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ON BINOCULAR FLICKER AND THE CORRELATION OF ACTIVITY OF 'CORRESPONDING' RETINAL POINTS.

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With best regards
C. S. S.

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The physiological initial stages of the reaction generated in either component of a pair of 'corresponding retinal points' proceed without touching any of the apparatus of the twin point. Only after sensations initiated from the right and left 'points' have been elaborated, and have reached a dignity and definiteness rendering them well amenable to introspection, does interference between the reactions of the two (left and right) eye-systems occur. Since left and right end-results emerge pure, hybridisation cannot have mixed the early stages in their evolution. The binocular sensation attained seems combined from right and left uniocular sensations elaborated independently.

THE following experiments attempt inquiry into the influence exerted on the reactions of a 'retinal point' by certain forms of activity at the 'corresponding point' of the other retina.

By 'retinal point' is here understood the retino-cerebral apparatus engaged in elaborating a sensation in response to excitation of a unit of retinal area. In the inquiry much use has been made of flicker as a visual criterion. Almost without exception the experiments have confined themselves to the central (macular) region of the retina[1]; and the intensity of the physical illumination used has been well above the threshold for the light-adapted eye.

SECTION I. **Symmetrical Flicker.**

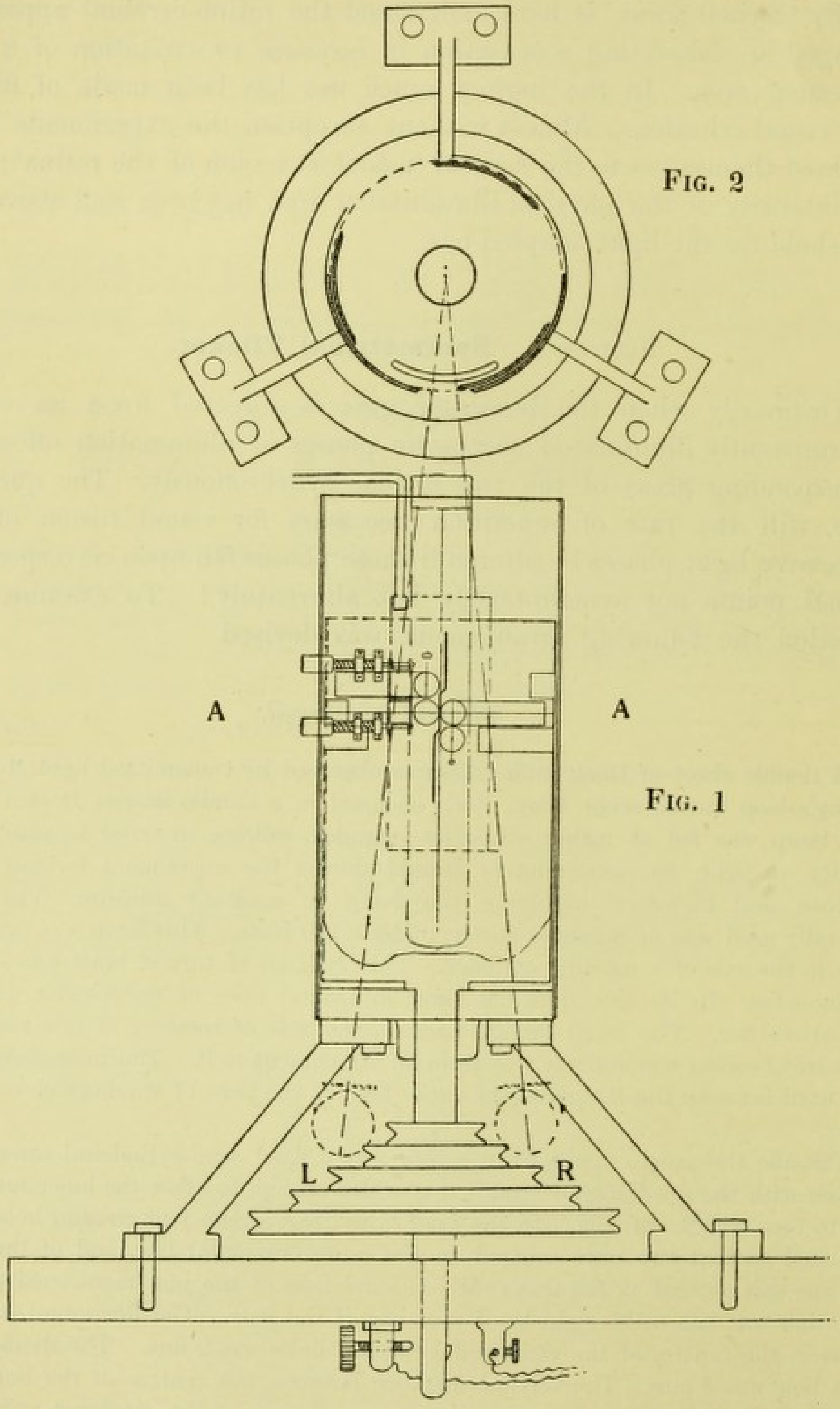
Ordinarily when the binocular gaze is directed upon an object intermittently illuminated, successive phases of illumination affect the corresponding areas of the two retinae synchronously. The question rises, will the rate of repetition necessary for visual fusion of the successive light phases be altered if those phases fall upon corresponding retinal points not synchronously but alternately? To examine this question the following arrangement was devised.

A. *Method employed.*

A double sheet of thick milk-glass was observed by transmitted light given by a single-loop incandescent lamp, itself enclosed in a candle-shaped frosted glass. The lamp was fed at rather above its intended voltage, in order to give white quality of light, by accumulators unused during the experiment for any other purpose, and therefore supplying the lamp in constant measure. The lamp generally used was of 8 candle power, under a 100 volts. This lamp was set vertically in the axis of a rotating cylinder. This cylinder of turned brass was 78 mm. in diameter. In its side were cut three horizontal rows of rectangular windows tier above tier. The lamp though fixed in the axis of rotation of this revolving cylindrical screen was entirely free from all attachment to it. The milk-glass plate was fixed between the lamp and the inner face of the tiers of windows close to the latter.

Outside the moving cylindrical screen was a fixed semi-cylindrical screen concentric with the revolving one and just of width enough to allow the inner revolving one to turn within it freely. In the fixed cylindrical screen four circular holes were arranged so that two were centred on the same horizontal line, and of the other two one was centred as far above the left-hand hole of the just mentioned pair as the other was below the right-hand member of the pair. The horizontal distance between the centres of the right and left-hand holes was 9 mm. The diameter of each hole was 8 mm. The vertical distance between the centres of the holes was exactly the same as that between the centres of tiers of the revolving cylindrical

[1] The experiments were the subject of a brief communication to the Royal Society's *Proceedings*, July, 1902, Vol. LXXI. pp. 71—76.



Rotating Lantern. Fig. 1. Elevation, seen from front. Fig. 2. Horizontal plan, through level of A—A, Fig. 1. Supports seen in perspective. The eyeballs, pupil screens, and convergent visual axes are indicated belonging to Fig. 2, but carried through Fig. 1. The plan of the lantern is given one-third actual size. Description in text.

screen, namely 11 mm. These four circular holes in the outer fixed cylindrical screen were, in the experiments, viewed from a distance such that when the line of visual direction of the right eye passed through the centre of the right hole it met at the axis of the cylindrical lantern the line of visual direction of the left eye, which latter line passed through the centre of the left-hand hole.

This being so the images of the lower left-hand hole and of the upper right-hand hole fused visually to singleness. They then appeared as the middle one of three arranged vertically one above another.

A black vertical thin screen set at right angles to the plane of the forehead was introduced between the eyes and the holes so as to screen from the left eye all view of the right-hand holes, and from the right eye all view of the left-hand holes. The distance of the eyes from the holes was in the observations on myself exactly 20 cm. For some observers a little less was used, their interpupillar distance being less than my own.

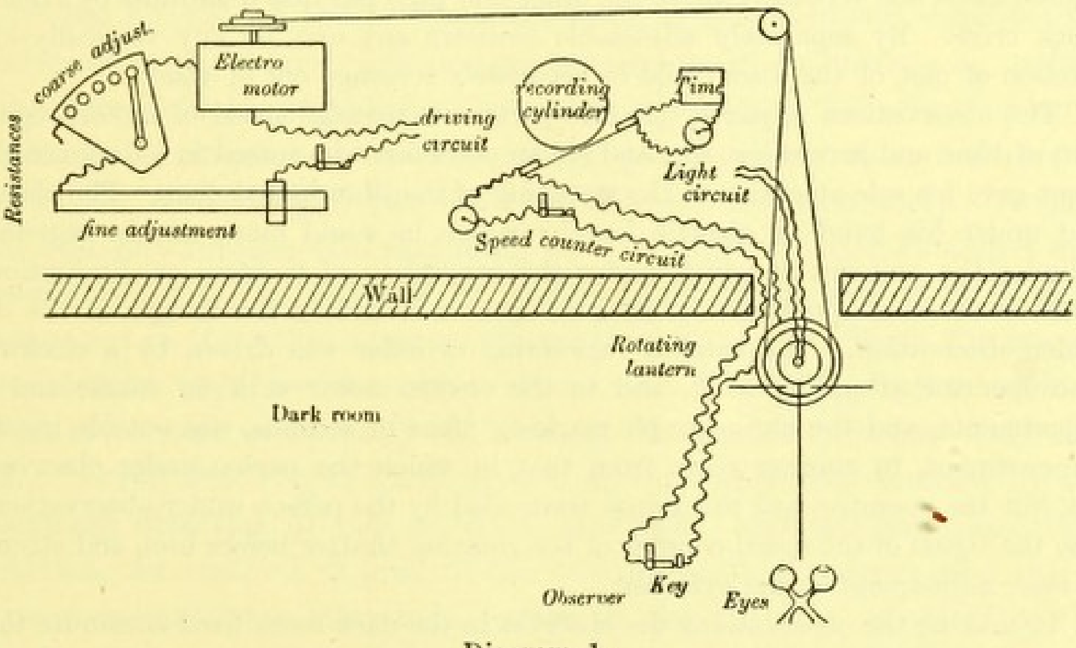


Diagram 1.

The spindle of the revolving cylindrical screen was furnished with a step-pulley. Thence a cord ran to a step-pulley fixed on the spindle of an electro-motor. The speed of revolution of this motor was controlled by a set of coil-resistances, which served as coarse adjustment, and by a fluid resistance in a trough 1 metre long, with a sliding electrode; this latter formed a fine adjustment. The speed of rotation of the cylindrical screen was recorded by marking the completion of each revolution of its spindle by an electro-magnetic signal writing on a travelling blackened surface. On the same surface the time was recorded by a writing clock marking fifths of seconds.

