SOME FACTS OF BINOCULAR VISION.

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Some interesting experiments in binocular vision were reported a few years ago by Professor Hyslop and Professor Venn in *Mind*[1] and in THE PSYCHOLOGICAL REVIEW.[2] The unusual conditions of vision under which these experiments were performed—both observers are able to carry out the adjustments of ocular accommodation and those of ocular convergence independently—seem to have prevented their conclusions from receiving the usual critical treatment which comes from general and extended experimental observation. A little practice has enabled me to follow the experiments of both, and while I am able to corroborate the results in general, important considerations prevent me from adopting the conclusions which Professor Hyslop reaches in his last paper. These conclusions may be summarized in Professor Hyslop's own words as 'looking to a central explanation of both distance and magnitude, independent both of peripheral conditions and motor impulses.' It is the aim of this paper to report certain experiments which seem to point in a different direction, and it will be possible, I think, to show where the error has crept in.

The apparatus for the experiments consists of two plane mirrors mounted in two frames which are hinged together in such a way that the mirrors may be inclined at various angles. Let *ad* and *bc* be the mirrors. (Fig. 1.) They may be folded so as to come into the positions $a'd'$, $b'c'$, or so that their positions are $a''d''$, $b''c''$. The whole may be held in the hand at a convenient distance from the observer's eyes. At the beginning of the experiment the mirrors are held in the same plane *adbc*, The eyes are converged in the directions *me* and *nf*, so as to

[1] *Mind*, Vol. XIII., p. 499; Vol. XIV., p. 251 and p. 393.

[2] PSYCHOLOGICAL REVIEW, Vol. I., p. 247 and p. 281.

receive the reflected rays from a luminous point *o*, the relative positions being so chosen that the pencil of light entering the right eye comes from the right mirror, and that entering the left eye from the left mirror. The points seen will be referred to a distance behind the mirror as great as that of the real point in front of the mirrors. If now the frame be slightly folded so as to bring the mirrors into an inclined position, with the angle of

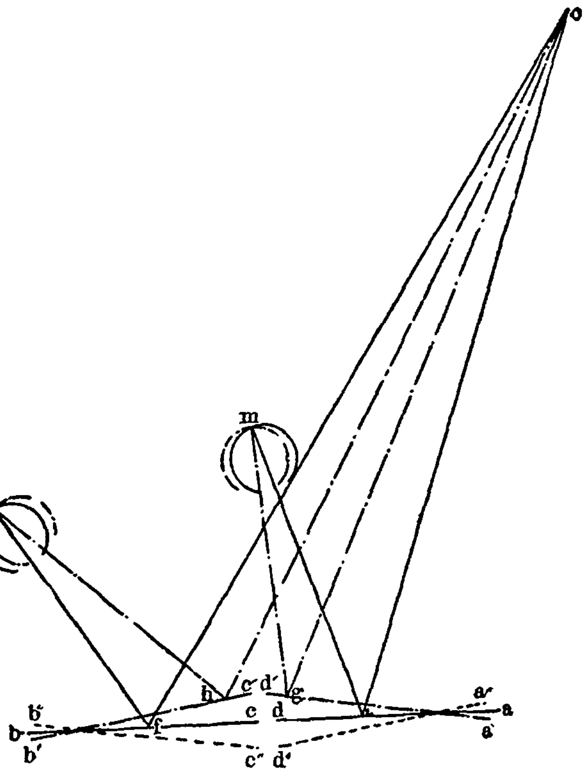


FIG. 1.

inclination turned toward the observer, as *a′d′* and *b′c′*[1], the points of incidence of the rays entering the eyes will travel from *e* to *g* and from *f* to *h*. The effect of this movement on the apparent distance of the point in depth will be imperceptible, as can be shown by closing one eye while the mirrors are being inclined. When, on the other hand, both eyes are fixed on the point, as the mir-

[1] The angle is exaggerated in the figure.

rors are slightly inclined, the point behind the mirrors is distinctly seen to approach the observer. The eyes must be converged in the directions *mg* and *nh*, and the fixation point evidently lies very much nearer the mirrors than when the optical axes were in the positions *me* and *nf*. A very slight inclination of the mirror produces a marked effect. Just the opposite phenomena follow an inclination of the mirrors when the angle of inclination is turned away from the observer. Here the point is seen to recede during the movement of the mirrors. The point of intersection of the optical axes also recedes. The whole series of phenomena is evidently explained by the fact that objects requiring a greater degree of convergence are judged to be nearer, and those requiring a smaller degree of convergence are judged to be more distant. It is to be noted that the judgments of position are certain only during the actual movements of the mirrors. As soon as the movement ceases the point seems to have that same sort of indefinite location in depth which is so characteristic of our judgment of the distance of the stars.

