COMMUNICATIONS

STEREOSCOPIC VISION*

I. EFFECT OF BINOCULAR TEMPORAL SUMMATION

BY

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UNTIL 1926 it was believed that stereoscopic vision required the simultaneous function of both eyes. Two simultaneous disparate retinal images were thought necessary to produce a synchronous discharge in the optic nerves before a sense of depth could be achieved. Langlands (1929), in his study of binocular depth acuity, showed that both eyes need not observe the scene simultaneously, provided that they viewed it alternately. With a sufficiently high rate of alternation of the "viewings" by the left and the right eyes a sense of depth could still be realized. Langlands did not study the time relationships between these alternate viewings in any detail as he was more interested in a quantitative analysis of the limits of stereoscopic visual acuity. The phenomenon of stereoscopy with alternate "viewings" has been studied by Pi Suñer (1947).

In the course of the present experiment, which was primarily designed to demonstrate a "scanning mechanism" within the occipital cortex, Langland's studies were repeated and greatly extended. The results of these experiments, though not confirming the existence of a scanning mechanism, did reveal a form of temporal summation within the visual system which had not been previously studied.

The present experiment was designed to study "stereoscopic vision" but not "visual depth perception". The difference between these two terms is profound. Visual perception of depth is determined by a large number of sensory and psychological factors. The least significant of these, from a practical point of view, is binocular stereoscopy.

The other factors which are chiefly responsible for the sense of depth have been studied in great detail by Riddoch (1917), Neff (1936), Pi Suñer (1947), and Vernon (1952), and do not concern us here, except in so far as they have been specifically eliminated from the experimental setting. They are based in large part on the psychological assumption that the object casting the largest retinal image will appear to be the closest to the subject. This instinctive assumption is rapidly and unconsciously modified if there is any previous information concerning the absolute size, shape, colour, or surface features of the object.

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All these psychosensory reservations which modify this basic assumption stem from sensory data which can be perceived by one eye alone. Hence they have been called "monocular clues to depth perception". These monocular clues account for most of the accuracy of depth discrimination at distances greater than 18 metres and explain very well why one-eyed people have so little difficulty in depth discrimination. They also explain why such people never complain that the world looks "flat". One subject (Riddoch, 1917) complained that his world was peopled with "pasteboard" models which did not appear to displace any volume. Such cases are due to cerebral lesions which have damaged those parts of the occipital lobes which, in normal people, apparently integrate all the monocular clues of perspective into a "sense of depth".

For distances under 18 metres, binocular factors begin to come into operation and are progressively more significant in producing a sense of depth as the distance from the object to the eyes becomes smaller. These binocular factors consist of convergence, accommodation, proprioceptive data from the extra-ocular muscles, and true disparity of retinal images. The first three factors play a small role and can be neglected in most experimental situations. Even when combined, they play such a small part in stereoscopy when compared with the effect of retinal disparities that for our purposes it is not important to consider them further.

In the present study, all the monocular clues have been assiduously eliminated, as have all binocular clues, except for the difference in parallax produced by looking at an object from two different positions. In other words, this experiment was designed to study that function of the brain which is concerned with recording and integrating a series of parallax differences (retinal disparities) to create an illusion of depth.

Apparatus

The basic form of this experiment is that of alternating exposures of each eye to a scene which, when viewed simultaneously by both eyes, would produce a marked sense of depth. The variables of this visual stimulation are:

- (1) The time between the end of the stimulus to the first eye and the start of the stimulus to the second eye (this will hereafter be known as the SHORT INTERVAL).
- (2) The time between the end of the stimulus in the second eye and the start of the stimulus to the first eye again (this will be known as the LONG INTERVAL).
- (3) The time allowed for each eye to view the scene (this will be called the FLASH DURATION).
- (4) The intensity of the flash exposure for each eye measured not in actual physical units but rather on an arbitrary scale.
- (5) The shape of the curve of each light impulse, the axes of this curve being light intensity *versus* time. It might have been, for example, a slowly rising intensity curve, a rapidly decaying curve, etc. An almost square wave impulse was used mainly for convenience in timing the onset and the termination of the pulse.

An all-electronic system would have ensured the absolute control of these independent variables. A simple mechanical system, however, was used in this pilot experiment. In it at least two variables were always linked together. But the final mathematical analysis of the independent effect of each variable was far simpler than anticipated. Some of the linked variables proved to have little effect on the outcome, and a complete analysis of the precise quantitative relationships between all the variables was thus not undertaken. The results printed here are specifically limited to the outstanding characteristics of the phenomenon studied.