The inner revolving screen by its revolution opened and obscured alternately for equal periods the circular holes in the fixed outer screen. The inner screen with its three tiers of windows was made in three pieces, each containing one tier of the windows. The piece containing the middle tier of openings was jointed in such a way that its openings could be set at any desired angular interval with the openings of the lowest tier. The highest tier was similarly jointed to the middle tier. In this way it could be arranged that the uppermost circular hole was open when the lower were closed, or was shut when the lower were closed, or was opened to any desired degree either before or after the lower; further, by removing the top gallery of the rotating screen it could be left permanently open. A similar relationship was also thus allowed between the middle holes and the lower.

By wearing weak prisms with their base-apex lines vertical the images of the right-hand and left-hand holes could be brought to the same horizontal levels. The right-eye prism was placed apex upward, the left-eye prism apex downward. The observer could then immediately fuse the four images to two by convergence. A horizontal fine thread halving each of the two middle holes, and similar but vertical threads halving the two other holes served to certify binocular vision to the observer. When the four holes were all allowed to act thus under the appropriate convergent binocular gaze they were seen by the observer as two small evenly lighted discs, one vertically above the other and each cut into quadrants by a delicate black cross. By separately adjustable shutters any one, or any vertically-edged fraction of one, of the discs could be separately screened out of vision.

The observations required, (1) an operator to manage speed of motor, registration of time and revolution, &c., and (2) an observer, who seated in a dark compartment gave his sole attention to the watching of the illuminated discs. The observer had under his hand an electric key by which he could mark on the registering cylinder the moment at which under the conditions of increase or diminution of rotation rate the appearance of flicker began or ceased in the images of the discs under observation. The smoked registering cylinder was driven by a clockwork. The operator attending to it, and to the electro-motor with its coarse and fine adjustments, and the chronograph marking fifths of seconds, was outside the dark compartment, in another room from that in which the person under observation sat, but the operator had the signal controlled by the person under observation, as also the signal of the speed-counter of the rotating shutter before him, and attended to their adjustment on the cylinder.

In making the observations the observer in the dark room fixed a minute thickening, marking the middle of each cross wire on the right- and left-hand discs. Besides the weak prisms he also wore artificial pupils between his eye and the prisms. The diameter of the artificial pupils was sometimes 3, sometimes 4 mm. Both prisms and pupils were carried in a Landolt frame capable of both vertical and horizontal and also of angular adjustments.

Blackened aluminium side-flaps attached to the frame could be turned so as to block the field of either eye, obviating closure by the eyelid, which with some observers is liable to disturb the posture of the head. Fixation of the observer's head was secured by a solidly made wooden rest, supporting adjustable chin and forehead pieces.

By the above arrangement the following conditions were, it is thought, attained. Images accurately similar were received by retinal areas fully visually conjugate. That is, the areas were not only of the so-called 'geometrical identity,' but were at the time of the observation in full binocular cooperation, owing to the concurrent convergence and accommodation. The slight discrepancy in amount between accommodation for a 21 cm. distance and convergence for a 23·5 cm. distance was corrected by making the prisms suitably convex, as in the Brewster stereoscope. Extinction and illumination of the images occurred *pari passu* in the two eyes, *i.e.* with like speed and in like direction. It could be synchronous or of any time-sequence desired. That the speed should be similar for the two was ensured by all the shutters being on the same spindle.

Each disc-shaped image would have on the retina a diameter of about 570 μ. That is, when foveal vision was directed upon it, the image would occupy a practically rod-free area containing about 2,800 cones. The direction of translation being the same for all the shutters the bright images on the two retinae were, if the shutters were set for simultaneous right and left images, commenced on 'identical' points of the two retinae, established progressively along 'identical' points, and finally extinguished in like manner progressively along 'identical' points. Or conversely if the shutters were set for accurately alternate right and left images the screening off began in one eye at a spot and moment identical with those at which the turning on of the image commenced in the other eye: so similarly it finished. With the speeds of revolution used for the observations, the time the shutter took to expose or occlude completely each bright disc varied between ·011″ and ·002″. Error that might have arisen on this score was avoided by the consensual direction of movement of the right- and left-hand shutters. Admitting an error of ·3 mm. in the cutting of the shutters, and this is an over-estimate, the maximum error in the turning on or off of the light from geometrically identical spots in the retinae is ·00042″ for the slow rates of revolution, and falls to ·000075″ in the high rates.

That the 'retinal points' to which the images were thus applied synchronously, or in desired sequence, were truly 'identical,' was certified, (1) by the paired physical images being seen single; (2) by the maximum disparation of the edges of the rotating shutters being about 7 μ on the retina, whereas 350 μ is about the vertical retinal disparation which limits binocular combination. Moreover, a contour travelling through a visual angle of 2° in $\frac{1}{90}$″, as in these observations, is not perceptible as a contour at all.

Difficulties due to change in pupil-width were excluded by the artificial pupils. Equality of brightness of illumination of the four milk-glass backed 8 mm. holes was obtained by making the straightwire candle-shaped lamp of considerable, *i.e.* 12 cm., length, and fixing it accurately in the axis of the cylindrical screen. The rotating screen was blackened inside to minimise reflection. That the brightness of illumination of the four holes was really equal was ascertained at outset of each series of observations by finding the rate of revolution of the circular shutter required just to extinguish flicker at each of the four holes. If the rate of revolution was the same for all, the equalisation of the lighting of the four holes was considered to have been attained.

In a number of observations made before the arrangement of the apparatus took its final form, a single haploscopic image was presented to the visual field. The right and left components of this image could be either synchronously or alternately presented, according to the disposition of the apparatus, and it was easy to change the composition of the haploscopic image from one form to the other. But to effect the change demanded a break of at least 5 seconds, and usually involved some disturbance of the observer by noise. This successive method of comparison was at a disadvantage on these accounts; it suffered in facility and precision. The measurements it yielded were however broadly similar to those obtained by the method of more immediately successive comparison adopted finally.

In the latter, the apparatus for which is described in the small print above, two haploscopic images, one close above the other, were placed in the central field. The right and left components of each of these could be either synchronously or alternately compounded in each. The foveal gaze could be turned from one to the other of them when and as often as the observer desired, and in the fraction of a second by a slight, *i.e.* less than 3°, movement of the eyeballs. The comparison thus instituted was much more facile and sure.

The two images concurrently presented were so near together that it was easily possible while fixating the narrow dark interval between them to observe both and watch for appearance or disappearance of flicker in either. But the sensitiveness of even the median (central) region of the visual field is not everywhere the same as tested by perception of flicker. It was preferable to keep fixating the two images alternately, first one, then the other, and thus to watch for the earliest appearance (or disappearance) of flicker in either, using for each the macular retina itself.

An image would fail to flicker when received on the fovea that would distinctly flicker when its image fell just outside the fovea. Thus the disc image that just did not perceptibly flicker when its centre was under foveal gaze would flicker perceptibly when the foveal gaze was fixed half-way down the interval between the two disc images. Exner[1] and Charpentier[2] have pointed out that the peripheral retina is more sensitive to flicker than the central, and Exner has shown that an area only 1330 μ from the fovea is more sensitive in this respect than the fovea itself. In the observations now in consideration the flicker sensitivity of points only 750 μ from the foveal centre was found perceptibly greater than that of the foveal centre itself. And this distance was found to reveal a perceptible difference, whatever might be the particular radial direction followed from the fovea.

Marked difference was met in the frequency of intermission required to extinguish flicker in the same physical light for different observers. The amount of individual difference is exemplified by the following rates of intermission all observed on the same occasion upon the same light.

TABLE I.

Observer	No. of phases per sec. to extinguish flicker	Remarks
G. C.	124·3	Emmetropic
C. S. S.	117·8	Myopic 3 D.
B. M.	115·4	Emmetropic
J. S. M.	106·2	Myopic 5·5 D.
A.	94·5	Hypermetropic 2 D.

The abnormal refractions had been corrected by lenses. These differences remained characteristic between the observers A., J. S. M., C. S. S., and G. C., throughout two years during which the observations were in progress.

How regularly these individual differences are maintained can be judged from the following figures taken almost at random from my note-book, and obtained without any intention of instituting a comparison from two observers on occasions about a fortnight apart, examining the same electric light under similar conditions.

TABLE II.

G. C.	91·26	C. S. S.	88·40
,,	91·00	,,	87·88
,,	92·04	,,	86·84
,,	94·81	,,	86·94
,,	95·81	,,	91·00
,,	92·92	,,	87·88

[1] *Sitzungsb. d. k. Akad. d. Wissensch. Wien*, 1868, Bd. LVIII. Abth. 2, S. 601.

[2] *Arch. d'ophthal. Paris*, 1890, Tome x. p. 340.

B. *Observations.*

With the apparatus thus arranged various binocular combinations could be investigated and compared either one with another or with uniocular images.

As shown above the apparatus allowed of similar images being thrown on strictly and fully conjugate points of the two retinae, either synchronously right and left or alternately right and left, with a time accuracy not less than ·00042″ for the slowest rates of intermission, and not less than ·000075″ for the highest. The first comparison made (Experiment I.) was that indicated above at the outset, namely, to observe if there were any difference between the rates of intermittence for just perceptible flicker in two binocular images, one made with synchronous right and left illuminations, the other with alternate right and left illuminations. This arrangement is expressed graphically by the accompanying diagram.

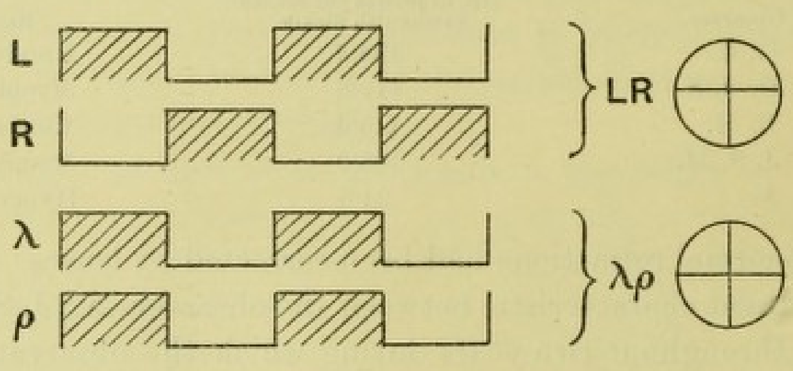


Diagram 2. Exp. 1.