New and important experiences appear if an object is used instead of a luminous point. When the mirrors are now inclined into the positions $a'd'$, $b'c'$, the object, as the point before, seems to approach the observer, but it also grows very distinctly smaller. This diminution in the size of the image can evidently not be due to the fact that the points of incidence travel from *e* to *g* or from *f* to *h*, for if this slight change has any effect at all, and it is so slight that it doubtless has no such effect, it would be in the opposite direction, for since the object is virtually brought nearer by the inclination of the mirrors, its retinal image is thereby increased in size. The decrease in apparent size is connected with the apparent approach. The whole matter will be clear if we recall the ordinary facts of perspective. If two objects unequally distant give the same sized retinal image, the more distant object will be the larger and a long series of experiences has taught us to judge in accordance with this fact. In ordinary experience, then, when an object approaches an observer the convergence will increase and, at the same time, the image on the retina will grow larger. But, under the conditions of the experiment, the retinal image remains constant (or, if anything, grows only slightly larger), while at the same time the convergence is increased. The lens does not change its degree of accommodation, so that the case is not complicated by any factor besides those of retinal image and convergence. There is evidently only one objective phenomenon which could give this unusual combination of retinal image and convergence, and that would be the approach of an object which was rapidly becoming smaller in size. The result is that we actually perceive an object in the mirrors which approaches and at the same time grows smaller. The converse may be seen by folding the mirrors slightly away from the observer; the object now seems to recede and to grow larger. The explanation is of course similar.

While the convergence is actually changing the appearances of movement in the object are very apparent; as soon as the movement of the eyes ceases the absolute distance of the object in space becomes more indefinite, just as in the case of the point in the first part of the experiment. The diminished size of the object, on the other hand, remains unmodified. This justifies us in concluding that the apparent magnitude of objects is due to the combination of retinal images and sensations of convergence under the general law that *of two objects requiring different degrees of convergence and yielding the same sized retinal images, the one requiring the greater convergence will seem smaller.* It will also appear nearer unless associated factors from past experience come in to disturb the localization. These associated factors are not strong enough to affect the judgment while sensations of movement are actually coming into consciousness, but may have some influence when the only sensations from convergence are the somewhat weaker sensations of position. In any case the effect of the two peripheral conditions, namely, retinal images and motor sensations (including sensations of mere position) are the determining factors. These factors, being combined in unusual relations, give rise to unusual perceptions. But the perceptions are in accordance with the ordinary rules of perspective as shown above.

All the above described facts may be easily observed by any one. The following experiments require in their second modification some ability to dissociate the closely related processes of convergence and accommodation, but an observer with strong eyes and a little practice can soon acquire the ability to perform them. The same pair of mirrors is employed, but they are so inclined that the angle towards the observer is considerably less than two right angles, as *ad*, *cb* (Fig. 2), and the eyes are so located that the only ray from the luminous point *o* which is visible in the left eye is incident on the right mirror, and

