ON RECIPROCAL ACTION IN THE RETINA AS STUDIED BY MEANS OF SOME ROTATING DISCS.

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SECTION I. *Introduction.*

JOH. MÜLLER described the elementary parts of the retina as being connected together by "reciprocal action[1]." The physiological result of application of a stimulus to any given point of a sensifacient surface is decided by not only the particular stimulus there and then incident but also by circumjacent and antecedent stimuli. That is to say—using the words "retinal point" to mean the retino-cerebral apparatus concerned with the elaboration of a light sensation in response to excitation of a single point of retinal surface—the excitability of the retinal point at any moment is partly the outcome of circumjacent, especially of immediately circumjacent, and of antecedent, especially of immediately antecedent, retinal events. The reciprocal relation between the degrees of excitability at points separated by an interval of space is evidenced by the phenomena of "simultaneous contrast": the phenomena of "successive contrast" show the reciprocal relation across an interval of time. To Hering we owe especially important observations on the subject. By him the reciprocal process influencing the excitability of retinal points across space or time is referred to as "induction."

The experiments described in this paper attempt to examine

[1] Müller. *Handbuch der Physiologie des Menschen* (1837–1840).

retinal "induction" by means of rotating discs. I am aware that in studying the subject thus by aid of moving chequered surfaces—that is, under intermittent excitation—time relations enter introducing complexity and preparing pitfalls for the observer. In the two well-known simultaneous contrast discs given by Helmholtz[1] the translation of surface is intended merely as a means towards the attainment of those smooth sensations—*e.g.* homogeneous greys—which offer such favourable fields for contrast. The rate of translation used is one ensuring perfect fusion of the sectors. So also in those few of the beautiful series of contrast experiments by Hering in which use is made of the colour top[2]. Advantages however as well as drawbacks accrue to the employment of moving surfaces even at lower speeds. Some of the induction (reciprocity) effects then obtainable from rotating discs under comparatively simple conditions of production seem striking enough for me to venture the following description and discussion.

SECTION II. *Preliminary experiments.*

Rood[3] has recently re-introduced to notice a method of photometry advocated but not on very convincing grounds by Schafhäutl[4] forty years ago. The method is based on Plateau's[5] research, and proceeds on the well-known relation existing in light-sensations between their intensity and the rate of frequency of repetition required to fuse them. In order to obtain a steady sensation from a reflecting surface intermittently illuminated—the illumination being of moderate intensity—the frequency of intermittence required increases as the illumination is heightened, and diminishes as the illumination is lessened. Illumination remaining the same, a disc half white, half black, must in order to give a steady grey sensation rotate more quickly than a disc half light-grey, half dark-grey. If the difference between the luminosity of the two grey halves be reduced the angular velocity necessary to excite homogeneous grey sensation is correspondingly diminished. When the difference between the greys is nil the uniform grey is obtained at zero of angular velocity, that is, without rotation. In all cases at frequencies of intermittence insufficient to produce uniform sensation but sufficient to confuse the limits of the individual stimuli the sensation has a

[1] *Physiol. Optik.* p. 411 and p. 413. Part II. 1860.

[2] *Pflüger's Archiv*, XLI. p. 1. 1887.

[3] *American Journ. of Science*, XLVI. p. 173. 1893.

[4] Universal Vibrations-photometer: *Akad. d. Wiss. München*, VII. p. 465.

[5] *Dissert. sur quelques propriétés des impressions &c.* Liége, 1829.

vibratory character, is of "flickering" quality. "Flicker" is not agreeable: the smooth perfectly steady sensation is perfectly agreeable; to pass from one to the other is a transition from painful to pleasurable: perhaps this explains the relative abruptness of our recognition of the transition. On this abruptness depends the delicacy of Rood's flicker photometry, and on the constancy of relation between light-intensity and rate of intermittence needed to extinguish flicker.

Fick[1] has shown that a more intense light sensation developes more speedily than does a less intense. Exner's[2] actual measurements found the time decrease nearly arithmetically with geometrical increase of luminosity of stimulus. Plateau[3] had noted that strong light-sensations suffer perceptible decrease more quickly than do weak—that is, had found his "duration of apparent constancy" more brief for the former; and Charpentier[4] has found the duration less for retinal points corresponding with the peripheral part than for those corresponding with the central part of the field of vision. According to Ferry[5] "the persistence of the retinal image" varies inversely as the logarithm of the luminosity of stimulus. With these facts in mind the delicacy of the flicker method led me to enquire whether "flicker" may be applied with success to the examination of the influence exerted on the intensity of light-sensations by contrast both of place and time, that is, using Hering's term "induction," by areal and by temporal induction.

At outset it is well to recall the fact that increase of rate of rotation needful to extinguish flicker accompanies increase of intensity of the intermittent stimuli up to only a certain pitch of intensity of stimulation. Beyond that pitch further increase of intensity diminishes the flickering of the resultant sensation even when the rate of rotation (frequency of intermittence) remains unincreased. This Bellarminow[6] points out, and I myself have seen from experiments carried out independently in my laboratory by Mr O. Grünbaum. I have therefore confined my observations to the wide and ordinary range of stimulation at which the experiments demonstrating Talbot's law are carried out.

Again, before making use of rotating discs for contrast phenomena it is needful, as a control, to see whether differences of mere radial

[1] *Arch. f. Anat. u. Physiol.* 1863.

[2] *Sitzungsb. d. k. Akad. d. Wiss. Wien*, 1868. *Pflüger's Archiv*, III. p. 214. 1870.

[3] *loc. cit.*

[4] *Archives d'Ophthalmologie*, 1890.

[5] *American Journ. of Science*, Oct. 1892. See also E. L. Nichols, *ibid.* Oct. 1884.

[6] *Archiv f. Ophthalmologie*, xxxv. p. 25. 1889.

distance influence the results. Marbe[1] and Schenk[2] (with Schmidt) have examined this point on discs with alternate equal black and white sectors. The former finds fusion rather more easy along arcs further from than nearer to the centre of the disc; the latter that with increasing speed of rotation "flickering" persists longer in the peripheral zone than in the central. I examined the question myself at the very outset of the present research, less to investigate it minutely than to know whether the disputed difference is either way enough in amount to disturb the results expected in my projected contrast experiments.