(1) **Visual Scene.**—The subject was required to look into an ordinary “three-dimensional” viewer consisting of two independent optical channels. For each eye there was a simple convex lens which served as an eyepiece and produced a moderately magnified image. When the observer looked into the viewer with both eyes, he saw only a single square background of ground glass illuminated from behind. A photographic plate, consisting of two almost identical images on a black-and-white transparency, was placed between the eyepieces and the ground glass. One image was on the left side of the rectangular plate, and was photographed with the left half of a stereo camera. The right side of the plate was the same scene photographed by the right half of the same camera.

With each eye the subject saw three black letters of exactly the same size and density (totally opaque) against a featureless white background. If he looked with either eye *alone* the three letters appeared to be on one plane and all equidistant from the observer. There was no indication whatsoever that one of these letters was “closer” than another. On the other hand, when the subject looked with both eyes simultaneously and under continuous illumination, it became clear that each letter was at a different distance. A sense of depth was created in this fashion which was uncontaminated by monocular clues or by other psychological inferences.

By using the optical formula $\frac{\text{Object Size}}{\text{Image Size}} = \frac{\text{Object Distance}}{\text{Image Distance}}$, it was possible to construct letters of three different sizes, which, when suspended at appropriately calculated distances from the camera lenses, nevertheless cast the same-sized image on the plate (Fig. 1).

FIG. 1.—Method of photographing three objects (A1, A2, A3) so that images are of identical size on plate.

The three A's were photographed so that the first letter was 60 cm. from the camera lens, the second 65 cm., and the third 70 cm. By adjusting the size of the letters (without altering the case or the shape) all produced images identical in every respect on the photographic plate.

One hundred such slides were made with random combinations of three letters arranged to lie at the apices of an equilateral triangle. On one-third of the slides the letter at the left base was actually the nearest, on one-third the letter at the right base was the nearest, and on the last third the letter at the apex was the nearest. These slides were presented to the subject at random.

One such slide is reproduced in full size (Fig. 2). When it is viewed with the convex lenses, the letters appear much larger, occupying about 20° of the central visual field, and the whole field is filled by the slide.

FIG. 2.—Full-scale reproduction of stereoscopic transparency. Note absence of all monocular clues to three-dimensional arrangement.

The only information contained in this pair of images is:

- (a) The alphabetical identity of the letters themselves.
- (b) The triangular relationship of the three letters.
- (c) The parallax differences between the two sides of the slide.

It is with this last alone that we are concerned.

(2) Optical System.—The light source was a 6-volt, 36-watt automobile headlight bulb, with a linear, thick filament, supplied by a transformer operating on 220 volts and 50 cycles. The variations in light intensity produced by the cyclical alternations are insignificant in terms of this experiment, since such a thick filament does not cool sufficiently between cycles to alter appreciably the character of the light emitted. No flicker was observed.

The light was placed in a box with condensing lenses at opposite ends (Fig. 3, opposite).

The two parallel beams so produced were reflected by mirrors directly to two short-focus lenses. These formed an image one-fifth of the size of the filament which was cast upon the surface of a rotating sector disk.

On theoretical grounds, it is clear that any focal plane shutter operating at the focus of a point source of light will permit the full intensity to be transmitted instantaneously as it moves past the dimensionless point-focus, and will also cut it off instantaneously. This dimensionless point-focus cannot, of course, be produced with real lenses, and the actual thickness of the images in this case was 0.5 mm. The calculated time before full intensity was reached (the so-called

"rise time") was less than 0.2 msec., while the total duration of the flash could be varied from 3 to 80 msec.

FIG. 3.—Schematic view of equipment for producing light pulses and ensuring isolation of light pathways. Inset shows detail of one type of sectored disk.

After passing through the sectored disk, the beams were reflected to fall upon the right and left surfaces respectively of the ground glass of the three-dimensional viewer. These features of the optical system are illustrated in Fig. 3, which also

shows that the separate light pathways were of identical length, thus producing equally bright illumination for each eye. Inspection of the figure will also reveal that this complete separation of the light paths could permit one eye to be kept in total darkness while the other eye was illuminated.

When the subject looked through the viewer with suitable prisms for proper convergence, one large square was observed—the result of the fusion of the two monocular squares. The light was of such an intensity that the eyes were light adapted at all times. Artificial pupils were not considered necessary.

(3) Mechanical Timing System.—The disk through which the light passed was composed of a transparent plastic 14" in diameter and $\frac{1}{4}$ " thick. It was centrally mounted on a thyatron-controlled constant speed motor. The motor speeds were calibrated stroboscopically and were controlled by a Wheatstone bridge. The surface of the disk was coated with black enamel paint except for those areas used for light transmission.

In Fig. 4(a) two opaque disks spin at identical speeds in the same direction. A transparent sector is left in each disk. When the sectors of the two disks finally rotate to the position illustrated in Fig. 4(a), the light beams pass through both sectors simultaneously, producing a square light pulse once every revolution. The left disk permits light to pass only to the left eye and the right disk only to the right eye.