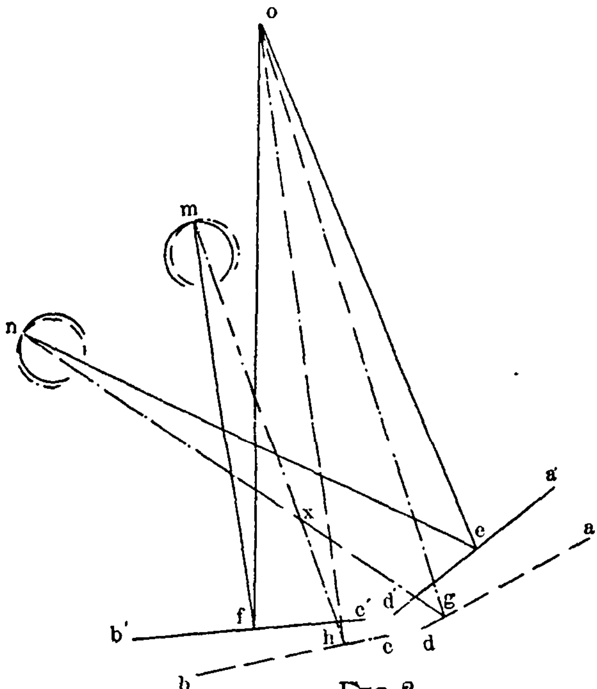


FIG. 2.

the pencil entering the right eye is incident on the left mirror. The only way in which the two images can be made to appear single is by converging the two eyes so that their optical axes shall intersect at the point where the two pencils of light intersect, that is, at *x*. The two eyes must be converged in the directions *mh* and *ng*. If this is done the point will be seen as single, but its location in space will not be at all definite. It seems to be behind a third mirror situated between the two original mirrors which are visible in indirect vision. If the angle towards the observer be made smaller, as $a'd'$, $b'c'$, the point will be distinctly seen to approach the observer. The points of incidence will travel along the mirrors from g to e and from h to f, but this change can be entirely neglected as in the earlier experiment. The opposite effect will be observed if the angle toward the observer is gradually increased; the point will then recede in a very noticeable degree. A reference to the figure will show how the change in angle of the mirrors is accompanied by a change in the degree of convergence. In all the cases described active movement of convergence is always accompanied by a decided appearance of change in the distance of the object in the third dimension, and this change in apparent distance always follows the rule that the greater the convergence the nearer the object. The rule holds without exception for relative degrees of convergence; when, however, the absolute distance is to be judged, other factors enter in and the object seems further away than the real point of fixation. This false reference of the point of fixation is doubtless due to the conditions which arise from the imperfect reflection of the mirror which gives added sense data, and to the conflicting sensations of accommodation to be discussed more fully in the next modification of the experiment.

As in the first series of experiments, important factors are introduced when we make use of an object rather than of the luminous point. A new complication arises in the fact that when the eyes are converged to the point x they will, under the ordinary circumstances of vision, also be accommodated so as to focus rays of light diverging from x. If an object whose rays of light are less divergent, as in the case of the real reflected object, is to be seen in clear outline the accommodation must be changed so as to adapt it for a point whose distance is greater than the point of fixation. That is, the accommodation must be for distant objects while the convergence is for a near object. This is difficult for the unpracticed observer and may be impossible for some. When the ability to accommodate and converge independently is once acquired, however, the object can be seen very clearly and sharply defined, even while the eyes are converged to the nearer point. If now we start with the mirrors in the position *ad*, *bc*, (Fig. 2) the object will be seen as very much smaller than the image in the plain mirror when observed with the single eye. Its relation to the position before convergence took place will be rather indefinite, but seems at first somewhat greater than before. If the angle is made smaller, as *a′d′*, *b′c′*, the image seems to grow very much smaller and approaches decidedly. As soon as the movement stops the location of the object again becomes indefinite, and it may appear at the same or even at a greater distance than before. The conditions are very much involved and yet the results all obey the principles that during active movement of convergence the greater the degree of convergence the shorter the apparent distance of the object, and, the retinal image remaining the same in size, the smaller the apparent size of the object. Here again, when the movement ceases the diminished size remains constant while the localization becomes less definite. The fact that the distance seems to be about the same when the mirrors are at rest, whatever the size of the object, speaks for the influence of the sensations of accommodations which are of no very great importance in the estimation of depth, but probably play some part. We shall find evidence later for assuming that accommodation has some influence in perception. The more important fact that while the relative position corresponds to the convergence, the absolute localization is not at the point of fixation, furnishes a greater difficulty, but here again it is to be noticed that the mirrors seen in indirect vision are smaller and the illusion of greater distance could easily arise, as it often does, when a concave lens is held before an object; the object is seen smaller and further away until the attention is called to the true relation of the image to the object.