I looked into the influence of radial distance first by using two discs 30 cm. diam. carrying 20 and 30 equal sectors respectively of alternate black and white. These were spun in the horizontal plane. The lighting was by three equidistant approximately equal electric lamps. The disc was covered from the observer by a horizontal screen as close to it as the side illumination would allow. Two round holes were cut in the screen, each 1 cent. diam.; these were 3—12 c. apart and could be set so as to lie along a radius of the disc. The observer did not observe the two holes together, but turned the eyes from one to the other, as the disc rotated beneath. It was easy to see that the disc spinning with slowly increasing velocity the sectors of the disc as they moved past the two holes suffered confusion as to their borders earlier at the hole nearer the periphery of the disc, where the linear velocity was greater, though the angular velocity the same of course as at the more central. At greater speeds when very marked at the central hole flicker was far less so at the peripheral; finally as the speed increased further flicker, both to myself and to other observers, disappeared at the peripheral hole while still perceptible at the more central. But the difference between the extinction-speeds of the flickers at the two holes was not so great as the marked difference in amount of flicker in the holes at lower rates would have led one to anticipate.

With this arrangement of the experiment it was not easy to observe under any but low luminosity. A black disc 30 cm. diam. was therefore made with 16 sectors cut out in it equal in angular measurement to intervening sectors left. This disc was rotated in a vertical plane in front of a vertical ground-glass screen illuminated from behind by an oxygen-hydrogen limelight. A lantern condenser and lens were used to concentrate and equalise the illumination of the screen. The rotation of the disc was by a water motor or a clockwork. The observations were made through two round holes as before. The same results as with the other arrangement were

[1] *Wundt's Philosophienstudien*, XII. 280.
[2] *Pflüger's Archiv*, LXIV. p. 165. 1896.

observed for low and medium illumination but with high light no difference in extinction-speed for the two holes was observable, and with very high light the flicker seemed to persist longer at the more peripheral than at the more central hole; but the difference was slight.

My results in this matter—as far as I have, in the above manner, studied it—agree with Marbe when the luminosity is low, with Schenk when the luminosity is high. To the question for which I particularly desired an answer I obtained the reply that in regard to the influence of radial distance upon "flicker" it is but small. Its value compared with the values of my contrast effects obtained later is quite insignificant, especially under moderate illuminations of the disc.

Another excellent investigation by Schenk (and Schmidt)[1] deals with "flicker" as influenced by the angular width of the sector. Filehne[2] noticed that with discs of equal alternate black and white sectors the frequency of intermittence of stimulation is not in exact agreement when discs of many sectors are compared with discs of few sectors. The discs of many sectors have, to extinguish flicker, to rotate relatively faster than theory demands. Mere linear velocity seems to assist the fusion of the sector sensations. Schenk's[3] examination of this phenomenon serves as a control in this respect for experiments brought forward in my communication. Fick[4] had suggested that unnoticed movements of the eyeballs may be responsible for Filehne's phenomenon. Concordantly with that suggestion Schenk finds it very greatly reduced when the observations are carried on through a narrow slit cut radially to the disc in a screen covering the latter.

From the above it was clear that in experiments dealing with comparison of speeds of rotation necessary to extinguish flicker in concentric bands on a disc it would be well (1) to separate the bands radially not more than is absolutely necessary, (2) to carry out comparison by alternate examination in the central field of vision the angular velocity of the bands remaining constant, (3) to observe by reflected light of low or moderate intensity, and (4) to keep equal not merely the total but the individual angular measurements of the sectors composing the concentric bands to be compared.

[1] *Pflüger's Archiv*, LXIV. p. 165. 1896.

[2] *v. Graefe's Archiv*, XXXI. p. 20.

[3] *loc. cit.*

[4] Cp. Schenk, *loc. cit.*

SECTION III. *Flicker dependent on Areal Induction.*

At the basis of the phenomenon of simultaneous contrast lies, as Fechner[1], Mach[2], and Hering[3] may be said to have proved, a reciprocal physiological relation between units of the retino-cerebral apparatus such that activity of the apparatus connected with a point of retinal surface P affects the reactions of the apparatus belonging to the retinal area circumjacent about P. This reciprocity, subconscious in origin, affects consciousness; it is a factor in the production of sensations, and influences inferences dependent upon comparison of those sensations. So intrusive is it psychologically that Joh. Müller[4] and Helmholtz[5] treated it as wholly a product of processes of judgment, a doctrine ably controverted by Hering.

It would be surprising if "simultaneous contrast" were the only indication of the physiological reciprocity between retinal areas. The principal phenomenon adduced in the present section cannot it seems to me be accurately described as an instance of actual "contrast," but it is very closely allied to simultaneous contrast because like it based on areal induction.

The following disc is prepared (Fig. 1). From an evenly tinted blue card such as is used for mounting sketches a circular disc 30 cm. diam. is cut. From its centre with radii of 7 cm. and 10 cm. are inscribed circular bands each 12 mm. wide. The disc is then bisected by a line, on either side of which one of the ring-bands is painted black, in such a way that the black half of one ring-band lies in the opposite half-disc to the black of the other ring-band. The rest of one half of the disc is then coloured yellow (chrome), of the other half black. Thus two concentric ring-bands each 180° blue, 180° black lie upon a background half yellow, half black. The blue 180° of one ring-band lying on the black of the background, the blue 180° of the other ring-band lying on the yellow of the background (Fig. 1). This disc when rotating rapidly gives of course two steel-blue concentric bands upon a dull yellow ground. The point for decision is,—will extinction of flicker occur in the two ring-bands at the same speed of rotation, that is, at the same rate of frequency of intermittence of stimulation? If the minimal speed of

[1] *Poggendorff Annal.* XXXVII., XLIV. &c. 1837, &c.

[2] *Sitzungsb. d. kais. Akad. d. Wiss. Wien*, 1866 &c.

[3] *Sitzungsb. d. kais. Akad. d. Wiss. Wien*, 1872 and later.