The diagram makes the lower composite image the 'synchronous' one, but in the series of observations the 'synchronous' was sometimes the lower, sometimes the upper, and the observer was never informed which it might be. Sometimes the observations were made on the transition from flickering to unflickering sensation; more often they were made conversely on the transition from unflickering to flickering sensation: the observer in the latter way had a more neutral line of approach to the critical observation. For it was found that when compared under rates of intermittence giving marked coarse flicker in both images, all observers found the flicker "less" in the 'alternate' than in the 'synchronous' combination (*v. infra*, p. 57). This marked difference however lessened progressively as the frequency of intermittence increased toward fusion point. The difference at the lower speeds inclined the observer to expect that complete extinction of the flicker would disappear the more readily in the image which at slow intermissions seemed to flicker the less. It was not easy to be sure that this bias was set aside in forming judgment on the final point of extinction of flicker in the two images. Usually, therefore, judgment was asked under conditions in which both images started perfectly free from flicker, the rate of intermittence being from the outset higher than necessary for extinction of flicker.

The judgment then given has been almost uniformly that there does exist a *very small* difference between the frequency of intermittence required for extinction of flicker in the 'synchronous' and 'alternate' combinations respectively. The difference is that in the 'alternate' combination flicker disappears at a slightly lower frequency of intermission than in the 'synchronous.' All observers agree that directly the frequency of intermission extinguishes flicker in both the discs the appearance of both is indistinguishably similar, and that there is then nothing to choose between the brightness of the two.

This difference in frequency for flicker extinction is very small in amount.

Some estimate of its amount, though it is too small to be measurable easily, may be gathered from the following observations. The observations have been made with various intensities of brightness of image, and various speeds of translation of the contours separating the phases, hence the various absolute values, but the conditions for comparison between the two columns in the table have always been maintained.

TABLE III.

	No. of phases per sec. just extinguishing flicker	
Subject of observation	Synchronism of similar phases in r. and l. retinae	Exact alternation of phases in r. and l. retinae
S. C. M. S.	97·3	95·8
B. M.	122·3	118·9
G. C.	123·0	119·8
,,	93·3	90·6
,,	73·4	71·8
C. S. S.	72·1	69·8

For almost all persons whom I have examined, a spot intermittently illuminated at a frequency of intermission just sufficient to extinguish flicker in it, when looked at with one eye only, still flickers slightly when looked at with both eyes. A like phenomenon is noticed by most observers when examined by the arrangement (Experiment 2), represented by Diagram 3.

The binocular arrangement then is said by them to require a just slightly higher frequency for extinction of flicker than does the uniocular. Again, if under a frequency of intermission just securing extinction of flicker in either of the component uniocular images separately, one of these images, previously screened off, is readmitted,

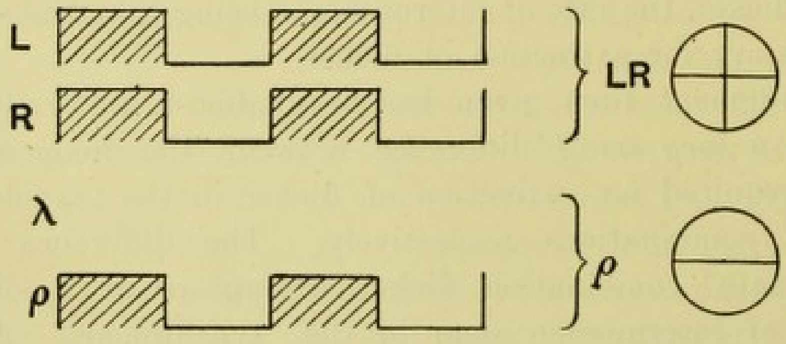


Diagram 3. Exp. 2.

so that the pair act together with a synchronous arrangement of phase, a trace of flicker appears at once in the binocular image. It may be urged that this is due to the fresh retinal area being more sensitive to flicker, and it is true that the flicker so introduced tends soon to become less, but a residuum of the phenomenon seems to remain.

Experiment 3. Conversely, under the arrangement indicated in Diagram 4, a number of the persons examined, but not all, decide that the binocular image requires for extinction of flicker a just slightly lower frequency of intermittent illumination than does the uniocular. Also, a number of these persons, though not all, find that when the 'alternate right and left' combination is observed under a frequency of intermission of illumination just sufficient to extinguish its flicker, the screening out of one of the component uniocular images brings with it a slight appearance of flicker.

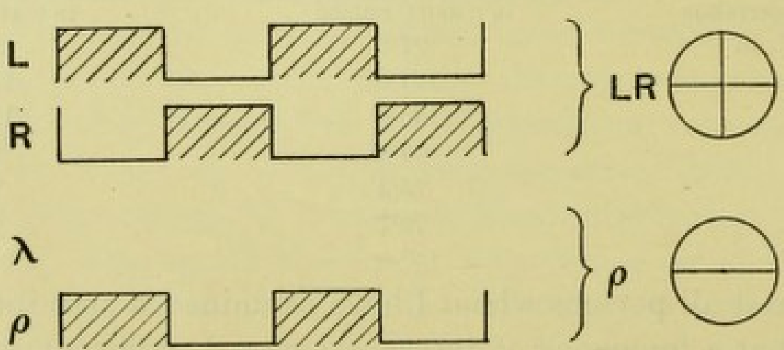


Diagram 4. Exp. 3.

From these observations it appears that similar phases of flickering illumination if timed to fall coincidently on conjugate retinal areas do *very slightly reinforce* each other in sensation, and if timed exactly alternately do very *slightly mutually* *reduce.* But the *broad outcome of the above experimental observations is that* so far from bright phases at one eye effacing dark phases at the corresponding spot of the other eye, *there is hardly the merest trace of any such interference.* To judge from its absence of influence on the flicker rate, the dark phase incident at retinal point A' does not, as regards sensual result, modify the bright phase synchronously incident at the conjugate retinal point A, and conversely. If the brightness of the bright phase or the darkness of the dark phase were lessened at A by A', the rate of frequency of stimulus requisite for extinction of its flicker must fall. But except in minute and perhaps equivocal degree it does not alter.

It may be that the alternate light and dark used in my experiments were of grades too intense to allow of their facile conjugate combination. Two greys not very dissimilar in tone and bounded by contours not disparate, fuse as we know to an intermediate grey (Fechner's paradox) without 'rivalry.' 'White' and 'black' on the other hand fuse with difficulty, are less congruent binocularly and tend to occasion merely an oscillating form of sensation, 'retinal rivalry.' But in none of the observations near the point of extinction of flicker has evidence of retinal rivalry between the already fairly-similarly luminous fields been noticeable.

I have incidentally repeated these experiments under conditions of illumination and retinal adaptation to light differing from those employed systematically for the rest of the inquiry. With quite low luminosities of the disc-images and under dark-adaptation of the eyes—after half-an-hour or longer in darkness—the results obtained have conformed with those found without dark-adaptation and under the much brighter illuminations otherwise systematically used. The LR and $\lambda\rho$ images have shown no distinct difference between them as to frequency of intermission required to extinguish flicker in each respectively. Several times the 'synchronous' combination has appeared to have its flicker extinguished slightly the less readily, just as noticed in the observations with higher luminosities and light-adapted eyes: but the difference when perceived has been so slight as to be perceptible with difficulty. The frequency of intermission required for flicker-extinction has under the low luminosities been of course extremely slow. A cylinder with only three openings per revolution was used in order to give more quickly moving edges to the alternate lights and shadows. There was also under low luminosities and dark-adaptation no distinct difference of flicker-extinction frequencies noted between the two discs when observed not on the central retina but outside that region, *e.g.* with either R or L image between the macula and the blind-spot, and somewhat nearer the latter. But I have not systematically pursued observations with various peripheral regions of the retina.

As far as sensual effect goes, the light phases at the one eye practically do not, therefore, interfere or combine at all with the coincident dark phases at the other; and conversely. Nor do they, in the alternate left and right arrangement, add themselves as a series of additional stimuli to the like series of stimuli applied at the other eye. If they did the revolution rate of the cylindrical shutter required for extinction of flicker in the upper binocular image *LR*, Diagram 2, would fall far below that required for extinction in the uniocular. This it does not do. It does not even fall at all, apart from the minute difference noted by some persons as mentioned above. A similar result is obtained under the, in some ways more decisive, conditions (Experiment 4), represented in Diagram 5.

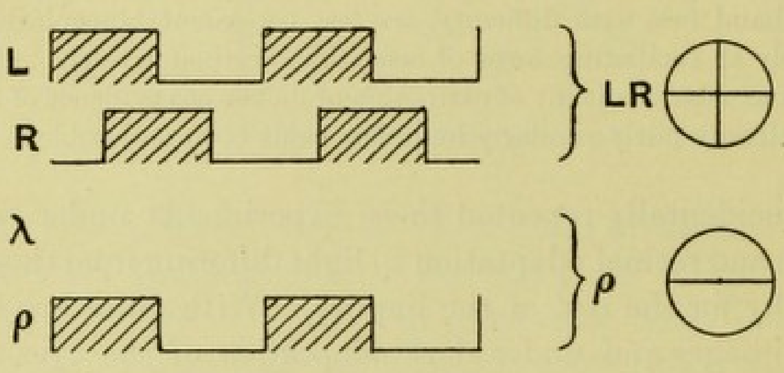


Diagram 5. Exp. 4.