There is only one point in which this series of experiments differs from the first, and that is in the dissociation of convergence and accommodation. The size of the retinal image here remains constant just as in the former series. This follows from the fact that the image is sharply focused on the retina, and since the rays from the object are equally divergent whatever the position of the mirrors, the lens must remain constant if the rays are always to be brought to a focus. That the size of the aperture in the pupil can have no influence on the size of the image followed from the general law of refraction that a part or the whole of a lens casts exactly the same sized images.

We turn now to the discussion of Professor Hyslop's experiments and conclusions. The earlier series differs from those which have been reported in this paper, in the fact that the figures were there drawn on paper or glass and the possibility of comparing a large number of successive experiences was thus lost. The experiments here described furnish important additions to the general body of fact which may be used in explanation, but even the less elaborate experiments with fixed figures seem to lead to conclusions which are favorable rather than adverse to the motor-sensation theory. In fact similar results have been used by Aubert,[1] Professor Le Conte,[2] Professor Martius,[3] and Dr. Rivers,[4] to establish the same conclusions that I have drawn from my experiments. Professor Hyslop's experiments are in brief as follows: Two circles are drawn at a distance of a few inches apart, and the eyes are converged so as to fuse the images, either by crossing the eyes or at a point nearer than the plane of the paper, or by distant convergence at a point beyond the plane of the paper, as represented in figures 3 and 4. A and B, A' and B' are the circles in profile. In order to get clear images at C and C', of course the accommodation must be unnatural. The result of crossing the eyes is that C is seen in direct vision considerably smaller than the original circle, and nearer to the observer's eyes. A and B are seen in indirect vision somewhat larger than C, but smaller than the original circle, not so near the observer's eyes. All of these results I am able to corroborate fully. I find also the converse of these facts when the eyes are converged at a point beyond the plane of the paper, as does Professor Hyslop. There is another important observation which has evidently not escaped Professor Hyslop, since it appears in his figures, but which he seems to have made

[1] *Physiol. des Netzhaut*, p. 330.

[2] *Sight*, p. 158 seq.

[3] *Philosophische Studien*, Bd. V., p. 601 seq.

[4] *Mind*, N. S., vol. V., p. 79.

no use of in his explanations. This is the observation that the distance between A and B, as seen in indirect vision, is very greatly increased; in fact, just about doubled, so that if we

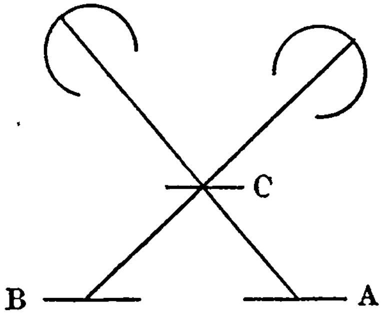


FIG. 3.

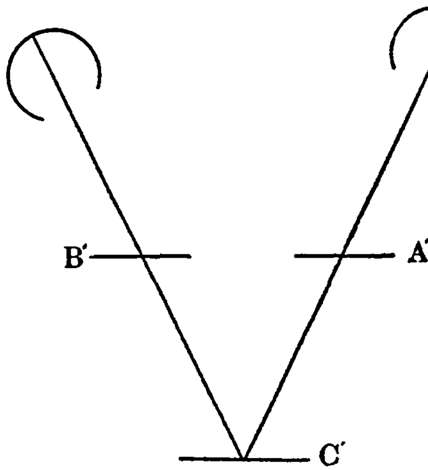
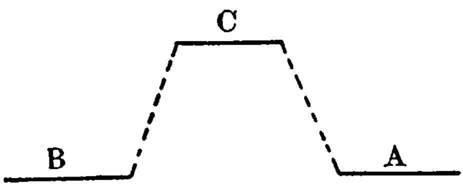


FIG. 4.



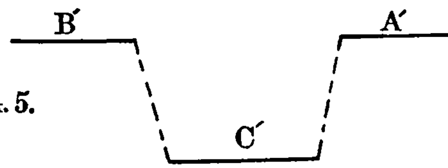


FIG. 5.

