Extension of Panum's Fusional Area in Binocularly Stabilized Vision*

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A novel phenomenon in stereopsis can be observed when viewing binocularly stabilized retinal images. This phenomenon is particularly impressive for random-dot stereoscopic images in foveal vision. If initially the left and right images are brought within Panum's fusional area (6-min arc alignment), fusion and stereopsis are perceived; the images can then be pulled apart symmetrically by about 2 deg in the horizontal direction without loss of stereopsis or fusion. The images are actually pulled apart on the retinae, since the binocular retinal stabilization compensates for the convergence-divergence motions of the eyes; hence a supra-retinal function must be responsible for this type of fusion. If the pulling proceeds too fast, or exceeds the 2-deg limit, or if the stimulus is occluded briefly, the fusional mechanism fails and the fused image abruptly breaks apart into two separate images which have to be brought within Panum's area again to re-establish fusion. For line stimuli, the maximum disparity without loss of fusion is much less than for random-dot patterns; it is always largest for disparity in the horizontal direction and is less in the vertical direction. These findings indicate that stereopsis and the classically conceived corresponding points greatly depend both on the class of stimulus used and on the recent history of the stimulation.

INDEX HEADING: Stereoscopic vision.

STEREOPSIS AND CONVERGENCE

IN 1841 Dove[1] demonstrated that retinal image disparity alone is adequate for stereopsis by using tachistoscopic exposures much too brief for any convergence motion of the eyes to be initiated. Although stereopsis is the result of central-nervous-system processing, convergence motions of the eyes are necessary to bring the stereo images within the critical limits of disparity. This interaction between stereopsis and convergence motions cannot be studied under ordinary vision, since it is impossible to apportion the registration process between processing in the central nervous system and convergence motions of the eyes. Tachistoscopic techniques on the other hand "freeze" the after images so that subsequent convergence motions are irrelevant. In both cases the experimenter is unable to control the relative positions of the images on the retinae with an accuracy better than the magnitude of the spontaneous eye movements. One way out of this dilemma is to experiment with binocularly stabilized retinal images, that is, with images which remain fixed on the retinae despite spontaneous or voluntary eye movements of the subject.

When attempting to fuse the two images of a stereoscopic pair, we commonly observe that the images have to be brought into close registration before they coalesce, but then the images can be pulled apart a considerable distance before fusion is lost. This does not seem surprising in ordinary vision. It might be assumed that after the stereoscopic pair is brought within Panum's fusional area, pulling apart of the images is compensated by corresponding disjunctive motions of the visual axes. In this article we report experiments in which the fused images are actually pulled apart on the retinae; nevertheless, fusion is maintained for some distance outside of the classical fusional areas. This phenomenon has important implications by itself, but in addition it can be used as a research tool to clarify some controversial questions. In particular, three such problems have been explored: (a) dependence of disparity limits on the classes of stimuli used; (b) directional anisotropy in stereopsis; (c) time dependence of the fusional processes. These aspects have all been studied previously, usually by use of tachistoscopic exposures, which portrayed binocular fusion as a static process. The present experiments, using stabilized retinal images, enable us to examine the dynamic nature of these processes.

Although there are simpler ways to prevent convergence–divergence motions during the pulling of the images than using binocular retinal stabilization, such as pulling the images temporalward beyond the divergence limit of the eyes, it would be difficult to monitor accurately the positions of the eyes. The advantage of the technique of binocular retinal stabilization is twofold: it permits us to control the position of the stimuli on the retinae, and it provides a high accuracy for tracking eye motions, which cannot be matched by other existing methods.

DEPENDENCE OF MAXIMUM DISPARITY ON THE STIMULUS CLASS

Classically, the maximum disparity for stereopsis has been measured by using dots or lines as stimuli. For

* This research is supported in part by the National Institutes of Health USPHS Grant NB 03627.

[1] H. W. Dove, Ber. Preuss. Akad. Wiss. 1841, 251 (1841) and Ann. Physik, Ser. 2, 110, 494 (1860).