With this arrangement no observer in my experiments has ever with certainty detected any difference at all between the uniocular and binocular images in regard to either the apparent rate of the flicker when moderately coarse, or the rate of intermission required for flicker-extinction. This arrangement (Diagram 5) seems the most crucial for deciding the point. In the 'alternate right and left' arrangement (Diagram 2, L. R., upper combination) the instants of change of phase falling together right or left, it might be that it did not matter as regards flicker-sensation whether the direction of change was from light to dark or dark to light: the rates of intermission being the same right and left, and the instants of their incidence being synchronous, it might then be that as regards flicker the arrangement was only tantamount to the 'synchronous right and left' arrangement (Diagram 2, lower combination) or to the uniocular intermittence of the same rate. The arrangement (Diagram 5) avoids this dilemma. Moreover it avoids both the minute reinforcement and the minute reduction of flicker inherent, according to the above given experience, in the exactly 'synchronous' and exactly 'alternate' arrangements. It may be termed for convenience of reference the 'intermediate' arrangement. The physiological stimulation it delivers to the conjugate retina is by any mode of count delivered at twice the rate of delivery for either retina considered apart from its fellow. *Yet the rate of revolution of the cylindrical lantern required to extinguish flicker in this experiment remains for the binocular image the same as for the uniocular.*

There arises the question whether we may regard the dark field covering the area correspondent with that to which in the other retina a bright image is presented, as non-existent visually. That assumption has been made above, and is indicated in the diagrams (Diagrams 3, 4, 5). In them, where one image is represented as uniocular, the conjugate area of the other retina is left out of the diagram altogether, as though the latter retina were non-existent, or for the time being blind. This seems permissible, because in all the experiments in which a binocular image was compared with one assumed to be purely uniocular, great care was exercised to ensure absence of all trace of detail or contour from the homogeneous darkness present at the time over the whole of the other retina, except where lay the one component of the compared binocular image. When all detail and contour were absent from the field containing this correspondent area, when in fact that field was perfectly void of contours, and homogeneous, unchanging and borderless, it was found that it mattered little what *depth* of darkness it might have; it might be a shade of grey or even a fair white, without perceptibly influencing the sensual vibrations given by the flickering image before the other eye. The absolute blankness of the field seemed to unhitch the region of retina which it covered from higher cerebral connexions, at least to prevent its reactions from contributing to consciousness. The condition seemed comparable with the familiar disability to see the dark field presented to one closed eye, when with the other eye the observer regards a detailed image[1]. As will be shown in the next section an unflickering image presented to one eye damps the flickering of an intermittent image concurrently presented to the corresponding area of the other. For these reasons the visual image resulting from the presentation of the bright disc to one eye only, as in the arrangements shown by Diagrams 3, 4, and 5, was regarded as being a truly uniocular product, uncomplicated by any component from the other retina. The corresponding area of this latter was considered as for the time being out of

[1] Cf. Helmholtz, *Physiologische Optik*, 2 Auf. S. 916.

action as regards sense, not so much by darkness as by ensuring borderless void homogeneity of field,—as when eye-closure affords visual rest. Under this blankness the 'retinal-points' become unhitched from the running machinery of consciousness, if—and this is essential—the 'corresponding' retinal area be concurrently under stimulation by a defined image. McDougall's[1] principle of competition for energy between associate neurones seems at work here, for with *both* eyes shut the dark blankness of eye-closure does become *visible*. Even with one eye open, if its field be undetailed and homogeneous, glimpses of the 'Eigenschwarz' of a closed eye become obtainable (Purkinje, Volkmann, E. Hering).

The stimulations of the two retinae being thus accurately conversely timed, some interference of the flicker sensations so generated might be expected to be discoverable. But the above experimental evidence indicates absence (practically entire) of any interference between the flicker processes so initiated. The right and left 'corresponding retino-cerebral points' do not when tested by flicker reactions behave as though combined or conjugate to a single mechanism. Their sensual reactions retain individuality as regards time relations even when completely confluent as judged by reference to visual space.

Section II. **Asymmetrical Flicker.**

In the foregoing experiments the sensual flicker reactions engendered at 'corresponding' areas of the two retinae appear (almost entirely) without influence one upon another. But in the experiments now following the flicker test reveals very considerable mutual influence between reactions initiated at the corresponding areas.

Suppose (Experiment 5) two binocular images LR and $\lambda\rho$ similarly combined from similar uniocular components, all individually equal in brightness and in intermission frequency. Suppose that of the components of one pair ($\lambda\rho$) one (ρ) be replaced by an intermittent uniocular image (ρ'), of the same physical brightness as that giving the visual image ρ, but of considerably higher intermission frequency. In ρ' all flicker will disappear at slower speeds of revolution of the lantern than those required to extinguish flicker in L or R or λ. Diagram 6 represents the arrangement.

The frequency of intermission required to extinguish flicker in $\lambda\rho'$ is then found to be much lower than the frequency required for

[1] *Mind*, 1902, N.S. xi. p. 316.

extinction of flicker in *LR*, or in *L* or *R* or λ separately. Thus the frequency for extinction of flicker in $\lambda\rho'$ was found (observer H. H.) to average 52·2 phases per sec., as against 61·9 phases per sec. for *LR*, or for *L*, *R*, or λ separately. With another observer (S. C. M. S.) its extinction occurred on the average at 48·3 phases per sec. as against 58·5 per sec.

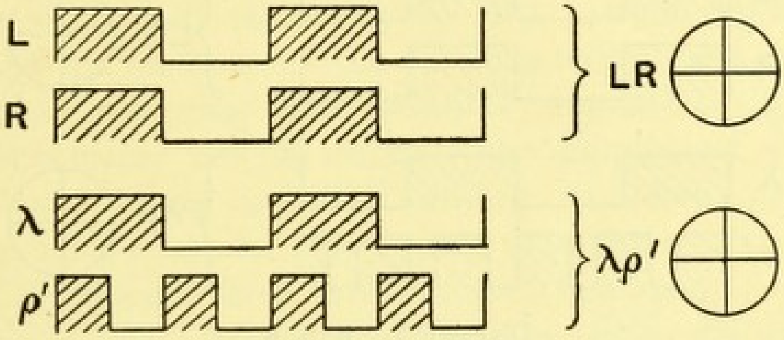


Diagram 6. Exp. 5.

Screening image ρ' out of the binocular combination $\lambda\rho'$, when the frequency of intermission was just high enough to free the $\lambda\rho'$ image from flicker, at once brought flicker into it; this disappeared immediately image ρ' was readmitted to the combination.

In this instance the intensity chosen for the steady illumination of the conjugate area was equal to that employed for the uniocular flickering image. The durations of the light phases and the dark per revolution of the lantern were equal, and the light and dark phases of the same intensity in both. But the phenomenon obtains also when the steady uniocular image is less bright (Experiment 6) or more bright (Experiment 7) than the flickering uniocular with which it is combined. The following are examples illustrating this.

Experiment 6. In the balanced pair of binocular images *LR* and $\lambda\rho$ made of carefully equalised intermittent uniocular images *L*, *R*, λ and ρ, the uniocular image ρ was replaced by one, ρ', of five times greater rapidity of intermission and giving a steady image of only $\frac{1}{5}$ the brightness of the images *L*, *R*, λ and ρ when steady. The frequency of intermission required to extinguish flicker in the binocular image $\lambda\rho'$ (Diagram 7) was then found to be 72·1 phases per sec., whereas in *L*, *R*, and in λ, *L*, and *R*, separately it was 75·5 phases per sec. as it had been in the previous $\lambda\rho$. The steady sensation from image ρ' therefore damped the vibration of the flickering sensation from the conjugate spot under image λ by an amount represented by 3·4 phases per sec. This was for the observer G. C. For another observer, S. C. M. S., the difference was greater, namely, six phases per sec., the flicker extinction rate being 56·4 phases per sec. for image $\lambda\rho'$, and 62·4 phases per sec. for images λ, *L*, *R*, or *LR*, or the previous $\lambda\rho$.

Again, for the same observer S. C. M. S. when the brightness of image ρ' was further reduced to $\frac{1}{12}$ that of the λ and the other uniocular images, the flicker extinction rate for $\lambda\rho'$ became 54·3 phases per sec. as compared with 61·2 phases per sec. for *LR* or the uniocular images λ, *L*, *R*, taken separately. In all these observations the image $\lambda\rho'$ was visually distinctly less bright than *LR*, or λ, or *L*, or *R* taken singly (cf. Fechner's paradox).

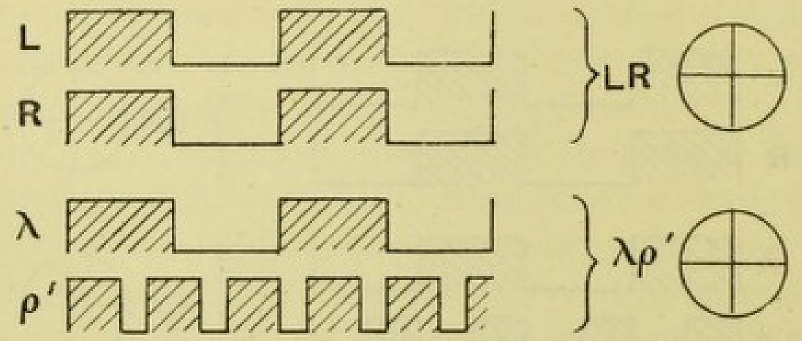


Diagram 7. Exp. 6.

Experiment 7 illustrates an observation in which for the image ρ in the binocular combination $\lambda\rho$ an image ρ' was substituted of three times higher frequency of intermission and giving a steady image of one-fifth greater brightness than the image *L*, *R*, and λ when steady. It was then found that the frequency of intermission required to extinguish flicker in the binocular image $\lambda\rho'$ (Diagram 8) was 57·8 alternate equal phases (of λ) per sec. Whereas in *LR*, and in λ, *L*, and *R*, taken separately, the number of such phases required was 63·6 per sec.

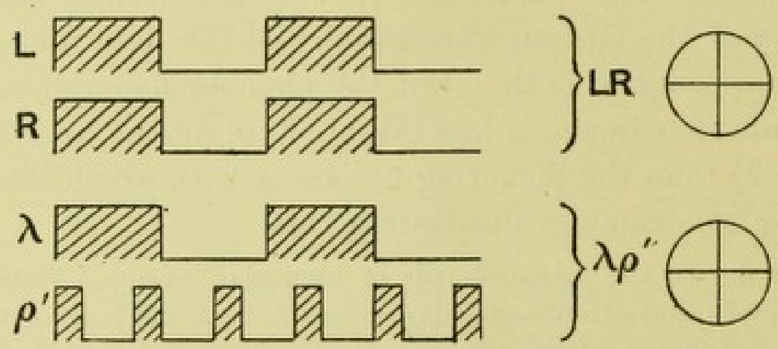


Diagram 8. Exp. 7.

The image $\lambda\rho'$ was distinctly brighter visually than was *LR*, or any of the uniocular images λ, *L*, and *R*.

Again (Experiment 7 A) with image ρ' steady and of twice the luminosity of λ, or *L*, or *R*, the binocular visual image $\lambda\rho'$ loses flicker at an intermission of 80·3 phases per sec., but binocular image *LR* not until 85·9 per sec.

These observations show, as did the observations represented by Diagram 6, that it is not merely the reduction of brightness in the combined image $\lambda\rho$ in the arrangement shown by Diagram 7 that lessens the flicker in the latter. In fact in the observations on the plan illustrated by Diagram 8 we have the, for flicker photometry, interesting case of a brighter intermittently illuminated surface flickering less than a duller one.

