is continuously excited by the appropriate X-substance in the retina, but, owing to the mutual antagonism of the cortical activities of the three systems, that of one inhibits that of the other two systems, the conditions being favourable to 'complete fading,' until in turn it is inhibited by the activity of the more rested of the other two.*

What determines the order of precedence of the predominance of the colour-systems it is hard to say. The frequent predominance of G in the first stage seems to be due to the fact that the G systems of my eyes are more vigorous than the others, the R and the B systems, a fact of which other indications will be noted below. But however this may be, it is clear that, when any one colour-system has once gained the predominance, the cycle is set up and must recur so long as there are the three X-substances at work in the retina.

One more feature of the after-images of bright lights is noteworthy and not, I think, described by Fechner. When the colours have quite died away, and can no longer be recalled by admitting light to the retina or by other means, there is usually visible a dull fuzzy grey occupying the area of the after-image, but distinguished from all the preceding phases of the after-image by its lack of definition; thus if the object fixated was the window-frame against a bright sky, the cross-bars of the window, which appear more or less clearly defined in all the coloured phases of the after-image are not to be made out in this last phase and the borders of the after-image are not sharply marked but fade away gradually into the darker surrounding area. If, during this stage, the eyes be opened and directed towards a dull W surface a patch, corresponding in shape and position to this last phase, appears slightly darker than the rest of the surface.

The hypothesis at once suggests itself that this dull grey after-image, which survives the after-effects of light on the colour-systems, is due to X-substances of the W system still remaining in the retina. This suggestion finds support in

the fact that in its peculiar indefiniteness of outline it closely resembles the after-image that follows stimulation by W light too feeble to produce a coloured after-image, and this, as we have already seen reason to believe, is due to the W system acting alone. If, as there seems good reason to believe, this W system is specially adapted for vision by light of low intensity, then stimulation by fairly bright W light must be for it a maximal or very violent stimulation, which may completely decompose all the available mother X-substance of the W system. There would then be set up in the W system a condition similar to that produced in the whole group of systems by excessively bright light, such as direct sunlight. The effects of such stimulation I have already discussed in section iii., and it is only necessary to point out that, if we assume the condition of affairs thereby set up in the whole group of systems to be in this case confined to the W system, we have a satisfactory explanation of this last phase of these after-images. The diffuse character of the after-image having its seat in the W system must be due to a greater diffusion of the W X-substance than of the X-substances of the colour-systems, and when we remember that the rods, the seat of the W X-substance, are much more closely packed together than the cones, this feature too becomes intelligible.

In my eyes the G apparatus seems to be the most vigorous and self-assertive of the three colour-systems, for as in the case described above (observation xxix.), it always predominates first over the other two, during fixation of bright W light, and it usually predominates in the first phase and alone affects consciousness in the last coloured phase of the after-image of bright W light. This is further borne out by the facts that a same-coloured after-image appears more readily for G light than for other coloured lights and is then more persistent, that G shows the phenomena of reversal less readily than R or B, and that a bright Y light always becomes and remains G after perhaps a short R phase.

In respect to the relative vigour of the three colour-systems there seem to be considerable individual differences. Of three other subjects of whose vision I have made some slight investigation in this connexion, in one the R system seemed to correspond to my G system in being relatively more vigorous than the other two, for in his case same-coloured after-images of R occur most readily, R predominates in and forms always the last slowly dying phase of the after-image of bright W light, and a bright Y light always becomes for him a blood R and remains so during prolonged fixation.

In the second subject the B system seemed to be the most vigorous, for in the after-image of bright W light B always appeared early and formed the last coloured stage which in my case is always G. In the third subject the relative vigour of the three systems seemed to be the same as in my own case.

Observation xxxv. has already shown the futility of Hering's suggestion that the colours which appear in the '*farbiges Abklingen*' are due to unperceived coloration of the W light fixated, for it shows that according to the duration of fixation the same W light may be followed immediately by R, G or B. Further, the colours appear after stimulation by every variety of W light that is bright enough to give more than a very dull grey after-image, after fixation of every kind of W paper exposed to all varieties of direct and diffused sunlight and of every shade of grey and white cloud. Hering also remarks that the colours of the after-image of W light are of low saturation. I have already stated that in a good case of '*farbiges Abklingen*' the colours that appear are the richest and most saturated colours that I have ever experienced, but the following simple observation will add weight to this testimony.

Observation XXXVII—I fixated for a few seconds through the upper part of the window a patch of bright W cloud. With covered eyes the after-image appeared a rich G, and on projecting it on to a sheet of W paper exposed to bright diffused daylight it still appeared as a G of very fair saturation.

The observations described above in this section are sufficient, I think, when viewed in the light of the foregoing sections, to prove the mutual antagonism of corresponding cortical areas of the different colour-systems and the occurrence of monocular struggle. *This antagonism, or tendency of the activity of any part of the cortical area of one colour-system to inhibit the activity of corresponding parts of the cortical areas of the other two colour-systems, exists then between the different colour-systems whether they belong to the same eye or to the right and left eyes respectively; but in the case of systems belonging to the same eye the antagonism is much weaker than between systems belonging to opposite eyes, and in the former case it makes itself felt, during the action of light in the retina, only under special conditions.*

This antagonism between the colour-systems of the same eye is indicated in the diagram, figure 15, by the broken line joining corresponding points of the cortical areas of the three systems. Throughout this section I have assumed that the psycho-physical processes underlying the sensations of R, G

and B go on in three anatomically distinct sets of neurons, as represented in the diagram (figure 15). The neurons of the three sets forming the colour-apparatus of either eye might of course be interwoven with one another in such a manner that no coarse lesion could affect those of any one set without also affecting those of the other two sets. We have no *a priori* ground for assuming that the three psychophysical processes may not consist in three different kinds of activity in one set of neurons, but I think the phenomena of monocular struggle and their essential similarity to those of binocular struggle, as demonstrated above, go far to prove the truth of the view that the R, G and B psycho-physical processes take place in three distinct sets of neurons. It would be highly satisfactory if we could suppose that the R, G and B X-substances are set free equally in all the cones and that each cone is capable of three corresponding kinds of excitement, and that it makes connexion in the retina with three kinds of fibres, each capable of taking up one kind of excitement from the cone. But the number of fibres in the optic nerve (Helmholtz, *Phys. Optik* S. 263) seems to be smaller than the number of cones, and it is perhaps necessary to assume that the fibres of the optic nerve concerned in colour-vision are capable of three kinds of excitement each of which diverges into its proper track at a higher level. In this connexion it is interesting to note that the fibres of the optic radiation, i.e., the fibres connecting the lower cerebral visual centres to the visual cortex, are much more numerous than the fibres of the optic nerve; according to Prof. Flechsig, five times as numerous.¹

In the succeeding sections I have to show firstly, that the theory of simultaneous contrast suggested in section iii. holds good also for simultaneous colour-contrast, and secondly that monocular struggle plays an important part in the after-images of coloured lights, and that it is the key to the understanding of certain phenomena that hitherto have been stumbling-blocks in the way of Young's theory.

¹ Die Localisation der Gestigen Vorgänge. 8. 37.

(To be concluded.)