If the disks continue to spin as before, but the two beams of light are lowered so that they fall below the line joining the axes of the disks (Fig. 4(b)), the pulses are no longer synchronous. The transparent sector of the left disk reaches the focal point of its light beam sooner than the sector of the right disk reaches the focal point of its beam. With the light beam lowered the subject will receive:

- (a) a flash in the left eye;
- (b) a period of total darkness for both eyes (SHORT INTERVAL);
- (c) a flash in the right eye,
- (d) an even longer dark interval for both eyes (LONG INTERVAL) before the next couplet of flashes occurs on the subsequent revolution.

This is illustrated by the time scale at the base of Fig. 4(b).

The duration of either of the two dark intervals in milliseconds will depend on the speed of rotation of the disk and the distance by which the focal-points of the light beams have been lowered from the line joining the centres of both disks. If the speed is held constant, the interval between the flash in the left eye and the flash in the right eye (Short Interval or S.I.) will increase as the beams of light are lowered. This will continue to be the case until the light beams are no longer intersected by the disk.

Two disks have been illustrated in Fig. 4, but only one disk was actually used (Fig. 5), which had the same geometrical properties. The two beams of light were brought to a focus on the painted surface of the disk: one at 6 cm. from the centre of the disk and the other at 14 cm. on the other side of the centre. Two series of concentric sectors were cut, so that the left-hand light beam always passed through the outer ring of sectors, while the right-hand beam passed through the inner ring of sectors (see Figs 5(a) and 5(b), overleaf, and inset in Fig. 3).

It is obvious that it makes no difference whether the light beams are moved and the disks are held fixed, or *vice versa*. In the experiment, the light beams were

held fixed and the thyatron-controlled motor on which the disk was spinning was raised or lowered with the aid of a lathe component called a "vertical rise". Great accuracy could be achieved in the movements of the disk. Figs 4 and 5

FIG. 4(a).—Beam of light brought to focus on line joining centre of two disks. At the moment, a square pulse of light is just beginning. Note that pulses are synchronous. The disks spin at identical speeds and in a fixed phase.

FIG. 4(b).—Disks still spinning at identical speeds and phase relationships unchanged. Here the two beams of light strike the disk below the line joining the centres, and the light pulses are no longer synchronous.

FIG. 5(a and b).—The same principle is illustrated as in Fig. 4, but here only one disk is used. By utilizing two concentric rings of sectors the same control of light pulses is achieved. Note that the beam ultimately destined for the left eye always passes through the outer set of sectors, while the beam to the right eye always passes through the inner sectors.

When the two beams are on the same line as the disk centre, the light pulses are synchronous (Fig. 5(a)), but when the light beams are lowered asynchrony results.

Note: Pulse duration controlled by varying sector width (not shown in diagram).

show that any movement of the disk will alter the ratio between the Long Interval and the Short Interval. The absolute time interval of these two periods in milliseconds (for any given position of the disk relative to the beams) is determined by the speed of rotation of the disk.

The procedure actually used in this experiment was to pre-set the ratio of the Long Interval to the Short Interval (L.I./S.I.) by placing the disk in a definite position relative to the light beams. The subject was then permitted to look into the eyepieces. The motor was slowly accelerated until the end-point was reached. (The nature of the end-point will be discussed below.) The actual alteration in the nature of the stimulation, as the motor was accelerated, is illustrated in Fig. 6, which shows the pre-set ratio L.I./S.I. of 4.0. As the motor was slowly accelerated, the ratio determined by the position of the disk remained constant. What did change, however, were the short interval, long interval, and flash duration measured in milliseconds.

FIG. 6.—A pre-set ratio $\left(\frac{\text{long interval}}{\text{short interval}}\right)$ of 4.0 was selected. The disk is accelerated gradually from 370 to 555 r.p.m. Although the ratio is constant, the absolute duration of the intervals has shortened. The duration of the light pulse changed from 6 to 4 msec. The short interval has been reduced from 30 to 20 msec. at 555 r.p.m. The stereoscopic end-point was reached (see text).

Fig. 7 (overleaf) illustrates a number of pre-set ratios. A large number of such ratios were used, varying from 1 to 80.

Fig. 6 shows that the variable of flash duration was not under independent control. It was impossible to know *a priori* the significance of this variable in affecting the results. A new arrangement had to be devised to make the flash duration as independent a variable as possible. Two new disks were made and were superimposed. One disk carried only the sectors transmitting light to the left eye, the other only those transmitting light to the right eye. These superimposed disks are shown in Fig. 8 (overleaf).