Here the conditions of experiment at once suggest a possible explanation. It is as though the dark phases of the intermittent illumination of the left retina (*e.g.* in Exp. 7) were lightened by the contemporary illumination of the 'corresponding' area of the other retina. Before accepting this plausible supposition it is however necessary to consider two objections. The illumination at the 'corresponding' spot obtains not only during the dark phases of the intermittent images at the other retina, but during the light phases also. If it brightened these as much as it lightened the dark phases the intensity of intermittence would remain practically unaltered, and the above supposition could not explain the reduction of flicker which the steady illumination of the conjugate area causes. But experiment shows that the brightness of a binocular image in the central field of the light-adapted eye is not the sum of the two component uniocular images. When the two components are of equal brightness the brightness of the compound is hardly greater, sometimes not at all (*v. infra*, Section III.) perceptibly greater, than that of either individual constituent.

Indeed the resultant binocular brightness of two component uniocular brightnesses, of such order of intensity as used in these experiments (and with the eye not adapted for dark[1]), seems to lie near the arithmetic mean of the two components (*v. infra*, Section III. p. 50). The addition of the steady brightness at one eye to the dark phase of the intermittent at the 'corresponding spot' would according to that lighten the latter, and its addition to the bright phase would if of equal brightness with that leave it practically unaltered.

If to an intermittent uniocular image R a steady uniocular image L is added by binocular combination, under the rule just mentioned, it is obvious it will not matter what, within wide limits, is the relative brightness of L to R; L's power to diminish the flicker of R will for all L's values remain about the same.

So far as flickering of R depends upon difference in brightness between its successive light and dark phases, this difference will be

[1] Piper, *Zeits. f. Psych. u. Physiol. d. Sinnesorgan.*, XXXII. 161, 1903.

lessened practically to a similar extent, whether the steady brightness of *L* be less than, equal to, or greater than *R*'s brightness. A paper disc, made up so as to represent in its concentric circles the hypothetical *LR*'s of cases iii. and iv. of Diagram 9, gives by diffuse daylight no clear difference of flickering of the two. But I have not yet examined the case *LR* iii. of Diagram 9 in the rotating lantern itself. I have however determined experimentally the amount of decrease of flicker in a uniocular image *R* under binocular combination with an unflickering

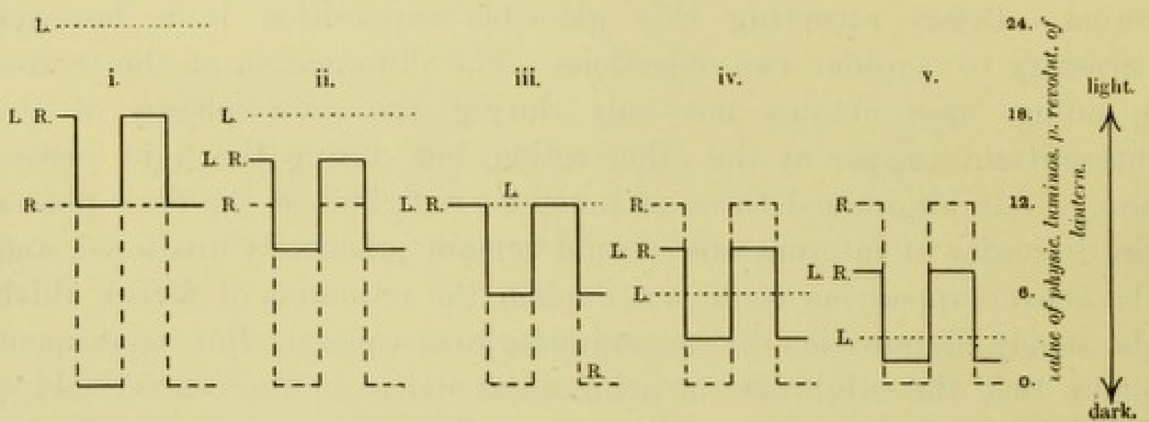


Diagram 9. The continuous line indicates the changes in the binocular image, the broken line those in the *R* eye image, the dotted line the steady luminosity of the *L* eye image.

image *L*, of physical luminosity respectively $\frac{1}{4}$, $\frac{1}{2}$, equal to, $1\frac{1}{2}$, and twice, that of *R*. The method followed was to take a 'standard' binocular intermittent image $\lambda\rho$, made up of two equal intermittent left and right uniocular components λ and ρ. Close beside $\lambda\rho$ in the binocular field was set an image *LR*, made up of a uniocular component *R*, exactly like each of the components of $\lambda\rho$, and of a component *L* of perfectly unflickering brightness. The physical luminosity of λ and ρ and *R* being taken as value 6, that of *L* was in the five cases 12, 9, 6, 3 and 1·5 respectively.

TABLE IV.

	Physical luminosity			
	Image L. (steady)	Image R.	No. of observations (G. C. and C. S. S.)	Mean reduction observed in fusion point for flicker of R, expressed in phases per sec.
i.	12	6	12	7·55
ii.	9	6	18	7·42
iii.	6	6	24	8·54
iv.	3	6	24	6·25
v.	1·5	6	28	8·20

These grades were except the first obtained by using an episkotister in front of the one of the lantern windows chosen to furnish image L, the physical luminosity numerically denoted above therefore involves a time unit, *e.g.*, a second, or a revolution, either of the cylindrical lantern for ρ, λ or R, or of the episkotister for L. Lest it be thought that the physical intermittence of the unflickering image was possibly of influence or a possible complication, it must be stated that the rate of the episkotister was far above that necessary to extinguish all trace of flicker from the visual image. Also, it was by experiment found that increasing or diminishing the speed of the episkotister by half did not modify the result, so long always as its speed remained above that necessary to extinguish flicker. Moreover for the determination where $L=12$ no episkotister but a steady light was used, and yet the measurement obtained was the same.

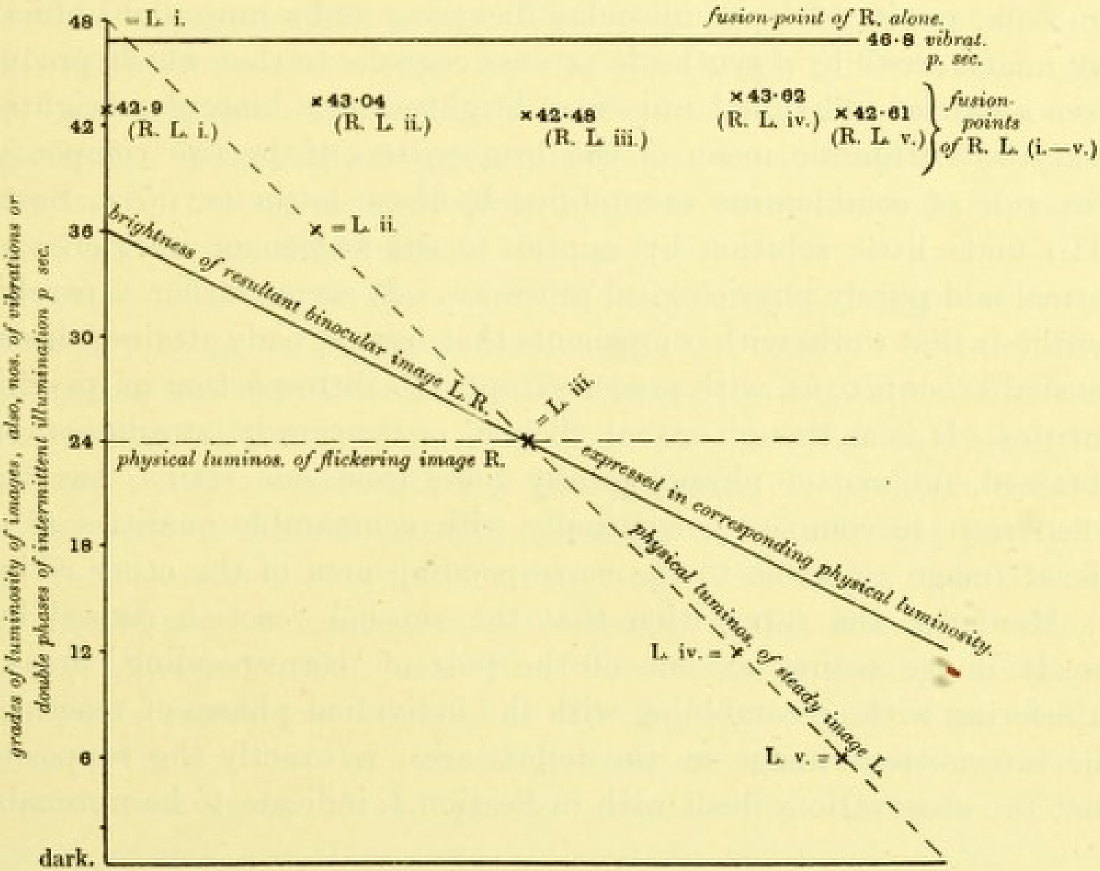


Diagram 10. **The heights of the Ls represent their physical luminosities not the frequencies of intermittence for extinction of their flicker.**

The amount by which the fusion-point (*i.e.* the point of speed at which flicker was extinguished) for image LR lay lower than that for the standard $\lambda\rho$, or for R, was taken as measure of the influence of the continuous steady image upon the flickering one. The results observed are given in Table IV. opposite.

The difference between the extremes of these measurements lies within the range of error of the observations. I conclude, therefore, that *the reduction of the flicker of an intermittent uniocular image by binocular combination of it with an unflickering uniocular image remains practically the same over a considerable range of variation of luminosity of the unflickering image.*

To return therefore to the plausible suggestion above, that in these experiments we have evidence of mutual interference between the purely physiological processes initiated at the corresponding spots of the right and left retinae; the suggestion meets no direct contradiction, but rather appearance of support from the determinations.

But, on the other hand, the above result at once suggests that the binocular product from a uniocular flickering and a uniocular unflickering image arises by a synthetic process cognate to that which produces from a pair of individual uniocular brightnesses a binocular brightness near the arithmetic mean of the brightnesses of the two components. The rule of combination exemplified by these latter (*v. infra*, Section III.) finds little solution by appeal to summation or interference of retinal and purely physiological processes. It seems rather a psychical synthesis that works with components that have already attained discrete sensual existence, *i.e.* with processes open to introspection as psychical entities. It is as though visual 'flicker,' or conversely 'steadiness,' once obtained, no matter physiologically how, from one retina, has then, when seen, to compete perceptually with comparable qualities of any visual image referable to the corresponding area of the other retina.