Fig. 1. Pair of random-dot stereo targets as used in this research. If the pictures are examined through a suitable stereoscopic viewer, a central square area of 40×40 picture elements can be seen in depth.

these stimuli the disparity limits depend on whether the criterion by which they are measured is fusion of the images or perception of depth in the fused image. The largest disparity that still gives rise to a single fused image is the horizontal dimension of Panum's fusional area or fusion threshold. The fusion threshold increases from 6-min arc in the center to 20-min arc at a peripheral angle of 6 deg.[2] Outside of Panum's fusional area, the left and right images do not fuse completely and parts of the image are seen as double, but stereopsis is still experienced if disparity is less than a critical value. Often one of the double images is suppressed, but with care the limits of stereopsis can be measured and are about four times as great as the fusion thresholds.[3] Stereopsis without fusion is also characterized by an association of increased disparity with increased perception of depth. With further increase of disparity this association ceases and the percept of depth is lost.

Measurements made with random-dot stereoscopic images as described by Julesz[4] (Fig. 1) differ from these classical results not only quantitatively but also qualitatively. Random-dot images provide information concerning the binocular disparity in each picture element, since no large textureless areas exist; thus they offer more stimulation for the fusional processes than do line targets or single dots, and much larger disparities can be tolerated before stereopsis is lost. Even more important is the absence of monocular perception of shapes in these stimuli; as a result, double images of the central square do not exist and are not perceived prior to fusion; after fusion, of course, only a single binocular shape is perceived. This means that for random-dot stereoscopic images there is no difference between fusion thresholds and the thresholds for stereopsis.

This basic difference between line stimuli and random-dot stimuli indicates that the observable mechanisms of fusion and stereopsis may depend on the stimulus class. It is also evident that parameters measured for one class of stimuli cannot be applied indiscriminately to another stimulus class. Our results bear this out, and some basic differences between the two stimulus classes have been clarified.

DIRECTIONAL ANISOTROPY IN STEREOPSIS

Directional anisotropy is a controversial problem in stereopsis. On one hand, the horizontal disposition of the eyes in our skulls results in directional anisotropy of stereopsis; while horizontal disparity gives rise to stereopsis, vertical disparity does not. On the other hand, the fusion mechanism does not have this all-or-nothing character: Panum's fusional area is about 6-min arc in the fovea for both vertical and horizontal disparity, although the vertical extent is probably a little smaller than the horizontal.

This discrepancy between fusional isotropy and stereoscopic anisotropy is also a function of the stimulus class. For point stimuli, vertical disparity has only a slight effect on stereoscopic performance; for example, a vertical disparity of 18-min arc causes a loss of only 50% of the stereoscopic acuity, but vertical disparity destroys stereopsis entirely for random-dot images if the disparity is outside of Panum's fusional area. Therefore, previous experiments, from which eye movements were not eliminated, have shown that only horizontal disparity generates the perception of depth although the fusional mechanisms are able to fuse both horizontal and vertical disparities. Further, vertical disparity is relatively harmless for the perception of depth with some classes of stimuli, but destroys stereopsis for other classes. In a later section we report experiments using stabilized retinal images; the suppression of eye movements makes the interpretation of the results of the directional anisotropy of the neural fusional mechanisms more clear-cut, and the dependence of this process on the stimulus class can then be evaluated.

TIME DEPENDENCE OF THE FUSIONAL PROCESSES

In normal vision the motions of the two visual axes are not perfectly correlated; this results in a constantly varying amount of binocular disparity. These errors of convergence and divergence are either caused by the drifting components of eye motion, which develop at rates of the order of 1-min arc/sec, or are consequences of the saccadic movements, which occur in very short periods, within an interval of 40 msec at most. The amounts of these errors of convergence or divergence are often much larger than Panum's fusional limits; nevertheless, even experienced visual observers do not detect loss of binocular fusion during prolonged viewing. Furthermore, no change in perceived depth is experienced, although there is about 50% probability that any saccade changes the disparity by 3-min arc or more

[2] K. N. Ogle, *Researches in Binocular Vision* (Saunders, Philadelphia, 1950).