In these conditions, it will be apparent that *rotation* of one disk relative to the other alters the ratio L.I./S.I. The ratio once set was held fixed by clamping the two

FIG. 7.—Effect of progressively lowering beams of light below axis of disk. The speed of rotation of the disk is held constant, but the ratio $\left(\frac{\text{long interval}}{\text{short interval}}\right)$ is gradually decreased. In this example the sum total of the various intervals is unchanged.

FIG. 8.—Two superimposed disks. On one four sectors are near the centre of the disk, and on the other the four sectors are nearer the periphery. The ratio L.I./S.I. was altered by turning one disk relative to the other. After a given ratio had been selected, the two disks were clamped together.

disks together. The sectors were so shaped that raising or lowering the disks on the vertical rise produced a variation, not in the timing of the two pulses, but rather in the duration of the pulse itself. When the disk was raised or lowered, the arc through which the point-focus of light passed was altered. In the neutral position (Fig. 9(a)), the beam of light passed through that part of the sector which was 45° in width. When the disk was raised 5 cm., the sector through which the light passed was only 3° of arc. Various flash durations could be used,

determined by sector widths from 3° to 45° of arc—an increase by a factor of 15. It was still true, however, that, for a given position of the disk relative to the light (i.e. for a given sector width), the faster the disk rotated the shorter was the flash

FIG. 9(a and b).—The same disk as in Fig. 8 (with only two sectors in each ring transmitting). In this geometrical arrangement of sectors, lowering the light beams reduced the duration of the pulse and the ratio L.I./S.I.

duration. The results will indicate that this small change in flash duration produced during the acceleration of the disk, even when under maximum control, did not alter to any significant extent the variations in the end-point, which were due far more to the ratio L.I./S.I.

Another consequence of this disk arrangement follows from the geometry of the sectors. If the disk were set, for example, for a ratio of L.I./S.I. of 3.96 for a 3° sector flash duration, and the disk were then lowered so that the flash duration was determined by a 45° sector, the ratio L.I./S.I. fell to 1.57. The sectors were so drawn that any increase in the flash duration was at the expense of the long interval rather than of the short interval. This is illustrated in Fig. 10, which shows the effect of a disk spinning at a constant speed with a starting ratio (for a 3° sector arc) of 10.4, and a gradual alteration of this ratio to 2.0 as the flash duration was increased. This occurred *despite* the fact that the disk was rotating at a constant speed.

FIG. 10.—Effects of changing pulse duration by using the disk shown in Figs 8 and 9. Not only was the pulse duration lengthened (from top to bottom) but the ratio L.I./S.I. was also changed.

Still another consequence of this change in flash duration by a factor of 15 was the effect on the subjective brightness of the field. At flicker fusion the brightness is determined by the Light-Dark ratio. Increasing the number of sectors or the width of any sector resulted in a brighter field at the flicker fusion frequency.

It can thus be seen that any change in the flash duration simultaneously altered the ratio L.I./S.I. as well as the brightness of the field. When the objective results are graphed, it will be possible to show the influence of each of these variations.

The Subjects

The subjects were instructed to look into the viewer; they were told that the three letters would appear to lie in the same plane, but that they would

eventually emerge from the featureless background, and would then appear to lie on three different planes. They were also instructed to pay no attention to flickering illumination or to any horizontal movement (*phi* phenomenon) of the letters. They were to report at once the moment that they could with *certainty* distinguish the sequence of the letters from the most distant to the closest. A good observer would learn this technique after a few trials and would thereafter report the end-point in a precise and reproducible fashion without ever making an error. The "scatter" from one test slide to another was very small with a "good" subject.

Unfortunately only 30 per cent. of the available subjects could be considered good ones for this experiment. A number of possible candidates had non-correctable visual defects in one or both eyes which precluded any stereoscopic vision. Other subjects had normal vision but were unable to see much depth using the stereoscope, even in the usual fashion with continuous illumination in both eyes. (This particular defect has been mentioned in previous studies on stereoscopic vision, but the reason for the failure remains obscure.) Still other subjects said that they saw depth clearly—in some cases providing "normal" quantitative data at appropriate disk speeds—but reported an incorrect sequence of the letters ("reversals"). It would appear that people with this type of response are not usually able to synthesize in their central nervous systems correct perceptions from purely stereoscopic (parallactic) data. Any subject who had this type of defect was not used in the main body of the experiment. One last group of subjects showed appreciable variations in threshold from one moment to another and made occasional errors. There was excessive scatter in their results and they fatigued easily, and for these reasons they were also eliminated. Too many physiological principles have been elucidated by studying the "good" subject alone for this systematic exclusion of the "bad" subject to be questioned.