Moreover, the supposition that the sensual reaction caused by a steady image acting at one of the pair of 'corresponding' areas, is interfering with or combining with the individual phases of reaction to the intermittent image at the fellow area, is exactly the supposition that the observations dealt with in Section I. indicate to be untenable.

SECTION III. **Uniocular and Binocular Comparisons.**

With intermittent lights throughout a wide range of ordinary intensities Talbot's law is unimpeachable for the single eye; and also for the two eyes if employed together under, as is usual, arrangements practically equivalent to the 'simultaneous' right-left method of Section I. It is interesting to discover how far the double retina will still observe Talbot's law when subjected to treatment that, if the retina did then observe the law, would readily reveal its integration to a functionally single retina. In other words, under a rapidly repeated stimulus, when one incidence of that stimulus has acted on a retinal point the question is: how far is it the same thing for visual brightness, whether the next incidence be upon the same retinal point or upon the twin point in the other retina? How far can the double retina, when functioning for singleness of perception in binocular vision, be considered as functionally combined to a single retina, and how far does it then react as does a single retina, if examined for Talbot's law?

The 'alternate left-right arrangement' of Section I. (Experiment 1, *LR*) supplies the required method of stimulation. With speeds of revolution of the lantern too high to allow flickering, the binocular image *LR* (Diagram 2) is seen to appear of equal brightness with $\lambda\rho$, and with the uniocular images λ or ρ taken singly. Therefore, in the above sense, Talbot's law not only does *not* hold for the double retina considered as functionally single, but it yields even no trace of observance of the law. The two corresponding points are therefore in this respect not integrated to a single retinal surface.

It was often noted that with all four lantern images of equal luminosity, using intermission-frequencies too rapid to allow flicker, the brightness of the binocular combination of any two did not distinctly exceed that of the uniocular. In certain instances the binocular combination did appear just distinctly the brighter. This was for instance the case when of the four lantern images the two on the same horizontal level were combined by simple convergence. This excess of brightness is the well-known phenomenon examined by Jurin[1], Harris[2], Fechner[3], Aubert[4], Valerius[5], and others. But there occurred frequent instances in which no excess was observed in the brightness of binocular combinations over that of their carefully balanced uniocular components. In the observations of the present inquiry the brightness of the physical images was always much above the threshold of the light-adapted eye; and no systematic observations were made with the eye dark-adapted. To obtain good conditions for comparison of the brightness of the binocular and uniocular images observed the following arrangement was employed.

[1] Smith-Kästner, *Lehrbegriff der Optik*, 1755.

[2] *Opticks*, 1775.

[3] *Abhandlung d. Akad. Wiss. Leipzig*, VII. 423, 1860.

[4] *Physiologie d. Netzhaut*, S. 287, Breslau, 1865.

[5] *Poggendorff's Annal.* Bd. 150, S. 17, 1873.

Experiment 8. Two images LR and $\lambda\rho\frac{1}{2}$ were placed in the visual field for mutual comparison. LR was composed of left-eye and right-eye equal and corresponding disc-shaped images as in previous experiments. $\lambda\rho\frac{1}{2}$ was composed of a left-eye image similar to L and R except that it lay just above or below them in the visual field. With λ's right half was combined the image of the right half of a lantern image similar again to the others, except that its left half was screened absolutely off into the blank undetailed darkness of the general field. When this was done the two opposite visual images LR and $\lambda\rho\frac{1}{2}$ regarded under perfectly steady ocular fixation, were stable, and no difference of brightness was discernible between them. Moreover no join was seen between the halves of $\lambda\rho\frac{1}{2}$ and no difference of brightness between the halves. After prolonged inspection of them rivalry became troublesome; but a judgment could be clearly arrived at before that happened.

In this experiment it might possibly be that equality of brightness between the halves of $\lambda\rho\frac{1}{2}$ was due to image $\rho\frac{1}{2}$ not really being in consciousness at all during the comparison. The image might possibly lapse under competition with the partly dissimilar correspondingly placed left-eye image λ. Some of the experiments carried out by McDougall[1] give validity to such possible objection. The perceptibility of the horizontal bar in the right half of the image $\lambda\rho\frac{1}{2}$ was guarantee however that at least part of the uniocular image $\rho\frac{1}{2}$ was present. But to ascertain more surely whether image $\rho\frac{1}{2}$ was really during the visual equation co-operating in consciousness with λ the following further arrangement was employed.

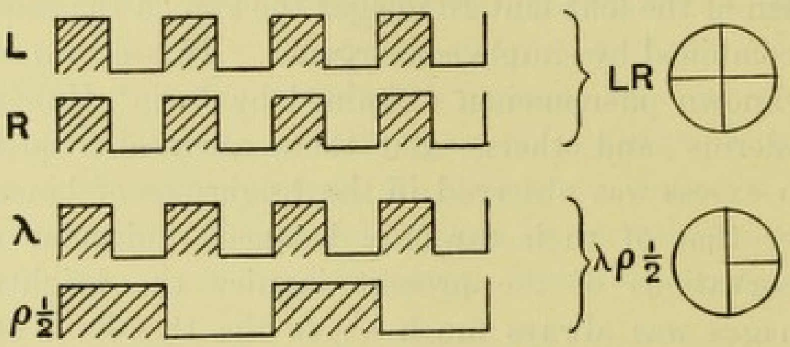


Diagram 11. Exp. 9.

Experiment 9, (Diagram 11). With the revolving lantern so arranged that images L, R, λ and $\rho\frac{1}{2}$ were all of equal brightness when steady and unflickering, $\rho\frac{1}{2}$ was given a lesser frequency of intermission, so as to flicker while the others did not. A speed of revolution of lantern was then used at which just a trace of flicker was perceptible in $\rho\frac{1}{2}$ when binocularly combined with λ. The equation $LR=\lambda\rho\frac{1}{2}$ was then found to hold while flicker was still just traceable in the right

[1] *Mind*, 1901, N.S. x. p. 63.

half of $\lambda\rho\frac{1}{2}$. There was then no join seen between the halves of $\lambda\rho\frac{1}{2}$ nor any difference between the brightness of the halves. So long as ocular fixation was steady no rivalry disturbed the observation.

In this case there could, I venture to think, be no question but that the one half of $\lambda\rho\frac{1}{2}$ was truly binocular, for the trace of flicker was perceptible during the actual performance of the comparison. Yet no difference of brightness was perceived between LR and $\lambda\rho\frac{1}{2}$, and the two lateral halves of $\lambda\rho\frac{1}{2}$ compared together were of like brightness.

Even where the binocular image *has* shown the well-known slight excess of brightness over its uniocular components it, under some conditions (*v. supra* 'alternate' arrangement), flickers no more or even less than they.

It is doubtful therefore to me whether the slight excess in brightness of the binocular image over its two equal uniocular components is really explicable as summation of the intensities of the reactions at the corresponding spots of the two retinae. Valerius[1] measured the increase to be one-fifteenth of the brightness of the uniocular image. Aubert's[2] diagram gives it as less than one-thirtieth. Aubert says it is not perceptible with brightnesses greater than that of white paper in diffuse daylight indoors[3].

In certain modes of experiment a uniocular image used as standard for comparison might itself be suffering some reduction in brightness owing to slight combination with the dark field presented concurrently at the corresponding retinal area. But 'rivalry' should reveal such influence. A better definition and greater vividness of detail assured by better accommodation and convergence under binocular regard, might possibly give an appearance of greater brilliance and intensity. But these are only suggestions.

I conclude that, with the intensities of illumination used in this research, although a binocular image does sometimes appear of slightly greater visual brightness than either of two similar uniocular images composing it, more often it has a visual brightness not perceptibly different from that of either of its two co-equal uniocular components. The case then falls within a general rule regarding binocular brightness attested by all observations that have borne on that subject throughout the present inquiry. Disc images of homogeneous surface, except for a cross-line, have been the objects of comparison. The rule was in my preliminary paper[4] stated thus: "the physiological sum of two luminosities,

[1] *Poggendorff's Annalen*, Bd. CL. S. 117, 1873.
[2] *Physiologie d. Netzhaut*, S. 286, Breslau, 1865.
[3] *Physiologische Optik*, S. 500, Leipzig, 1876.
[4] *Proc. Roy. Soc.* LXXI. p. 75, July, 1902.

perceived through conjugate retinal areas, is of a value intermediate between the individual values of the two component luminosities." I think it better stated as follows: *a binocular brightness compared with its uniocular components is of value not greater than the greater of those, nor less than the lesser of them; when free from oscillations of rivalry its value is somewhat, but not far, above the arithmetic mean of the values of the two uniocular components as expressed by the measures of the physical stimuli yielding them.*

The various combinations cited in Experiments 2, 3, 4, 5, 6, 7, and 8 have all, when steady and unflickering, given brightnesses illustrating the above rule. Other illustrations are

$$\lambda = 1000, \quad \rho = 250, \quad \lambda\rho = 680,$$
$$\lambda = 1000, \quad \rho = 350, \quad \lambda\rho = 750,$$
$$\lambda = 1000, \quad \rho = 550, \quad \lambda\rho = 835,$$
$$\lambda = 1000, \quad \rho = 750, \quad \lambda\rho = 920,$$
$$\lambda = 1000, \quad \rho = 1000, \quad \lambda\rho = 1000.$$

But I have not worked with combinations where the physical luminosity of one uniocular component has been less than $\frac{1}{13}$th the physical luminosity of the other. It was near these that Aubert, and just beyond these that Fechner, noted decline of the darkening effect of the darker component. In my own few observations beyond that point the oscillations of rivalry have made judgment difficult. The more manageable examples are but demonstrations of 'Fechner's paradox,' and fall under the above general rule. Hering[1] suggests that rivalry is really occurring even with similar right and left uniocular images; he says these react according to a law of 'complemental shares,' and offers a theory, such as the name he gives implies, in explanation of the phenomenon. My Experiment 9 seems to offer difficulty to such a view.

In the light of the above formulated rule, the difference in visual brightness between binocular combination of two images and their effect when superposed on a single retina, is not surprising, although great. A single instance will suffice as illustration here.

Experiment 10 (Diagram 12). *L* and *R* are co-equal uniocular images, each of physical luminosity higher as 33 to 25 (roughly represented in the Diagram) than that of either of the two images λ and ρ, co-equal uniocular components of the

[1] *Beiträge z. Physiologie*, Heft v. S. 310, Leipzig, 1864.

binocular image $\lambda\rho$. L seen beside λ is visually much the brighter; so also when seen beside $\lambda\rho$.