[4] *Physiologie*, 1841. Bk. V., Sect. 1, Cap. 3.

[5] *Physiol. Optik.* p. 417. Part II. 1860.

rotation giving homogeneous sensation is higher for one band than for the other, areal induction ("contrast in place, simultaneous contrast") is influencing the bands in respect to their efficiency as physiological stimuli. Physically the light reflected, during any number of com-

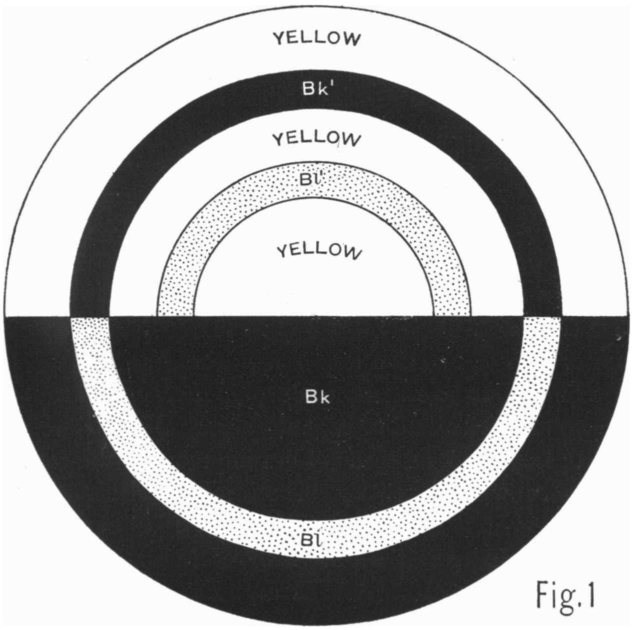

Fig. 1

plete revolutions, from any point of the two ring-bands is exactly the same—if the blue card is of equal tint and the black paint of equal blackness. To see how far the choice of the card and paint had succeeded in securing this equality two tests were applied.

(1) Photograms were taken from the disc (several separate specimens of the disc were made and photographed) in rotation. No difference between the two bands was discernible in the photograms[1]. (2) When the disc is rotated at speeds sufficient to give homogeneous sensation the tint of the two ring-bands appears exactly the same.

The disc when at rest gives an appearance of great difference between the blue-halves of the two ring-bands, that on the yellow background appearing much more saturated than that on the black. If the apparent difference in saturation between the two is due to error in

[1] The photograms and the discs were demonstrated before the Physiological Society, November 14th of last year, cp. *Proc. Physiol. Soc.* p. xviii. This *Journal*, vol. xx.

judgment based on perception of the relation of each blue to its background that difference is hardly likely to persist if the two different backgrounds be fused to a single sensation. If on the other hand the difference in saturation is due to alteration in the excitability for white of the retino-cerebral apparatus in the parts corresponding with the two strips, then it may be expected that a higher rate of intermittence—a higher rate of rotation of the disc—will be required to fuse one black-blue couple than to fuse the other black-blue couple. As a fact it is found that in medium daylight 22 rotations per sec. extinguishes flicker in one ring-band, while the other requires 34 rotations per sec. A difference very great indeed as compared with any given by mere difference of the radial distances (7 cm. and 10 cm.). The influence of radial difference was further completely controlled by making the contrasted couple in some discs the further from the centre, in others the nearer to the centre.

The greater rate of rotation required to fuse *Bk′ Bl* (Fig. 1) than to fuse *Bl′ Bk* tells us that the speed of development of the retino-cerebral reaction is higher in the case of stimulation by *Bk′ Bl* than of stimulation by *Bl′ Bk*. Inasmuch as speed of development of the retino-cerebral reaction increases with intensity of stimulus (Fick[1], Exner[2]), the flicker phenomenon in ring-band *Bk′ Bl* allows us to say that *Bk′* and *Bl* behave physiologically as if the difference of luminosity between them were much greater than between *Bl′* and *Bk*, although we know the physical difference of luminosity between the components of each couple to be exactly the same. The difference of *Bl* from *Bl′* is in the same direction as if *Bl* were, as compared with *Bl′*, under higher illumination. By increasing the illumination of the disc the strip *Bl′* (Fig. 1) can be made of approximately the same apparent tint as *Bl* under the illumination originally used. Then it is found that the speed of rotation necessary for giving unflickering sensation from *Bl′* and *Bk* under the new illumination is greater than that required under the original illumination.

The unflickering sensation so produced is a lighter steel-grey than that produced by *Bk′ Bl* under the original illumination. But under a wide range of different illumination when the angular velocity is sufficient to give homogeneous sensations from both of the two ring-bands *Bl′ Bk* and *Bl Bk′* the homogeneous sensation of steel-grey is in the two indistinguishably similar. *Bl′*s excess of physiological lumino-

[1] *loc. cit.* [2] *loc. cit.*

sity above Bl''s is therefore exactly counterbalanced by a deficit of physiological luminosity in Bk' as compared with Bk. In other words the increment of excitability for luminosity conferred at the locus of incidence of Bl is exactly counterbalanced by a decrement of excitability for luminosity at locus of incidence of Bk'. Stated by Hering's assimilation-dissimilation theory $\frac{Bl}{Bl'}$ is as regards dissimilation as $\frac{Bk}{Bk'}$ is as regards assimilation. It is interesting that this equality in the ratios is not obvious on appeal to judgment. Judgment based on comparison of the two blues Bl' and Bl and of the two blacks Bk and Bk' when the disc is stationary declares without hesitation that the difference between the blacks is much less than between the blues. Some observers fail to see any difference at all between the blacks, although they find a marked difference between the blues. Error of judgment thus, far from as in Helmholtz's doctrine[1], producing the contrast, actually minimises it.