[3] K. N. Ogle, J. Exptl. Psychol. 44, 253 (1952).

[4] B. Julesz, Bell System Tech. J. 39, 1125 (1960). For an up-to-date review see: Science **145**, 356 (1964).

in 40 msec (for details see Experiment No. 3), which is an order of magnitude above stereoscopic acuity.

This stability of stereopsis during saccades and drifts may be the result of a number of processes. One possible cause might be the neural fusional processes mentioned above; several experiments were performed to test this hypothesis. These experiments were designed to test the rate at which images formed on disparate areas of the two retinae can be fused by processes other than the normal disjunctive motions of the visual axes.

The classical work on binocular disparity has already modified the original notions of retinal correspondence, which regarded particular locations in the visual cortex as point-by-point identical in their coordinates on the two retinae. The time dependency of stereopsis as revealed by our findings further modifies the idea of corresponding points and we present some additional experiments designed to examine this process without contamination by eye motions.

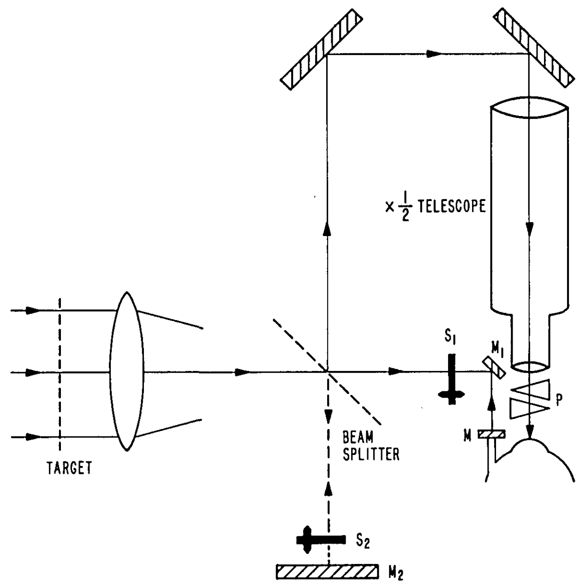

FIG. 2. Left-eye component of equipment for producing binocular stabilized images. Parallel rays enter from a projector at the left.

GENERAL EXPERIMENTAL METHOD

Apparatus

The left-eye component of an apparatus which provides a stabilized image is shown in Fig. 2. The monocular operation of this equipment has been described in detail elsewhere[5]; for the present work, the apparatus was duplicated for the right eye; the distance between the two halves of the equipment can be adjusted to suit the interocular distance of the subject. A pair of identical achromatic prisms P is mounted at the eyepiece of each telescope; the two prisms can be rotated independently through equal angles in opposite directions, thus varying the power of the combination, also the prism-assembly can be rotated as a unit. By suitable manipulation, the subject can adjust the optic axis of each side of the equipment to coincide with a comfortable fixation direction of the corresponding eye.

Adjustment Procedures

A problem always arises in these experiments concerning the correct initial positioning of the stabilized image in the center of the fovea. In normal vision there is only a very small region of the fovea which the subject accepts as giving sharpest vision; evidence has been advanced by Polyak[6] that this region is as small as 10-min arc diameter (not to be confused with Panum's fusional area). This is not the case, however, for stabilized vision; in some circumstances the target may be moved as much as 30-min arc with equal satisfaction to the subject. This finding of increased area of sharpest vision under retinal stabilization is a phenomenon in its own right, not to be discussed here. The following procedure was therefore adopted in an effort to minimize this shifting of retinal locus. Rotary shutters S_1 and S_2 block the light reflected from the contact-lens mirror M and the stationary mirror M_2, respectively. If S_1 is open and S_2 closed the subject sees the target in stabilized vision; if the shutters are reversed he sees the target in normal vision. Both shutters may be opened simultaneously, allowing the subject to see a stabilized image superimposed on a normal image. The subject is first presented with a stereo-pair of images seen in normal vision; he adjusts the position of each target in its holder so that he can see a fused image of the pair in the center of field of view without muscular effort other than that associated with normal fixation. In the case of small targets, such as points of light, no ambiguity arises in making this adjustment; but when an extended target is used the subject is instructed to fixate a particular region of the target; alternatively a temporary fixation mark is introduced in corresponding positions of the left and right target. This fixation mark must be close to the center of the target; otherwise the subject is unable to maintain reliable fixation upon it.