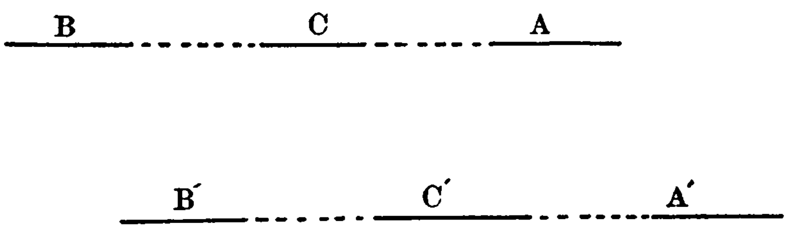


FIG. 6.

think of C as lying between A and B, the distance AC and the distance BC are about equal to the original distance AB. Furthermore, Professor Hyslop, while he has been at great pains to discuss all of the possibilities of some change occurring in the size of the retinal image, seems to have overlooked the possibility of an explanation without the assumption of any change in the size of the image. But, since the image is sharply defined on the retina, the lens must be accommodated as it would be in monocular vision. There is therefore no ground for the long discussion as to the possible changes in the image due to accommodation. Still less is there reason for refuting the supposition that difference in aperture would affect the size of the image. The oblique distances from the eyes to the circles in both cases (Figs. 3 and 4), are slightly different from the perpendicular distances, but the differences are not appreciable and have no perceptible influence. The smallness of C in the first case and the increased magnitude of C' in the second case offer no difficulties in the light of the explanation given of the results with the mirrors. The retinal image is constant in size, the convergence is different, and the object which is, on account of the convergence, perceived as nearer in the first case is interpreted as smaller, while in the second case it is more distant and interpreted as larger. The estimation of absolute depth is very indefinite, but may be made clearer by bringing up some small object, such as a pencil, in the plane of the paper. The difference in the size of the circles in indirect vision and the central images furnishes a more complex phenomenon. It is necessary to bear in mind that we are dealing here with a case, which is essentially a case of monocular vision. Yet the binocular influences are present and must play some part in determining even this monocular perception. That the binocular and monocular tendencies are in conflict, appears from the fact that the circles are pushed farther away from each other, that is, the distance AB in indirect vision is very much increased. This increased distance will seem to grow shorter if the attention is turned toward one of the circles visible in the indirect field. Professor Hyslop has pointed out that the distance in depth of the central circle and of those in indirect vision is apparently different; the indirectly seen circles appeared to be nearer the plane of the paper. The apparent increase in the distance apart is due to an illusion, as the result of which the perspective distance is mistaken for the horizontal distance. What is really seen is represented in Fig. 5, what is thought to be seen is represented by Fig. 6. This illusion is due to the indistinctness of indirect vision and tends to disappear when attention brings out the perspective. The differences in size of the indirectly seen circles when compared with the original circles may be explained largely, if not completely, as the influence of the accompanying binocular sensations on the monocular perception. The circles are seen as somewhat nearer and consequently smaller in the first case, as more distant and larger in the second. Apart from the special complication here pointed out, these phenomena are perfectly analogous to those which appeared in the experiments with the mirrors. The explanation may be extended so as to include certain other cases which Professor Hyslop uses in his criticism of the association and motor-sensation theory.

The case of after-images remarked by Professor Hyslop and independently reported by W. Scharwin and A. Novizri in the *Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, Bd. XI, Hf. 5, furnishes a striking parallel. An after-image appears larger the more distant the plane on which it is projected.[1] The retinal image is in such a case exactly the same size whatever the distance of the plane may be. The change in apparent size is to be explained in the same way as in the cases described.