A similar instance of "Urtheilstäuschung" acting in exactly the converse manner to that suggested by Helmholtz—and, in regard to the important degree to which "Urtheilstäuschung" may affect observation, thoroughly bearing him out—is the following. Some persons unaccustomed to examine visual contrast have at first difficulty in admitting that there is a difference between the strips Bl and Bl' (Fig. 1). They have been told at outset that the disc is prepared from a piece of evenly-tinted blue card and the unpainted even-blue back of the card has been shown to them, and they then on looking at the face of the disc frequently have told me that the two strips appear of quite equal tint in saturation and in every other respect. On rotating the disc before them they however like others point out without hesitation that one ring-band is "flickering" while the other is "steady." This shows how in them the rôle of judgment is exactly the converse to that allotted to it by Helmholtz in his theory of "simultaneous contrast." They are really subjected like other observers to very different excitations from Bl and Bl'; yet, in all good faith, after hearing that the two bands are made of the same piece of evenly-tinted card they assert that their sensations derived from the two are not unequal. Their judgment suppresses the actual inequality of their sensations, and does so without their desiring that it should. Their judgment warped by their previous knowledge leads them to ignore the simultaneous contrast which is really taking effect in them—that it is really taking

[1] *Physiol. Optik.* 1860.

effect in them is proved by their acknowledging the actuality of areal reciprocity in themselves by acknowledging the "flicker" difference which is as patent to them as to others. The knowledge and idea of the physical equality of the bands acts in them much as does suggestion on a hypnotic subject. Because they *know* two things are the same they cannot *see* a difference between them.

I cannot myself believe satisfactory any explanation of "flicker" that does not recognise the as it seems to me fundamental intimacy of connection between it and Talbot's Law. A lucid theory for that Law has been advanced by Fick and to it actual measurements by Exner have contributed. It is tempting to explain by so lucid a theory the flickering developed in this and following experiments. I will however merely say that if the oscillations of light sensations obeying Talbot's Law suggest the linear reactions of extensile and elastic structures under brief applications and removals of a given force, or the volume reactions of a gas under a pressure subject to brief alternating equal increments and decrements, then the effect of areal induction in the flicker experiment here under consideration is comparable with that of altering the temperature of the elastic material. As an analogous instance living muscle might be taken, inasmuch as it is a physiologically elastic body: alteration of its functional activity, *e.g.* by warmth or by nervous action, influences its extensibility and elasticity. The analogy may assist toward a conception of the retinal change. One might further say that the change induced in the retino-cerebral apparatus is like that which we call increase of (or conversely loss of) 'tonus' in a skeletal muscle—in the latter case the essential situation of the change lies in certain spinal neurons. Like the 'tonus' of the spinal neurons, which is under the influence of various spinal spatial relationships, the tonus of a retinal point is under the influence of various retinal spatial relationships; alterations in the extensibility and elasticity of its own sensifactory apparatus delicately mirror the changes occurring in the tonus of the point, just as do muscle-fibres the changes in their spinal neuron. The solidarity of the spinal cord is great enough for its tonus at any one point to be a function of the whole spinal status—indeed of the condition of the entire nervous system—to be a function that is of the living of other spinal parts, especially of those adjoint to it, as well as of that of the individual part itself. The retina likewise functions as one entity and the tonus of a locus in it is dependent not on the state of that individual locus alone but on that of all others, but especially of adjoint retinal loci. Simultaneous contrast and areal induction flicker seem two phenomena allied inasmuch as both rest on areal reciprocity. The local exaltation or depression effected by areal reciprocity in the retina may be likened to the local spinal exaltation and depression I have called attention to in the locality of severed (or conversely excited) sensory spinal roots[1], with local hyperæsthesia or diminished knee-jerk for criteria[2].

The disc, figure 1, is an example of various arrangements prepared upon the same principle and illustrating the same effect. It is natural to ask concerning the disc figured what becomes in it of the blue increment conferred on *Bl'* by the yellow field. The disc when whirled fast enough to eliminate flicker gives the ring-band *Bl' Bk* no bluer than *Bl Bk'*. This result is, it may be urged, favourable to the "Urtheiltäuschung" theory of simultaneous contrast. I for my part do not at all deny to "judgment" a rôle in many examples of simultaneous contrast. In Waller's contrast experiment[3] it certainly is active. I gave an instance above in which judgment indubitably diminished the influence on consciousness of the actual action in the retina of areal reciprocity: as it can diminish conscious effect of this action so most certainly can it also heighten it. But to explain the fact that the contrast effect upon *Bl'* does not make the homogeneous steel-grey *Bl' Bk* more blue than *Bl Bk'* "judgment" need not be invoked. The more likely explanation to me seems that the yellow field adds as much blue quality to *Bk'* as to *Bl'* although the increment is bestowed in a place where the conditions for its detection by direct appeal to consciousness are less favourable than at *Bl'*.

The question whether "white-black value" alone or "colour-brightness value" with "white-black value" (Hering) has to be reckoned with in flicker-photometry, has been recently treated by Schenk[4]. In connection with that interesting work it is noteworthy that the replacement of yellow (chrome) in disc (figure 1) by white (chinese) does not appreciably increase the difference in flicker between the two ring-bands.

Of various patterns of disc that can be used one of interest is that in fig. 2. It shows how little mere angular disposition matters to the net result. Ring-band *Bk' W'* flickers much more than ring-band *Bk W*. That direction of rotation affects the degree of flicker in the ring-bands in this disc is a matter which falls under consideration in Section V. of this paper with other similar facts there treated. The blue colour developed in the ring-bands on whirling the disc slowly will be dealt with in another communication—it is allied of course to the phenomenon

[1] *Philosoph. Transact.* CLXXXIV. B. 1893.
[2] *Proceedings Roy. Soc.* LII. p. 17. 1893.
[3] *Proc. Physiol. Soc.* 1891, p. xliv. This *Journal*, XII.
[4] *Pflüger's Archiv*, LXIV. p. 607. 1896.

of Fechner's disc—the so-called "artificial spectral top" of the toy shops.