These images were reflections of the lantern images, thrown by first surface mirrors on a Lummer-Brodhun mat white porcelain screen. The mirrors were fitted to 'Basler Stativs,' and the fine adjustments of these allowed the images L and R (or λ and ρ), to be (1) placed side by side or (2) physically superposed, on the screen. The physically combined image $\lambda+\rho$ seen uniocularly was much brighter than $\lambda\rho$ binocular combination. $\lambda+\rho$ physically combined, was also seen much brighter than LR, the binocular combination of L and R.

Again, binocular combination of a less bright image with a more bright gives a visual image of less brightness than the latter (as stated in the rule above). But the application of the less bright to the same uniocular area as the more bright gives a visual image of greater brightness still.

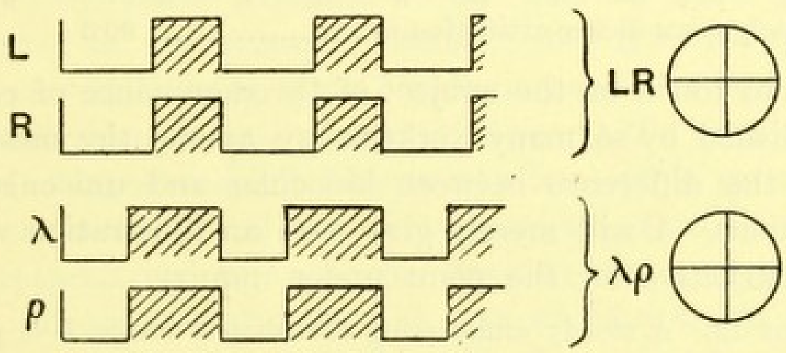


Diagram 12. Exp. 10.

As above described, a steady image presented on an area of one retina 'damps' the flicker of a flickering image concurrently presented at the corresponding area of the other. A steady image actually physically superposed on the same retinal area as a flickering one also reduces the latter's flicker: this is of course in accordance with Weber's law. The modes of interference seem however incomparably different in the two cases; and experiment shows that the two interferences are often of quite different value.

Experiment 11. A pair of the lantern images reflected as in the last cited experiment. The images can be placed on the screen (1) side by side or (2) superposed. The rotating lantern is so adjusted that one image, L, has twice the physical luminosity of the other R, when flicker has been extinguished in the latter. L is steady and without flicker. Image R viewed by right eye loses flicker at an intermission frequency of 68·6 phases per sec. Binocular fusion of R viewed by right eye with L viewed by left eye produces a visual image whose flicker is lost at 65·9 phases per sec. Physical images L and R superposed on screen and viewed by right eye give a visual image whose flicker is lost at 59·8 phases per sec.

Experiment 11 A. Observer G. C.

Binocular fusion of R and L gives flicker extinction at 65·5 phases per sec.
Physical „ „ „ „ „ „ „ „ 59·4 „ „

Observer R. S. W.

Binocular fusion of R and L gives flicker extinction at 55·9 phases per sec.
Physical „ „ „ „ „ „ „ „ 54·7 „ „

Experiment 11 B. L image has $\frac{1}{2}$ the luminosity of R when R is also unflickering:

Observer R. S. W.

Binocular fusion of R and L gives flicker extinction at 106·6 phases per sec.
Physical „ „ „ „ „ „ „ „ 100·3 „ „
R separately gives flicker extinction at...................... 113·3 „ „

Observer S. C. M. S.

Binocular fusion of R and L gives flicker extinction at 91·0 phases per sec.
Physical „ „ „ „ „ „ „ „ 87·8 „ „
R separately gives flicker extinction at...................... 99·3 „ „

Finally, to touch on the subject of 'predominance of contours,' the facts, established by so many workers, are among the most significant concerning the difference between binocular and uniocular fusion of visual reactions. I will merely give here an illustration which seems specially instructive for the point under inquiry.

Experiment 12. A steady unflickering disc-shaped image L is present to the left eye: across the disc is a narrow dark line. An image R of similar size and shape but without the dark line is presented to the corresponding area of the right eye. If the luminosity of L is progressively diminished, a value of luminosity is reached at which its cross line, though visible when L alone is observed (*e.g.* right eye closed) is lost or uncertain in the binocular image RL. This reduction of the luminosity of L much exceeds the reduction at which its cross line is lost when image R is concurrently thrown on the same area of the same retina, *i.e.* left retina. Thus, in one experiment the diminution of luminosity of L required for loss of the cross-line under physical superposition of R and L on the same retina was 84 per cent., while the diminution of luminosity of L required for loss (or great uncertainty) of the line in the binocular image was 96 per cent.

Not only the ease, but the *mode* of disappearance of the cross-line, was significantly different in the two cases. In the "physical superposition" the dark line became gradually thinner and fainter, and finally imperceptible, as the image L was lessened in luminosity. In the case of binocular fusion the dark line oscillated out of and back into perception more and more, the disappearances predominating more and more, as the darkening of L proceeded. At a reduction of 84 °/₀ of the luminosity of L the cross-line was steady, dark, and sharp in the binocular image.

SECTION IV. General Conclusions.

The aim of this inquiry was information as to the nature of the conjunction between the uniocular components in certain simple binocular perceptions. The question concerns the nature of the tie between 'corresponding retinal points,' meaning by 'retinal point,' as said at the outset, the retino-cerebral apparatus engaged in elaborating a sensation in response to excitation of a unit area of retinal surface.

That a perception initiated from corresponding retinal points is commonly referred without ambiguity to a single *locus* in visual space has often been regarded (Newton[1], Wollaston[2], Rohault[3], Joh. Müller[4]) as evidence of community of the nerve apparatus belonging to the paired retinal points. Their visual image appears *single*. Wollaston supposed the twin points attached to one and the same nerve-fibre, which bifurcated at the chiasma. Rohault and Müller supposed the points to be served by twin fibres "from one and the same ganglion-cell in the cerebral substance." Later (cf. Aubert), the visual singleness, spatial fusion of right and left impressions to a single perception, was taken to mean confluence of the nerve-processes, started in right and left retinae respectively, to "a single common centre or point of the sensorium[5]." The discovery later still that the fibre-tracts from corresponding halves of the retinae both go to the occipital region of one and the same hemisphere, has also been inferred to mean a spatially conjoint visual sensorium common to both retinae. But in such questions the inferences obtainable from comparatively rough anatomical features are crudely equivocal and often remote in bearing. Were there to exist such a common mechanism situate as a unit at conjunction of the two convergent systems and were phases of excitement timed so to arrive from one retina as exactly to fill pauses between excitations transmitted from the other, then there should be evidence of this in the time relations of the phenomena induced. The state of excitement should tend to be maintained across periods that would otherwise chequer it as pauses.

The retino-cerebral apparatus may be regarded as a structure of linked branching nerve-elements forming a system which expands as traced centrally from the retinal surface. It may be figured as a tree,

[1] *Opticks*, Quer. 112. [2] *Philosoph. Trans. London*, 1824.
[3] *Physique*, I. 31. [4] *Elements of Physiol.* Vol. II. p. 1199, Baly's edit. 1843.
[5] *Physiol. d. Netzhaut*, 1865.

with its stem at the retina and an arborisation spreading into the brain, its ramifications there penetrating a vast cerebral field, interlacing with others in a cerebral forest composed of nervous arborisations. The simile fails, because in the nervous forest the arborisations make functional union one with another. Is the intimate connexion between the perceptions adjunct to paired 'corresponding points' the outcome of a close concrescence of their neuronic or neuro-fibrillar arborisations, making of them practically a single upgrowth common to twin (right and left) stems rooted in the corresponding retinal units? If so, how low down, how close to their origin, are the twin systems grafted together, giving structural community to all the superstructure? Or suppose each 'retinal point' represented as a system of branched tubing, ramifying more and more as it passes inwards from the retina; do the reactions of paired 'retinal points' indicate that the two systems combine to a common one? If so, how early do their functional processes conjoin; how near to the retinal origin does the intercommunication begin?

Effects of excitation, represented as changes of pressure in the systems, valves preventing reflux toward their retinal ends, will, when similar stimuli are applied synchronously to the two stem-pipes, if their systems intercommunicate, reinforce each the other. Conversely, alternate stimuli will each tend to neutralise the effect of the other. There will be 'interference,' algebraic summation, compounding of vibrations, as with a medium subjected at once to two sources of vibration.

In the chain of nerve-elements attached to a sense-organ we infer in general that to the activities of the most peripheral links *per se*, psychical events are not adjunct. Psychical processes, beginning with least complex and ascending toward development through many grades, attach to the chain in such a way that for the simplest only the more peripheral portions of the chain need be connected with the sense-organ, while for the more and more complex the central portions in addition become more and more extensively involved. But in the higher reactions of definite psychical aspect, *e.g.* sense perceptions, the lower apsychical and less definitely psychical activities also are implicate. Where from two sense-organs, *e.g.* two units of retinal surface, the two nerve-chain arborisations are mutually connected, so that the lower activities of the one are communicated by low-level side-connexions to the elements forming the other, there analysis must fail to distinguish in the full reaction what higher components may be separately referable to one only of the two individual chains. The processes apsychical, or so indefinitely psychical as to baffle introspection, at root of the psychical processes amenable to introspection, must by their coalescence defeat attempt to trace the final psychical product to either of its two possible sources, so long as both sources are open for its origination.

Were the nervous reaction, initiated at the retina, early in its path along the retino-cerebral nerve-chain, to enter mechanisms common to both 'corresponding retinal points,' there must, under 'alternate' or 'synchronous' right-left arrangement of stimuli (Section I., Diagram 2), be a coalescence of events which, though apsychical in themselves, would involve subsequent confusion together of the sense-reactions of the two eyes. A state of things wholly different from this is revealed in the results above experimentally obtained. Talbot's law might in that case be expected to hold good for the paired corresponding points, functioning together, just as it does for the point of a single retina. That is to say, it might be expected to amount to the same thing, or approximately the same thing, whether two quickly successive flashes of a light fell both on one and the same member of a pair of 'corresponding points,' or whether the first fell upon one member, the second upon the other. But the experiments show that the effect in the two cases is widely different. In other words, Talbot's law is not applicable to the double retina, that is, to the two retinae functioning together in binocular vision. The experimental results go to disprove the existence of any such fusion or interference between the apsychical or even the subperceptual events arising from corresponding retinal points. At most they indicate hardly discernible traces of such interference (Experiment 1). Moreover they indicate on the contrary that such simpler forms of binocular perception as have been dealt with here are themselves fusions of elaborated uniocular *sensations*. Since left and right end results emerge pure, 'hybridisation' has not mixed the early stages in their evolution.