Other facts, derived from the fusion of stereoscopic figures under various conditions, furnish, in Professor Hyslop's view, insurmountable difficulties for the motor-sensation theory. If two stereoscopic figures made with circles in such a way as to give the frustum of a cone when fused by crossing the eyes, be drawn on separate pieces of paper so that the distance between the figures can be changed by moving the papers further away from each other, or nearer to each other in the same plane, the results will be the following. "Thus we move the circles farther apart while increasing the convergence to retain fusion, the frustum shortens while its magnitude diminishes. On the other hand, as they approach each other and the fusion is sustained,

[1] I find the fact mentioned by Aubert as a discovery of Lehot (Fechner Repertorium, 1832).

the frustum lengthens and the magnitude increases, and all this while the figures occupy the same plane." The increase in

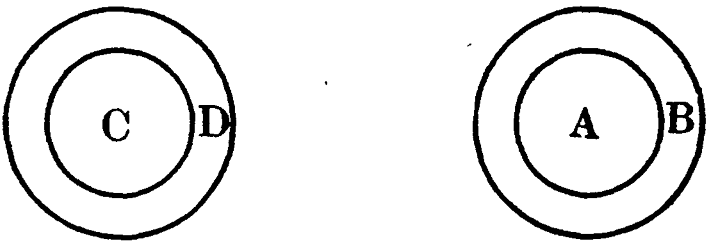


FIG. 7.

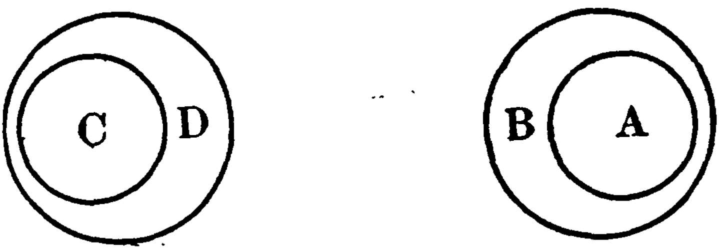


FIG. 8.

FIG. 9.

magnitude of the circles offers no difficulty in this case. The actual change in the distance of the figures from the eye as they are moved in a given plane may be of some slight influence but this factor is not appreciable; the retinal images are practically constant in size. The variation of the fixation point, which recedes when the figures approach each other and advances towards the observer when the figures are drawn apart, sufficiently explains the change in the apparent size of the circles. The length of the frustum is another matter. Under ordinary circumstances this decreases as the object recedes, so that when an object recedes to an infinite, or even to a very great distance, all appearance of solidity is lost. In the case in hand, the object in question does really recede when the figures approach each other. The spaces between the circles will share in the enlarging effects of this receding movement, but when the frustum is spoken of as lengthening reference is not made to this increase in length taking place concomitantly with the other dimensional changes. The length of the frustum increases relatively more rapidly than it should to preserve the original proportions. This increase is still more important when we think that under normal conditions the frustum would naturally become proportionally even smaller. The explanation of this change in the length of the frustum is to be sought in the binocular parallax. This can be shown by the familiar fact that four circles drawn as in Fig. 7, where *A* and *B*, and *C* and *D* are concentric, when united by crossing the eyes give no stereoscopic effect whatever; the binocular parallax is practically zero. When the binocular parallax is positive, as in Fig. 8, the result is a frustum of a cone with the small circle towards the observer; when the parallax is negative as in Fig. 9, the result is a frustum of a cone with a large circle nearer the observer. As the positive or negative parallax is increased the frustum grows longer as may be shown by separating the centers of the circles *AB* and *CD* more and more.

The binocular parallax under the conditions of the experiment with which we started, increases when the figures approach the median plane as will be seen by referring to Fig. 10, where the angles *anb*, *bnc* and *cnd*, are larger than the corresponding angles *a′nb′*, *b′nc′* and *c′nd′*; *abcd* represents here the profile of two such circles as are represented in Fig. 8. The first position *abcd* lies nearer to the median plane than the second position *a′b′c′d′*. The point *n* represents the nodal point in the eye. The size of the retinal image will undergo some changes also when the circles are moved away from the median plane, but these changes are not of importance when the distance through which they are moved is small. *The lengthening of the frustum is therefore a function of the visual angle and increases when the figures approach the median plane.* A similar result appears when the object recedes in depth from the observer, the binocular parallax will decrease as the distance