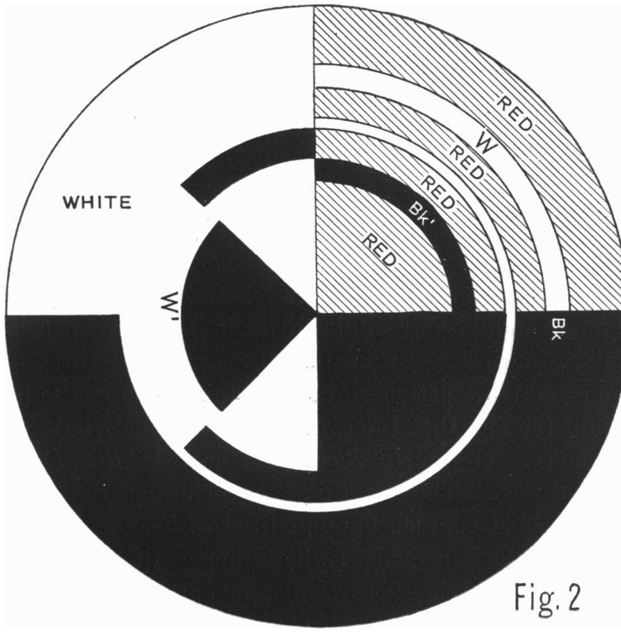

Fig. 2

When it is desired to estimate the actual speed of rotation or degree of illumination at which flicker is just extinguished in the ring-bands of discs like fig. 1, it conduces to accuracy to introduce a yellow sector—30° is quite enough—into the middle of the black half, and similarly a black sector into the middle of the yellow half. This somewhat reduces the difference in flicker between the two ring-bands, but it also greatly reduces the flicker in the dull yellow background. For that reason the flicker in the ring-bands is more accurately observable. The slightness of the effect upon the flicker of removing the 30° of reciprocal area from the arc depends greatly, as experiments given at the end of this paper prove, upon the area of removal being placed in the middle of the arc.

The relative difference between the angular speeds of rotation requisite to extinguish flicker in the ring-bands, *e.g.* in the pair of ring-bands *Bk' Bl* and *Bk Bl'*, fig. 1, is not the same under different illuminations. The difference between the rates of rotation required is greater in low lights than in moderately high lights.

The above experiment proves a difference in excitability in the retinal apparatus to have been induced in the places of incidence of stimuli *Bl* and *Bl'*, and that without permitting consciousness of any difference between the backgrounds. Consciousness of that difference is thus excluded altogether from the problem. This result quite supports Hering's position as to "simultaneous contrast." "Simultaneous-contrast" and "reciprocity-flicker" are obviously related: both are properties of the same surfaces, *e.g.* the above discs. The view that the former arises in "judgment" clearly accords less with that naturally suggested by the foregoing examination of the latter than the view which considers contrast to be of subconscious physiological origin. But I hold that an "areal induction flicker" experiment cannot *directly* contribute to a "simultaneous contrast" discussion. Accurate comparison between the flickering colour from ring-band *Bl Bk'* and the steady colour from ring-band *Bl' Bk* is difficult, if not impossible. So long as a sensation is of markedly flickering quality its intermittence obscures its other qualities. "Flickering" quality has a resemblance to painful quality in this respect. I find by experiment it is difficult to judge even roughly of relative amounts of black and white in two discs or two zones of one disc so long as the rotation is too slow to extinguish flicker and to give homogeneous sensations. Advantage is taken of this fact in the following experiment, which attempts to deal with "simultaneous contrast" itself.

SECTION IV. *Simultaneous-contrast Discs.*

Let a disc, fig. 3, be of light grey tint. For a width around its centre of rather more than half the radius cover it with black through 105°. Let the rest of the width of the disc except three or four millimeters next to the already blackened zone be blackened for 125°. On whirling the disc at a speed insufficient to perfectly fuse the grey and black sectors it is, for most people, a very difficult thing to detect which is the darker, the outer or inner flickering grey field; the two fields are to all observers almost exactly alike, to many quite alike. Add to each of these concentric fields 90° of yellow (naples) except along the concentric arc-bands *g' g''*, which remain grey. The flickering is increased and the difficulty of distinguishing between the depths of the yellowish greys is as great as it was between the purer greys so long as the speed of rotation is not sufficient to give perfect fusion of the sectors. Add now to the concentric band possessing 105° black a short arc of black. Add it in such a way that the arc juts from the even radial grey arc-band *g'* jutting 20° into the inner of the concentric in the peripheral part of the inner concentric field not quite close to the junction of the inner and outer fields. Whirl the disc, preferably in the direction that black follows yellow and precedes grey. Two deep grey ring-bands on