The results of this experiment are thus restricted to those subjects who performed so reliably on numerous trials over a period of several weeks, that any change in their performance could be related to a change in the experimental conditions. Such subjects were studied under varying conditions of stimulation and showed characteristic results which will now be described.

Results

(A) **Subjective Results.**—When the subject looked into the viewer he observed two phenomena in addition to the one towards which his attention was formally directed. He was immediately aware of the flickering white background. As the speed of the disk increased, the flickering became faster and finer and finally disappeared.

The second phenomenon was considerably more important, on practical as well as on theoretical grounds. The subject was always startled, at the practice trials, when he observed horizontal movement of the letters. (This

type of movement, which has been known for many years to psychologists and is the very basis of the cinematographic effect, has been termed the "phi phenomenon".) The whole subject has been reviewed in exhaustive detail by Neff (1936) and Vernon (1952). The slower the rate of intermittence of the light, the coarser (larger) the apparent horizontal movement. As the disk accelerated this movement became a finer oscillation from side to side, and became smoother.

This apparent horizontal movement is related to the flickering background, as it is obviously of the same frequency as the flicker. When the threshold of stereoscopy was approached, the horizontal oscillatory movement was quite small, and did not prevent the subject from observing the end-point—a phenomenon quite distinct from the movement. For some subjects the apparent movement was still present to a moderate degree when they could see the scene in depth, but for others, including the author, the phi phenomenon had long since disappeared when the letters slowly began to place themselves at different depths. Similarly, the presence or absence of flicker was independent of the end-point.

The first phenomenon of stereoscopy took the following form:

The letters began to oscillate forward and backward in the plane perpendicular to the photographic slide. This movement was at right angles to the phi phenomenon and was qualitatively unlike it. For a second or two, one letter was closer to the subject than another, and just a moment later, it seemed to recede slowly into the background. It did not jerk back and forth with the frequency or the speed of the flicker, as did the phi phenomenon. This state of slow to-and-fro movements of the letters could be prolonged indefinitely by keeping the disk running at the same speed. The subjects began to sense a depth phenomenon, but could not yet, with certainty, list the sequence of the letters, which constantly changed in their relative positions. This state was probably the physiological end-point.

It was necessary, for a reliable determination, to run the disk just a bit faster. When this was done, the to-and-fro movements ceased and the letters slowly began to move towards the subject. The letter which was destined to be the closest moved out from the plane of the background earliest, and could be distinguished as the "closest". Almost every subject stated that he was sure which letter would turn out to be the nearest, because this was the first one that moved forward quite markedly at this stage. When this happened the proper position of the remaining two was still in doubt, the closest letter stimulating the retinal points which are more disparate than the retinal points stimulated by the "farthest" letter (when the visual axes are parallel).^{*} But as the disk was slowly accelerated, the second, or middle, letter emerged from the background upon which the third, or

^{*} An analogy can be drawn at this point to a "two-point discrimination test" used clinically in neurological practice. In this analogy, the two retinal points can be compared to the cutaneous points of the test. As in all tests for "cortical" sensory thresholds, fluctuations are found in the absolute threshold.

most distant, was still seen. *This* was the end-point used for all the results reported below.

At this stage the subject saw quite clearly that the three letters were all at different distances from him. He insisted that he was correct, and at this stage, could not be persuaded to change his mind. This emergence of the three-dimensional scene was chosen as an end-point because it developed suddenly, was easily recognized, and was psychologically impressive. All new subjects were told that this feeling of sudden, absolute certainty would constitute the end-point.

It is important to note that, when the disk ran still faster, the letters protruded even more markedly from the background, until finally they were as three-dimensional in appearance as they were when the slide was viewed under continuous illumination of both eyes. It was quite difficult to determine the exact point when maximum depth effect was achieved, and for this reason, the obvious stage of abrupt recognition was chosen for the end-point.

It is of considerable psychological interest to note that the subject who once sees a true stereoscopic scene at a given rate of rotation will persist for some time in seeing this scene in depth although the disk is markedly slowed. His threshold for this slide cannot be determined in the reverse direction—from the stage of stereoscopy to its dissolution at slower speeds—since he already “knows the answer”. A new slide will give the absolute threshold again. The first slide may be re-used when the subject has forgotten the sequence of letters on it. Thus, with one hundred slides the combinations of letters are so numerous that the subject cannot remember a particular slide for more than a few minutes.

One further psychological effect was noted. When the letters were arranged so that the sequence, as described by the subject, spelled out a word such as D-O-G or M-A-D, the subject tended to see the scene in depth at a significantly lower threshold than if the combination of letters was meaningless. This was a minor factor which was easily corrected. In no case did it ever alter the threshold value by more than 10 per cent. The phenomenon was not studied further.