But the difference between the modes of stimulation left and right (Experiments, Section I.) is a difference that, although it should be potent if the left and right physiological machinery were conjoined to unity, should constitute no difference when left stimulation is compared with right stimulation by the perceptual product which each yields. *The left eye and right eye flickering visual images, each viewed singly, do* NOT (apart from the faint cross-line for recognition) *differ to introspection*. If the sensations derived from the left eye and right eye respectively appear under introspection indistinguishably alike, what ground is there for mutual interference between them? It is much as though, of the left and right lantern images, each were seen by one of two observers, with similar vision, and as though the minds of the two observers were combined to a single mind. It may be recalled that binocular unification of images, as we possess it, seems a comparatively late achievement of phylogenetic evolution.

When the visual product of the two retinae is thus regarded it is not surprising that Talbot's law fails for the binocular cyclopean retina. It fails because the binocular sensation is a fusion of uniocular sensations, and from no two similar sensations can a resultant sensation be compounded different from its components. Were Talbot's law to hold in the above sense for the binocular retina there would, under the 'alternate left-right arrangement' (Section I.), at rates of intermission too high for flicker, result from an image L of brightness x, and an image R of similar brightness x, a combined image LR of brightness $x+x$, the value of the summed brightness being in accord with the Weber-Fechner rule of summation of sensual intensities. But, as shown by the experiments of Section I. (and Experiments 9, 10, Section III.), not only does this summation not occur, but nothing like it occurs. The binocular result most often does not perceptibly differ from either of its two co-equal components.

But the experiments (Section II.) with uniocular components dissimilarly flickering, and with flickering components concurrent with steady components, evidenced (unlike the experiments of Section I.) interference between the two eyes. This result might be interpreted as the outcome of community of the physiological mechanisms attaching to the paired 'corresponding retinal points.' But the other experiments, *e.g.* Section I., exclude the existence of this community. And the explanation just offered for the absence of interference in Experiments Section I. will account for the presence of interference in the Experiments Section II. From two components perceptibly differing between themselves in regard to some quality (*e.g.* flicker) a single combined sensual quality is obtained, intermediate between that of the two components taken singly. If the perceptible difference, *e.g.* in flicker, between the components is wide, the fusion is liable to phasic oscillations of predominance of one or other component. Where the difference in flicker is wide, such 'rivalry' between the right and left components is in fact not unfrequently seen. One component may at the height of its phase be alone perceptible at the focus of attention, the other component being inhibited out of focal attention or even out of conscious vision altogether. The inference is that only *after the sensations initiated from right and left 'corresponding points' have been elaborated, and have reached a dignity and definiteness well amenable to introspection, does interference between the reactions of the two (left and right) eye-systems occur. The binocular sensation attained seems combined from right and left uniocular sensations elaborated independently.*

And in harmony with this view stands the evidence adduced in Section III. The rule there formulated regarding the relation of binocular to uniocular brightness is an instance. Further, the difference between the sensual result of superposition of two similar images upon one and the same area of a single retina, and of placing them upon corresponding areas of the two retinae, could hardly be so great as it is, did apsychical or subsensual reactions underlying 'brightness' combine or interfere in the two retinal systems. If the binocular combination is a synthesis of a left-eye with a right-eye *sensation*, the difficulty disappears. Similarly, the 'prevalence of contours' in binocular vision, and the phenomena of 'retinal rivalry,' are explicable if each member of a pair of corresponding points yields a sensual entity which, when not widely dissimilar from that yielded by its twin point, fuses with that to a binocular sensation. In 'retinal rivalry' we have an involuntarily performed analysis of this sensual bicompound. The binocular perception in that case breaks down, leaving in phasic periods one or other of the simpler component sensations bare to inspection.

It is 'retinal rivalry' that in my judgment produces the marked difference in character of the flicker of the 'alternate' and 'synchronous' arrangements respectively at frequencies of intermission much below that required for extinction of their flicker. The 'alternate' arrangement then yields a flicker which though very marked is described by most observers as "less than" that of the 'synchronous' arrangement. It is "less decided" and "more irregular and hesitant," so that the observer is led to anticipate that as the frequency of intermission in both discs is increased flicker will disappear from the 'alternate' arrangement the earlier (*v. supra*, p. 34). 'Retinal rivalry' cannot of course occur in the 'synchronous' arrangement; but with slower and slower frequencies of intermission it becomes for the disc with 'alternate' arrangement more and more perceptible and obvious. Now 'retinal rivalry' is itself evidence of the physiologically independent development of two uniocular sensations. The difference therefore between the flicker given by the 'alternate' and 'synchronous' binocular discs under slow frequencies, argues, just as does their want of difference under higher frequencies, for physiological independence of the right and left component 'points' of 'corresponding' pairs.

Helmholtz in opposition to Panum[1] argued in favour of a purely psychical origin for 'prevalence of contours.' He invoked an explanatory 'direction of attention.' An inference he drew at the time regarding retinal rivalry accords with the inference drawn above from the flicker observations dealt with here, viz.[2]: "dass der Inhalt jedes einzelnen Sehfeldes, ohne durch organische Einrichtungen mit dem des anderen verschmolzen zu sein, zum Bewusstsein gelangt, und dass die Verschmelzung beider Sehfelder in ein gemeinsames Bild, wo sie vorkommt, also ein psychisches Act ist." A finely illustrative experiment on contours given by E. Hering[3] is applicable in the same sense.

McDougall[4], in applying to 'retinal rivalry' and 'prevalence of contours' his principle of competition of inter-related nerve-elements for energy, also argues a "separateness of the visual cortical areas for the two eyes." He brings forward striking experiments in evidence of this. In one of these he[5] shows that an after-image, left from excitation of one retina, is more strongly revived by subsequent weak diffuse excitation of that same retina than of its fellow. More recently, in experiments proving reinforcement of visual sensations by the activity of the ocular muscles, as evidenced by after-image observations, he[6] shows that activity of the intrinsic muscles of an eye sends up to the brain an influence, reinforcing the activity of the cerebro-retinal tract of that eye, while it exerts no such effect upon the corresponding tract of the other eye, or exerts it in a minor degree only.

With this separateness of the mechanisms, wherein are produced the sensations generated in the two retinae, the results recorded here from a different line of experimentation accord well. In certain respects the independence of the two mechanisms seems rather greater in regard to the tests applied in this inquiry than to those employed by McDougall. But the visual phenomena investigated in the two cases are not easily comparable. The chief evidence for some slight low-level communication between the right and left eye-systems, elicited by my

[1] *Physiologische Untersuch. üb. d. Sehen mit zwei Augen*, Kiel, 1858.

[2] *Physiologische Optik*, 2 Auf., Leipzig, 1896, S. 921.

[3] Hermann's *Handbuch d. Physiologie*, Bd. III. S. 384.

[4] "The Principle underlying Fechner's 'Paradoxical Experiment' and the Predominance of Contours in the struggle of the two Visual Fields." This Journ. p. 114.

[5] *Mind*, 1901, N.S. x. p. 56.

[6] *Mind*, 1903, N.S. xii. p. 473.

work, has been the slightly lower frequency of stimulation found necessary for flicker-extinction under 'alternate left-right' excitation than under 'simultaneous.' The slight excess of brightness of the haploscopic over the uniocular image, recorded by so many observers, and shown by Piper[1] to be much more considerable for the dark-adapted eye, may be taken as evidence in the same direction.

Binocular colour mixture may at first sight seem suggestive of a purely physiological fusion as the basis of binocular colour sensations. The facility of binocular colour mixture I find about the same when the uniocular colours are presented to 'corresponding points' by the 'simultaneous left-right,' or by the 'alternate left-right,' or by an 'intermediate arrangement' (Section I.). Of binocular colour mixture E. Hering writes[2]: "Hat man durch haploskopische Betrachtung zweier farbigen Flächen eine Mischfarbe erhalten und lässt dann genau dieselbe farbigen Lichtmengen auf eine und dieselbe Netzhautstelle fallen, so ergibt sich eine ungleich hellere oder weisslichere Mischfarbe." "Mischt man aber die beiden Farben binocular, so ist die resultirende Mischfarbe nur ungefähr gleich hell, wie die Einzelfarbe. Diese Thatsachen genügen schon, um selbst in den Fällen, wo die binoculare Mischung vollkommen gelingt, dieselbe der unocularen nicht gleichzustellen." With this conclusion my rule given above (page 50) is in complete agreement.

The compounding together of right and left images areally non-identical, but not widely dissimilar, is (Panum, Hering) the basis of visual 'relative depth-perception.' The compounding of visual images partly dissimilar—flickering with unflickering—seems a simpler case in the same category of synthetic actions. In the flicker experiments the visual components do not differ as to space-attributes and their combination has therefore no resultant differential space-attribute. But the synthesis gives in each case a compromise between the components in regard to the attribute wherein they do differ; in the flicker experiments, that is in regard to the sensual steadiness of the brightness. This amounts to the same as the rule formulated above for binocular combination of brightnesses of different intensities, but steady.

In these final considerations I have for the moment disregarded the evidence given in Section I. of minute, yet to most persons perceptible difference between the rates for flicker extinction under 'simultaneous' left-right and 'alternate' left-right stimulation described there. This difference may evidence a slight community

[1] *Zeits. f. Psychol. u. Physiologie d. Sinnesorgane*, XXXII. p. 161, July, 1903.

[2] Hermann's *Handbuch der Physiologie*, Bd. III. Tl. I. S. 596, 1879.

or interference between the apsychical processes or subperceptual sensations derived from twin corresponding points, and a very slight low level intercommunication between their two systems. The slightly more perceptible flicker some persons obtain when observing an intermitting physical image binocularly instead of uniocularly, may likewise indicate the same very slight degree of intercommunication. The often recorded slight excess of brightness of an image seen binocularly as compared with one seen uniocularly may also depend on the same cause. But these appearances are too slight to practically invalidate the broad conclusion drawn in the preceding paragraphs.

The above experiments on binocular flicker and brightness show that during binocular regard of an objective image each uniocular mechanism developes independently—at least as to steadiness of brightness and intensity of brightness—a sensual image of considerable completeness. The singleness of the binocular perception results from the combining of these elaborated uniocular sensations: it is the product therefore of a psychical synthesis that works with already elaborated sensations contemporaneously proceeding. Such synthesis lies obviously more within the province of study of the psychologist than of the physiologist.