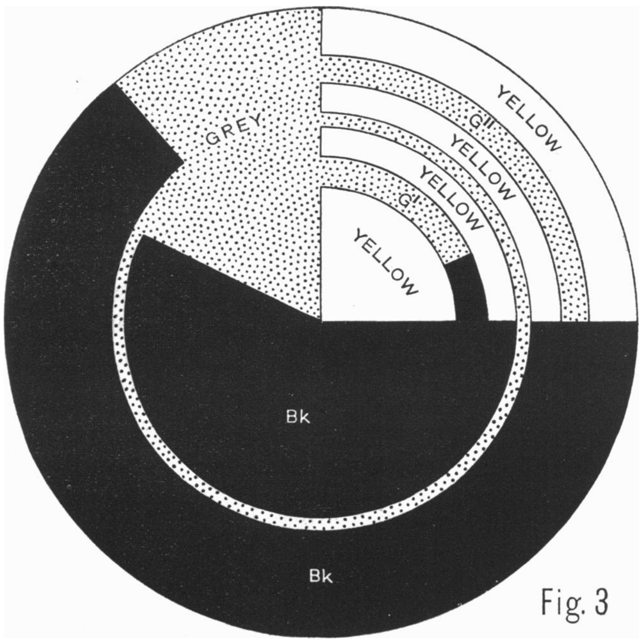

Fig. 3

a circular yellowish grey field then are seen, and at speeds just sufficient to secure flickering sensation the inner of the two ring-bands appears considerably the darker, and both appear on a slightly flickering but otherwise equally tinted field. The darkening effect induced on the black arc by the yellow adjacent to it in virtue of areal reciprocity makes the inner ring-band appear darker than outer, although the proportion of black to grey is equal in the two. That this simultaneous contrast effect persists when the difference between the backgrounds of the two black components has been dismissed from consciousness by whirling fast enough to completely confuse throughout to fuse the backgrounds proves consciousness of the backgrounds to be unessential for the simultaneous contrast. If the strips be observed through two holes in a screen, each hole not wider than the width of the strip, the appearance of the two strips and ring-bands is, when the top is whirled, alike. Radial distance makes no obvious difference to the effect, the contrasted band has as much effect when the outer as when the inner of the pair. The narrow untinted ring dividing the dull yellow field into peripheral and central portions conduces greatly to the contrast result, by rendering the comparison between the depth of tint of the two backgrounds less easy and less accurate. At speeds sufficient to give complete fusion of the sectors in the backgrounds, the two concentric zones of dull yellow can be detected to be of different degrees of dulness, and the darker appearance of the deep grey ring-band is then no doubt chiefly due to simultaneous contrast, based on the obviously lighter colour of its background. The interest of the experiment lies in the effect produced at those lower rates of rotation when the sectors composing the two grey bands are in each completely fused, and the backgrounds although not completely fused are *confused* more than sufficiently to render any consciousness of their dissimilarity or difference of their relation to the two strips altogether out of question.

SECTION V. *Flicker dependent on temporal induction.*

Areal induction as was shown above takes effect even when by translation of a surface the knowledge of the actual relationship of a small area of it to the rest as background is not allowed to enter, or has been dismissed from consciousness. The areal induction can be employed as an adjunct to raise or lower the efficiency of a stimulus at appropriate moments of a sequence in time. In this way it can assist investigation of the influence of temporal (successive) induction upon "flicker." With the discs now to be described, temporal induction can be shown to very considerably determine degree of "flicker."

Let a paper disc, thirty centimeters diameter, and half black, half white, have upon it two 40° black arcs, which jut from the black into the white half and at the opposite radius two exactly counterpart 40° white arcs which jut into the black half. These pairs are so placed (fig. 4) as to compensate one for other, so that throughout the entire disc the angular values of black and white are equal. According to the rules of flicker-photometry the illumination of the disc being everywhere equal, and the angular measures of the sectors equal (180° everywhere), flicker should disappear from the whole surface of the disc at the same minimal speed. The angular velocity which just suffices to extinguish flicker and give homogeneous grey sensation should be the same for all parts of the disc. Experiment shows, however, that this is not the case. When the direction of rotation is opposite to that of a clock hand, the ring-bands corresponding with the two white notches flicker at speeds much higher than suffice to extinguish flicker elsewhere in the disc. The black of the black teeth and the white of the white notches are

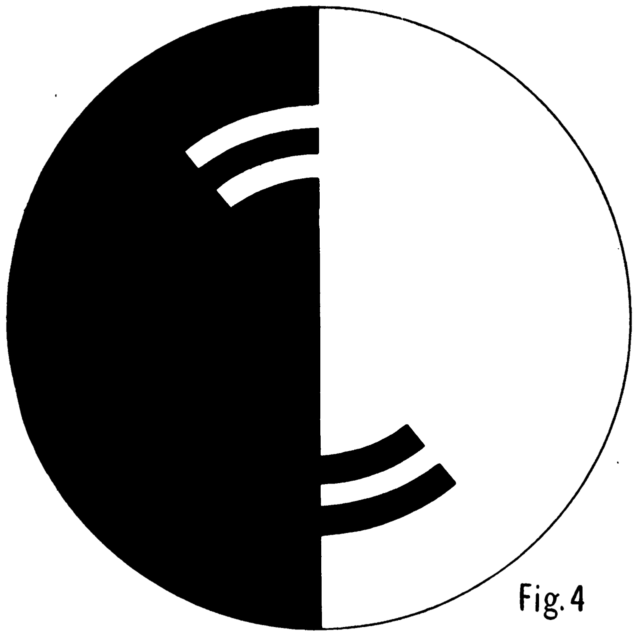
Fig. 4

intensified by areal reciprocity. To produce homogeneous grey from this, the blackest black and the whitest white in the disc, a more frequent intermittence and repetition are required than for the black and white elsewhere. The "simultaneous contrast" effect in the black and white teeth and notches is not so obvious, though the difference in flicker value is very great indeed; this is in accordance with the fact that simultaneous contrast is not very consciously developed on strong black and white surfaces.

On whirling the disc in the same direction as a clock hand, flicker persists longest in the ring-band corresponding with the white space between the two black teeth and with the black tooth between the two white notches. The flickering of the ring-bands is therefore affected by the *direction of rotation* of the disc. It will be remembered that direction of rotation also affected the degree of flicker in the ring-band in the disc, fig. 2, *vide supra.* So does it also in that described in Section IV. *vide supra.* The explanation of this influence exerted by the mere direction of the rotation seems to me as follows.

The action of the areal induction (reciprocity) is mutual. White next to black intensifies the black and is intensified by the black. Suppose that quantity of surface influences the degree of action in such a way that the reaction between two juxtaposed surfaces is proportioned to the relation between their quantities of area. If the effect of the greater surface upon the smaller is *per* unit of surface greater than the effect of the smaller upon the larger, then the intensification of the white of the white notches in the black will *per* unit of surface be greater than the intensification of the adjoining black. Exactly the converse will be the effect with the black teeth and the white field surrounding them, the teeth will *per* unit of surface be intensified more than the white field. Take now the disc, Fig. 5, when whirled in the direction of a clock hand, the ring-band corresponding with the