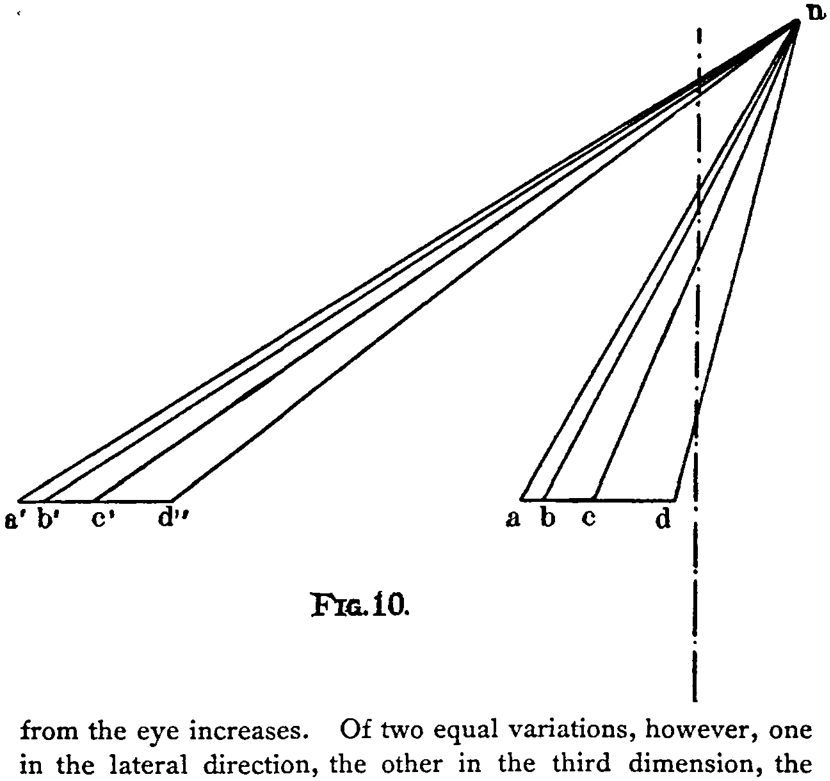


FIG. 10.

from the eye increases. Of two equal variations, however, one in the lateral direction, the other in the third dimension, the former will have the greater influence in modifying the binocular parallax. This proposition can be mathematically demonstrated for all distances great enough to come into consideration for our experiment. These established results explain another series of facts which Professor Hyslop has described. If two stereoscopic figures are drawn at a given fixed distance and moved backward and forward in the third dimension, the relative size of the circles will remain constant, but the frustum will increase in length as the figures move away, and it will grow shorter as they approach. The fact that the size of the circles seems to remain constant is what we should naturally expect. When fusion once takes place the size of the image is determined by the relation of the size of the retinal image and the degree of convergence. If now the figures are moved away, the convergence and the retinal image vary just as they would if a real object at the point of fixation were being moved away. The relative size, therefore, seems to remain constant. Not so with the binocular parallax. The figures are at a fixed distance apart, and when moved away from the eyes they will approach relatively nearer to the median plane. At an infinite distance they would be on the median line, and near at hand their distance from that line reaches its maximum. This approach to the median plane when the figures move away gives a relatively smaller decrease in the binocular parallax, a result which is in contradiction to all ordinary experiences, for usually when an object moves further away the binocular parallax decreases without this counteracting influence. Here again, we are confronted by a series of conditions which seem contradictory to experience. The interpretation of the sense data will, however, be fully determined by peripheral conditions. The object observed will seem to change, for that is the only possible objective condition under which the unusual combination of sense data could possibly be presented.

All of the results from these various experiments furnish ground for accepting the association and motor-sensation theory of visual space rather than the contrary as Professor Hyslop concludes. The sense-data presented in every case are interpreted in accordance with past experiences. Where such combinations of data arise as are not in conformity with any single past experience, the interpretation immediately permits the assumption of a change in the object itself; the size of the object changes or the position of its parts in the third dimension seems to vary. The relation fixed by past experience between the various sense-data is more constant than the belief in a single particular case, so that, although we know that the object remains constant in size, it is interpreted as changing, this perception being more readily adopted than any modification of the fixed relation between the various kinds of sense-data. The light thrown by this fact on the general theory of space perception as well as on the question of perception in general requires more discussion than can be allowed after the detailing of these empirical facts. In general, however, the conclusion is to be emphasized that analysis of the phenomena furnishes striking evidence in favor of the motor-sensation theory rather than against it.