During the second stage of the procedure, shutters S_1 and S_2 for the left eye are closed while both are opened for the right eye. The subject thus sees the target in normal vision stationary in the field of view, and simultaneously a stabilized image which under the action of spontaneous eye movements floats around and about the normal image. The subject then adjusts mirror M_1, which can rotate about both horizontal and vertical axes, until the stabilized image coincides (apart from its spontaneous motion) with the normal image. During this adjustment the subject must maintain fixation on the fixation mark in the "normal" image. This requires considerable training, for there is a

[5] D. H. Fender and P. W. Nye, Kybernetik. **1**, 81 (1961).
[6] S. L. Polyak, *The Retina* (The University of Chicago Press, Chicago, 1941), Ch. 15, p. 204.

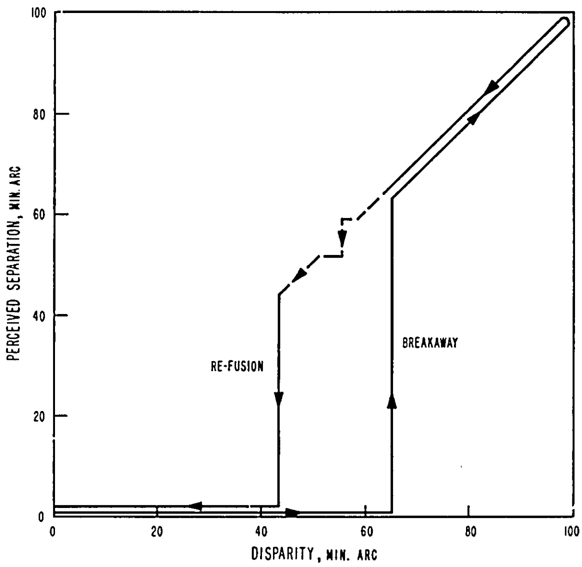

FIG. 3. Breakaway and fusional limits for vertical lines moved into horizontal disparity; stabilized vision. The dotted line indicates a region of transient fusion between the lines and fiducial marks. This is not reproducible from one experiment to the next.

compelling desire to track the stabilized image visually. If this adjustment has been made carefully, the stabilized image now occupies the same retinal location as was selected by the subject for normal viewing. The procedure is now repeated for the other eye.

Next, shutters S_1 and S_2 are opened for both eyes. It is generally found that there is a small amount of interaction between the two eyes during this setup procedure and that when both eyes see both images, some small adjustments of the positions of the stabilized images have to be made. To assist the subject in this, lightly colored filters may be introduced into one or both sides of the apparatus; these identify which target belongs to which eye.

Finally S_2 is closed for both eyes; the subject is now viewing a binocular pair of stabilized images which are fixed on roughly corresponding areas of the two retinae. It is found that with some small adjustments the targets fuse and stereopsis results even though the subject is denied fine disjunctive eye movements to effect complete registration of the images.

Experimental Procedures

In order to test the area over which fusion is possible, the targets were moved slowly and symmetrically temporalward in the visual field until the subject reported a break of fusion; the detailed nature of the break is described with each experiment. The angular separation of the targets was noted. The targets were then moved nasalward until fusion took place once more; the separation at which fusion was reestablished was noted. Observations were taken around this cycle many times; the procedure was occasionally halted and the setup routine was repeated, so that different areas of the retinae were used as starting positions.