(B) Objective Results.—Up to this point all the subjective phenomena have been related to the speed of rotation of the sectorized disk. We must now translate the r.p.m. of the disk into more meaningful physiological terms.

(1) *Effect of Change of Ratio of L.I./S.I.*—The change in the ratio of L.I./S.I. was the most important variable in determining the maximum permissible time between the flash in the first eye and the flash in the second eye.

Example.—The ratio of L.I./S.I. was set at 2.86, the disk was slowly accelerated until the end-point was reached. At this point the disk was spinning at 163 r.p.m. The calculated S.I. was 46.1 msec., the L.I. was 132 msec., and the calculated flash duration for each eye was 3.07 msec. These values indicate that the S.I.

would be as long as 46.1 msec. with stereoscopic fusion still possible. When a new ratio was chosen (such as 33.9) the S.I. changed; *i.e.* the disk was required to spin at a different speed.

It is clear, therefore, that the S.I. was not a physiological constant but a dependent variable in this experimental situation. The major factor which was varied is the ratio L.I./S.I., and it is this change which produced the alteration in the S.I.

When the S.I. was plotted against the variable ratio L.I./S.I. (Fig. 11), an interesting relationship between these two variables developed, in which they were not only related inversely, but followed, with surprising accuracy, a hyperbolic curve. This was true for *every* subject. Fig. 11 shows this curve for one subject (J. C.) and also the mean value for eleven subjects under identical conditions. This graph indicates that the mean values for all subjects follows the same shaped curve as the curve for an individual subject. With only eleven subjects one cannot, of course, speculate on the normal spread. Nine of the eleven subjects gave results that were within 10 per cent. of each other. Two subjects provided identically-shaped curves, but gave values which were 75 to 100 per cent. higher than the mean of the other nine subjects. The mean values in Fig. 11 include these two subjects and this explains why the curve for the combined values is so far "above" that for the single subject J. C., who was one of the nine "more normal" people.

FIG. 11.—Curve A: Mean values for eleven subjects constructed from 820 determinations. Curve B: One subject, number of determinations for each point shown in box.

At this point it can quite definitely be stated that, the longer the interval before the second couplet of flashes, the shorter must be the interval between each of the two flashes of the couplet for stereoscopic vision to result. The curve tapers asymptotically as the ratio L.I./S.I. approaches infinity, sug-

gesting that a minimum value for the S.I. can be obtained. This minimum value for subject J. C.—with the given illumination conditions—would be about 13 msec. By mathematical extension, if the couplets are separated by an infinite period of time, the component flashes of a given couplet may not be separated by more than 13 msec. for stereoscopic vision to result in this subject.

It must be stated quite explicitly that the use of the revolving disk precluded the production of an isolated couplet. The inference that an absolute minimum value for the S.I. exists for every subject is derived from the shape of this curve. Indeed, this inference is substantiated by Langlands (1929), in whose study just one couplet of flashes in a non-repetitive system was used. He found, in two subjects, that intervals of 25 and 18 msec. between the flashes could still result in stereoscopic vision. If the interval were greater than this, stereoscopy did not result. Langlands used very faint flashes from Leyden jars for his illumination and also used a slightly different type of visual test object in which not every monocular clue was eliminated. While we cannot compare his recorded minimum values with ours, his data confirms our inference concerning the asymptotic nature of the curve and allows us to determine precisely the rate of decay of this temporal summation.

The other end of the curve represents the lowest possible ratio of 1.0. In this case there are no longer any "couplets", but, rather, equal intervals between the flashes (Fig. 7, bottom line). The interval between two flashes may be much longer (up to 182 msec. for one subject) and still permit stereoscopic fusion. This effect of repetition of the stimulus clearly reflects a process of temporal summation within the visual pathways.

The important variable which determined the maximum possible interval between component flashes of a "couplet", and yet allowed stereoscopy to result, was the ratio of L.I./S.I. This ratio is, indeed, nothing more than a reflection of the frequency of couplet repetition. When this ratio is high, we are dealing essentially with a single couplet. There should thus be a definite relationship between the S.I. in milliseconds and the L.I., just as there was a relationship between the S.I. and the ratio L.I./S.I. This was indeed the case, and the shape of this curve, too, was hyperbolic.

It is of some importance to try to locate the region in which this temporal summation is accomplished. Is it a function of retinal "persistence" or does it result from a more central process, perhaps in the visual cortex itself? To answer these questions, at least in part, two other variables must be considered.