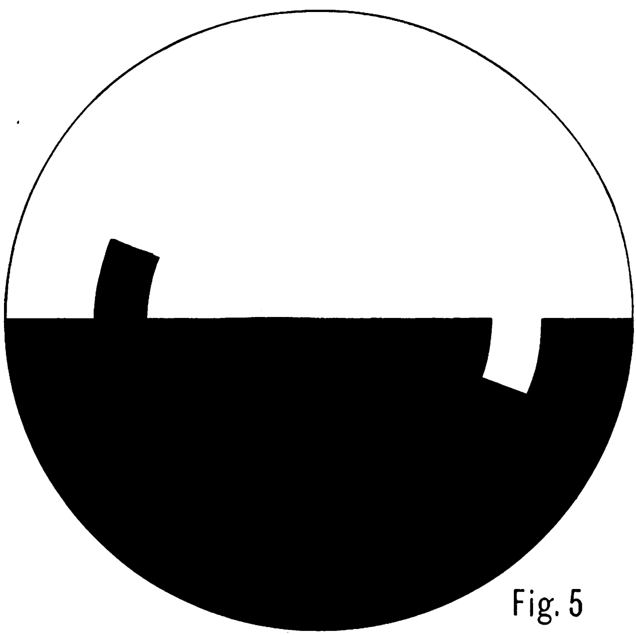

Fig. 5

tooth and notch flickers at higher speeds than does the disc elsewhere. Whirled in the reverse direction the flicker in the ring-band is not greater or hardly greater than in the disc elsewhere. The experiment shows that persistance of flickering sensation is greater when in the rotation of the ring-band the passage is from ordinary white to intensified black, and from ordinary black to intensified white, than when the sequence is in this disc from intensified black to ordinary white, and from intensified white to ordinary black. When the spin gives upon a retinal point the latter sequence the intensified black follows a previous stimulation by unintensified black,—lasting in the example, disc fig. 5, for four-ninths of the period of the disc. Similarly the intensified white then follows a similar period of unintensified white. The retinal excitability for black is presumably falling throughout the continuance of the stimulation by black, therefore the effect of the intensified black will be less when it succeeds a period of stimulation by black than when it succeeds a period of stimulation by white, the more so in that throughout the latter period the excitability of the retina for black is waxing and not merely not waning.

This argument is supported by the effect of whirling a disc prepared as in Fig. 6. This disc is arranged so that areal induction, although strongly present, is so distributed as to neutralize itself, and at the same time does not allow play of a second factor that will be dealt with

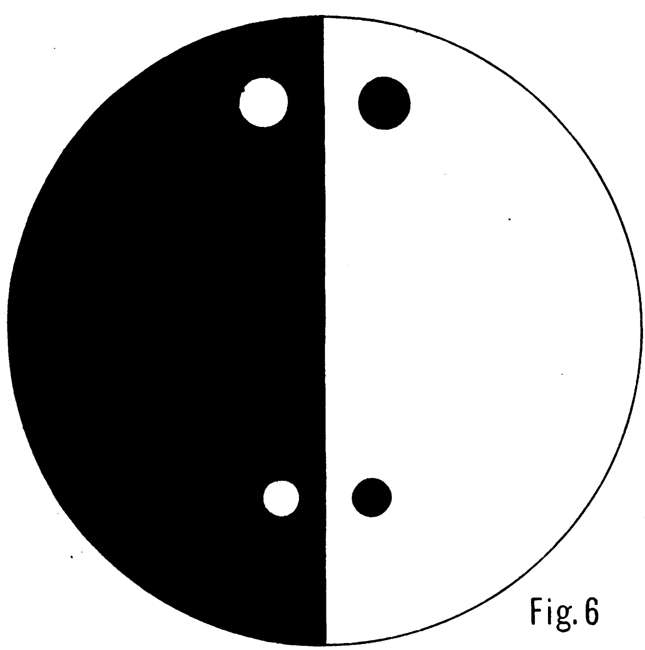

Fig. 6

in the paragraph next after the present. On rotating the disc in the direction of clock hands, the inner of the ring-bands—that corresponding in Fig. 6 with the pair of smaller black and white circles—is lighter grey and flickers more than the outer ring-band. Rotation in the opposite sense makes the outer ring-band lighter grey than the inner. The effect of the round *white* spot predominates or not over that of the round *black* spot according as the stimulation by the spot succeeds a longer or shorter period of exposure of the black sector.

Another circumstance is coadjutant to the same end in discs such as Figs. 4 and 5. Areal reciprocity, other things being equal, varies inversely with the distance of retinal separation of the reciprocal loci. This relation which in its broad features is obvious enough, has been established in detailed fashion by Mach's papers[1]. In the black tooth and in the white notch (Fig. 5) intensification by reciprocity between each and its surrounding field, although effective all over the tooth and all over the notch is maximal only at the free end of each. Followed from attached base to free end in each, the intensification gradually increases and culminates at the terminal border. The application of the stimulus, the blow, or if preferred as regards black, the decrement of stimulus, is more abrupt when the incidence of notch and tooth upon a retinal point begins with the free end of either. That its peculiarly high physiological efficiency is largely due to mere abruptness of impact is borne out by the fact, which I have found by actual experiment, that the mere angular length of the tooth or notch makes little difference, *ceteris paribus*, to the amount of flicker produced.

The physiological intensity of the alternate stimuli in the two sequences can be approximately figured as in the accompanying scheme, Fig. 7. In it the line *NG* represents a neutral grey; times are indicated by abscissæ along *NG*. The white stimuli are expressed by ordinates on the *W* side of *NG*, the black by ordinates on the *B* side of *NG*. The length of the ordinates from *NG* is intended to be proportionate to the intensity of the stimuli, or if black be considered not a stimulus, the approach toward physiological saturation of the black is represented by the length of the ordinates below *NG*. The sequence indicated by the dotted line presents more abrupt changes in stimulation than that indicated by the unbroken line. The broken line indicates the sequence upon a retinal point when the disc Fig. 5 is rotated in the same direction as a clock hand; or in the disc Fig. 4 as regards its outermost ring-band when the disc moves against clock hand direction. The retinal point—always using that expression in the wide sense stipulated at outset—is more affected by a tap than by a push, even

[1] *Sitz. d. kais. Akad. Wien, loc. cit.*

although there be as much energy kinetic in the latter as in the former. Reciprocity in time (successive contrast) is here added to areal reciprocity (simultaneous contrast).

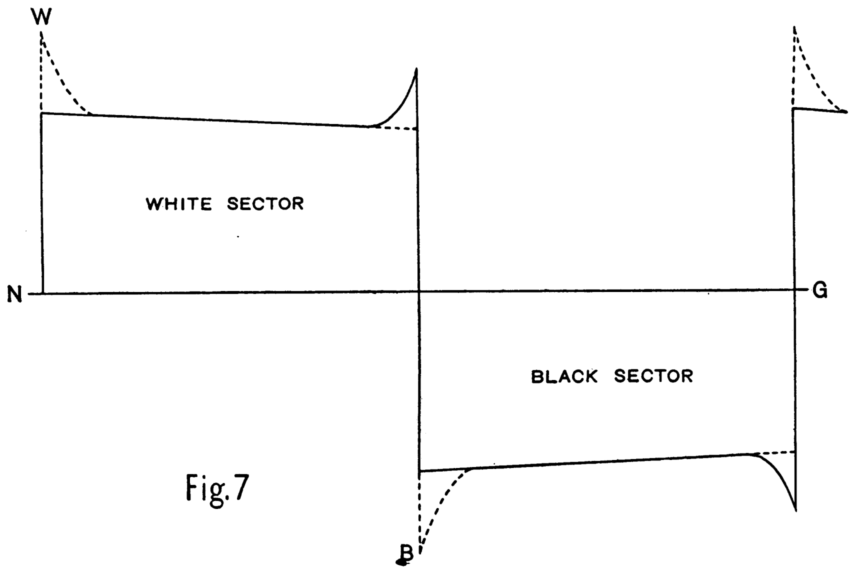

Fig. 7

I have found the best pattern of disc on which to demonstrate this effect to be that shown in Fig. 8. The ratio of the angular measure of the total white to the total black is the same at every radial distance from the centre. By subdividing the black sector contributing to the grey of the background against which the three ring-bands lie the flicker in their background is made to disappear at a speed of rotation much below that necessary for extinction of flicker in any of the ring-bands. This renders easier the observation of 'flicker' in the ring-bands themselves. When the disc spins in the direction of a clock hand flicker persists longest in the middle ring-band of the three, that corresponding with the isolated white notch. When rotation is reversed, flicker persists longest in the ring-bands corresponding with the double white notches. If the ring-bands are watched through holes in a screen in such a way that not more than the full width of the ring-band is visible the differences in flickering quality disappear from them.

An interesting simplification of this (Fig. 8) disc is made by omitting the outer or inner fellow of the *double* white notch and correspondingly narrowing the black arc connecting the two black sectors. The ring-bands thus are reduced from three to two. The disc then appears bilaterally symmetrical, but nevertheless displays great difference in 'flicker' according to the sense of rotation.

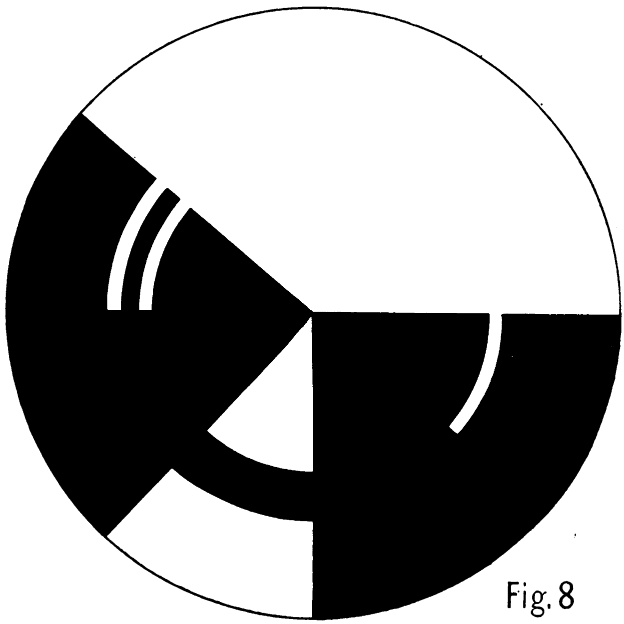

Fig. 8

The difference between the rates of rotation requisite to extinguish flicker in the two opposite directions is surprisingly great, for instance under good illumination 35 revolutions per second as against 51 revolutions required for the opposite direction. Of course at still higher speeds flicker is extinguished in the whole surface of the disc and then the grey becomes uniform everywhere.

SECTION VI. *Successive-contrast Discs.*

It was pointed out above in Section V. that when the disc Fig. 6 is whirled in the direction of clock hands, the ring-band corresponding with the more peripheral pair of black and white circular spots appears of darker grey than that corresponding with the pair lying more centrally. This description of course applies only to the appearance of the disc when whirled at no very high rotation-rates. The same effect is even more strikingly obtained when, instead of round spots, short bands along arcs are used. I make the arc-bands of equal width as measured radially on the disc, and each of 15° angular measure. The adjacent edges of these arcs I place each 10° distant from the diameter at which the white and black halves of the disc meet. Of the arc-bands the two which lie imbedded in the black may if desired be coloured, *e.g.* red, instead of remaining white. The resultant reddish grey should be quite similar in the two ring-bands. It is so when the disc is whirled at high velocity. But the effect obtained on whirling more slowly in the direction of clock-hand movement is that of an outer chocolate-mauve ring-band and of an inner salmon-pink ring-band, both on a grey black ground. On reversing the direction of spin of the disc the outer ring-band becomes salmon-pink, the inner mauve. If the white arcs are left uncoloured, outer ring-band and inner ring-band are respectively lighter grey and darker grey than the medium grey background, depending as above explained on the direction of the rotation. The short black arc appears darker in virtue of successive-contrast when it follows white than when it follows black, and the short white arc (or short vermilion arc) analogously appears in virtue of successive-contrast lighter when it succeeds black than when it succeeds white. The areal induction is so arranged as to affect the two ring-bands equally in whichever direction rotation occurs.

At high speeds of rotation the distinction between the ring-bands is lost. It is obvious that it must be. It is remarkable that for this perceptible action of successive-contrast so short a time is necessary. It is still detectable when the disc rotates 18 times per second, leaving less than $\frac{1}{30}''$ of time for its production. No doubt the amount of its action in this short period would be less appreciable than in this experiment it is, were not the disc playing the part of, so to say, a circular rheotome and summing up the values of repeated small quantities.

It is a pleasure to me to have this opportunity of thanking Dr W. H. R. Rivers, of Cambridge, for criticism very valuable to me especially as regards the scope of Talbot's law. To Mr O. Grünbaum I am indebted for carrying out some measurements of the exact speeds required under certain conditions to extinguish flicker in various of the discs.