(2) *Effect of Brightness.*—The results plotted in Fig. 11 were recorded when all the four possible sectors for each eye were uncovered. The field, as viewed by the subject *after flicker disappeared*, was twice as bright as it would have been if two sectors were open, and four times as bright as it

would have been if only one sector were open. The quantitative results of these various changes in illumination differed, although the same hyperbolic curves were obtained for each level of brightness. This feature is demonstrated in Fig. 12, which shows the differences in the absolute values obtained with three different brightness levels for one subject (E. M.). Inspection of these curves shows that, the brighter the light at any given ratio, the shorter the S.I. *had to be* for stereoscopic fusion (although the difference became progressively less significant as the ratios increase).

FIG. 12.—Effect on one representative subject of altering the number of transparent sectors. For any given ratio, the fewer the open sectors, the shorter the interval between flashes had to be for stereoscopic fusion.

In both monocular and binocular flicker fusion experiments, it has been similarly established that, the brighter the light, the faster the disk must spin (the shorter the interval between flashes) for flicker fusion to result. But the similarity of this response to changing brightness is superficial. Measurements of comparative brightnesses are only valid at or above the flicker fusion point. It is impossible to compare the brightness of one field at flicker fusion point (one open sector) with the brightness of another field which is still flickering violently (four open sectors)—when stereoscopy can result in either set of conditions.

The temporal summation of stereoscopic fusion might still seem, however, to be merely a function of the persistence of the retinal image—as is said to be the case in flicker fusion. But two findings refute this possibility. The well-marked dissociation between the critical flicker fusion threshold and the stereoscopic threshold indicates not only that the latter function is independent of the former, but that it stems from an entirely different physiological process.

Secondly, the letters emerged from the plane background sequentially:

the first letter to come forward as the end-point approached was the one destined to be the closest. If this were a purely retinal summation of subliminal stimuli, we would expect all the letters to emerge simultaneously, since the retinal sensitivity is not greater for one pair of letters than for another. That the pairs of letters did emerge in sequence indicates a "lag" in integration. Such a "lag" clearly implies a far more complex process than can be explained on the basis of known retinal physiology.

(3) *Effect of Flash Duration.*—Reference to the legend in Fig. 11 indicates that, for the subject J. C., the flash duration was 8.25 msec. when the ratio was 1, and was 15.1 msec. when the ratio was 21. Although the major variable was the change in the ratio L.I./S.I., it was nevertheless observed that at each point in the curve the flash duration had a slightly different value. To be certain of the meaning of the curve the effect of this slight variation in flash duration must first be determined.

Figs 8 and 9 show the mechanism by which flash duration was altered. The alteration of the position of the light beam relative to the disk produced three different changes in the stimulus pattern:

- (i) It changed the flash duration itself—the primary objective.
- (ii) It unavoidably altered the ratio of L.I./S.I.
- (iii) It necessarily changed the brightness of the scene at the stage of flicker fusion.

The importance of the ratio L.I./S.I. has been discussed. It is now useful to separate out the effects of flash duration and brightness, which, in the equipment used, were linked variables.

The brightness of a light the beam of which is interrupted by a sectored disk will depend on the ratio of total transmission time to total non-transmission time. In a disk which has one transparent sector of 360° in width, the brightness will be that of the 36-watt lamp and we can arbitrarily call this one unit of light flux. In another disk with one sector of 3° width, the total light reaching the eye will be $3/360$ th (or $1/120$ th) of the full illumination (Fig. 13, Curve A, overleaf).

A disk with one sector of 45° width produced Curve B (Fig. 13) with $45/360$ th (or $1/8$ th) of the full illumination. Using a disk with four open sectors of 3° each (Curve C), the total light was $12/360$ th (or $1/30$ th) of the total light flux. The increase in brightness produced by a prolonged flash duration could not possibly be the sole explanation for the position of Curve B relative to Curve C. If brightness were the only significant result of increasing flash duration, Curve B should have fallen in the region of the hypothetical Curve D. From the actual position of Curve B, it must be assumed that increasing flash duration had an influence on the duration of the S.I. opposite to that exerted on the S.I. by the factor of brightness *per se*. In Curve A the average flash duration was 3.5 msec., in Curve B it was 7 msec., and in Curve C it was 42 msec. These two factors, brightness

FIG. 13.—Effect of changing flash duration contrasted with effect of changing total brightness. The effect of increasing brightness is distinct from the effect of increasing pulse duration.

of scene and duration of flash, are variables which will cause the basic curve (Fig. 11) to deviate in opposite directions.

The variation in flash duration from one end of the curve (Fig. 11) to the other was from 8.25 to 15.1 msec. (less than 100 per cent. increase). This variation could hardly have affected the position of the curve, since an increase in flash duration of 1200 per cent. (from 3.5 to 42 msec. in Fig. 13) had so small an effect on the S.I. when compared with the large effect due to the change in the ratio S.I./L.I.

Summary

(1) A scene flashed in *one* eye sets up a percept somewhere within the visual system which persists for a measurable period of time (maximum S.I.) and can later be utilized by the brain for a more complex integrative process—stereoscopic fusion. This is memory—specifically memory of the positions of three letters in relation to each other and to the fovea centralis. This is a memory of the *positions* of various objects in the coordinate system of *each* retina. Even a brief recall of the coordinate values of such a monocular stimulation cannot properly be called “parallactic memory”, since parallactic information cannot be obtained by one eye. Parallax is determined from the perceptual data of both eyes and these raw data must be “recorded” according to some inherent coordinate system.

(2) If a slightly different coordinate stimulus is presented to the second eye within the necessary time interval (maximum S.I.), the brain will still be able to fuse it with the retinal coordinates of the letters flashed to the first eye, and this will result in a sense of depth.

(3) The period of time after which the first percept has decayed to such an extent that it can no longer be used for fusion was found to range from 6 to 13 msec.—if the visual stimulus were limited to a *single* “couplet” of flashes.

(4) If a *series* of subliminal stimuli are used, this interval is dependent on the time before the next cycle of “couplets” begins. The decay period is related to the interval between the “refresher” stimuli. If the refresher stimulus arrives after a short period and is frequently repeated, the brain can use the first percept for a longer period of time than would otherwise be possible. In physiological terms, the duration of the useful memory of the first percept depends on the temporal summation of stimuli within the system.

(5) This temporal summation is not a retinal function, but is probably an aspect of the central mechanism of binocular stereoscopic fusion. This is in contrast to the phenomenon of flicker fusion, in which the major locus of the summation process resides in the retinal neurones rather than in the brain. Although the phenomenon of retinal persistence must influence all visual perception, there is here a further physiological process, with characteristics of its own which cannot be explained on the basis of known retinal physiology.

(6) The amount of light reaching the eyes and the duration of the exposure are also variables, but of less importance. They have been shown to act in opposite directions.

(7) The shape of the curve of temporal summation is hyperbolic in form and resembles the “learning” curves produced in psychological experiments.

(8) The original purpose of this experiment was to show that stereoscopic vision or binocular fusion results from alternating “attention” by the brain to the retinal images from the two eyes. It was expected by this technique to show that the “Short Interval” would have a fixed value which might represent the time interval (multiple or submultiple) between the recurrent sweeps of a scanning mechanism. It was hypothesised that, if the short interval were made either slightly shorter or slightly longer, it would destroy stereoscopy by an interference phenomenon. This, however, is obviously not the case. Extending the short interval does indeed abolish stereoscopy but shortening it does not alter stereoscopy. In addition, the short interval was found to be a variable factor and not a fixed value in the conditions of repetitive stimulation. It was not possible either to affirm or to deny the existence of a scanning mechanism by this technique.

(9) The experiment has shown that the temporal summation, previously described in “simple” internuncial pools, exists in a similar form for such “higher” or more complex integrative actions of the nervous system as stereoscopic fusion.

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size, brightness, and colour of the stimulus can be accurately controlled. If the patient is accustomed to wearing a distance correction, this can be worn during the test without interfering with the field of view, since the excursion of the eye needed for the test is well within the boundary of the spectacle frame; the image of the stimulus does not suffer from the distortion which arises in the conventional method because of its oblique position when situated away from the centre of the screen. Such distortions are quite marked when a strong correction is worn. The patient's attention is kept more alert since he has to fix a spot which the examiner is constantly moving about. In the conventional method, with a screen 2 metres square, the stimulus, when placed at the edge of the screen, is further from the eye by a distance of nearly 30 centimetres, so that the visual angle subtended by it is smaller. This effect is further increased by the relatively slit-shaped aperture offered by the pupil at that angle. In this new method the distance between the stimulus and the eye is constant. Lastly, it is of great importance that any method of campimetry should provide some means of concealing the stimulus from the patient's view to check his responses. In the present method this is done by means of a push-button switch which extinguishes the light only and which the examiner can hold in his free hand.

CORRIGENDA

In the article entitled "Stereoscopic Vision" by Robert Efron in the December issue (*Brit. J. Ophthalm.*, 1957, 41, 709), on p. 727 in the last sentence, please read:

In Curve A the average flash duration was 3.5 msec., in Curve B it was 42 msec., and in Curve C it was 7 msec.

On p. 728, fig. 13, key, please read:

Curve B 45° flash of 42 msec.
Curve C 3° flash of 7 msec.

It is regretted that it was stated in the review of "The Effect on Binocular Vision of Variations in the Relative Sizes and Levels of Illumination of the Ocular Images", by H. F. Gillott (*Brit. J. Ophthalm.*, 1958, 42, 126), that the price was 50s. This should read 15s., plus 1s. 6d. postage.