TABLE I. Horizontal disparity at which vertical-line targets fuse or separate. The standard deviations quoted in this and all subsequent tables refer to the values obtained for one subject.

Visual condition	Fusion point (min arc)	Breakaway point (min arc)
Normal	60± 7	87± 9
Stabilized	42±10	65±14

This was the only target-movement routine permissible in this experiment; the individual visual axes tried to track the target displacement, but the divergence movements were severely limited. Target motion in the nasalward direction causes extreme convergence until the contact lenses strike the fornices and are displaced on the eye, destroying stabilization. Similarly, displacement of one target only, in any direction, causes large movements of both eyes in that direction until the same effect occurs.

Four subjects (B, F, G, and N), all of whom have had considerable experience in wearing contact lenses and viewing stabilized images, were used for various portions of this study. Each subject had his own individually moulded, tightly fitting contact lenses; the vision of each observer was corrected by the contact lenses for viewing targets at infinity. In general, the results for all subjects were substantially similar; results are therefore quoted for only subject N except in a few cases where other subjects are mentioned for comparison. In stabilized vision, the mean value of disparity measured for any subject fell within the standard deviation of the values given for subject N in the following tables and diagrams; any major variants of the responses of the other subject are noted in the text.

EXPERIMENT NO. 1. FUSION OF LINE TARGETS

Method

The target used for this experiment was a single vertical black line subtending 60-min arc vertically and 13-min arc wide. It was viewed in a white surround; identical targets were used for both the left and right fields. The experiment was performed with normal vision and with stabilized vision as described above. For stabilized vision the contrast was set so high that no fragmentation or disappearance of the lines was ever experienced.

Results

The subjects could all adjust the lines to fusion in normal and in stabilized vision; they reported the percept as a single line, steady and unchanging. As the lines were moved apart in stabilized vision, the percept did not change and no subject was able to detect a

TABLE II. Vertical disparity at which horizontal-line targets fuse or separate.

Visual condition	Left target up Fusion (min arc)	Left target up Breakaway (min arc)	Right target up Fusion (min arc)	Right target up Breakaway (min arc)
Normal	17±3	70±5	40 ±1	53±1
Stabilized	14±6	22±6	8.7±0.2	16±2

change of the perception of depth of the line. This is to be contrasted with the normal-vision case in which disjunctive motion of the targets produces a very powerful perception of changing depth.

In either viewing condition, the break from fusion was always sudden and well defined; the subjects then perceived two lines in the visual field. The perceptual separation of the lines after fusion had been lost could be estimated by the subject, since each target included a few small subsidiary marks at known angular spacings from the line. The subject was therefore able to read the position of the line seen by one eye against the fiducial marks seen by the other. This method is not highly reliable because from time to time fusion occurs between the line and one of the scale points. In the normal-viewing condition, the perceptual separation of the lines after break was described as fluctuating; estimates of the separation were equal to the true separation within an error of about 15-min arc. In stabilized vision the separation appeared to remain constant.

When the disparate targets were moved towards each other, refusion of the images took place when the disparity was reduced by about 30% in either normal or stabilized vision. The results are given in Table I and are illustrated (for stabilized vision only) in Fig. 3.

The two lines were then positioned horizontally and moved into vertical disparity, giving the results shown in Table II. It is noticed that there is considerable discrepancy between the values obtained when the disparity involves moving the left target up or when the right target is moved up. This is, in part, because there is no certainty that the subject sets the initial position of the image to the center of Panum's area. Frequent resetting of the image may randomize this error. This value is smaller than the value obtained for horizontal disparity.

Finally, the lines were set at 45 deg to the horizontal axis and then separated so that the targets were moved temporalward and up or temporalward and down, but

TABLE III. Oblique disparity at which inclined-line targets fuse or separate.

Visual condition	Left target up Fusion (min arc)	Left target up Breakaway (min arc)	Right target up Fusion (min arc)	Right target up Breakaway (min arc)
Stabilized	28±11	39±12	10±2	25±2

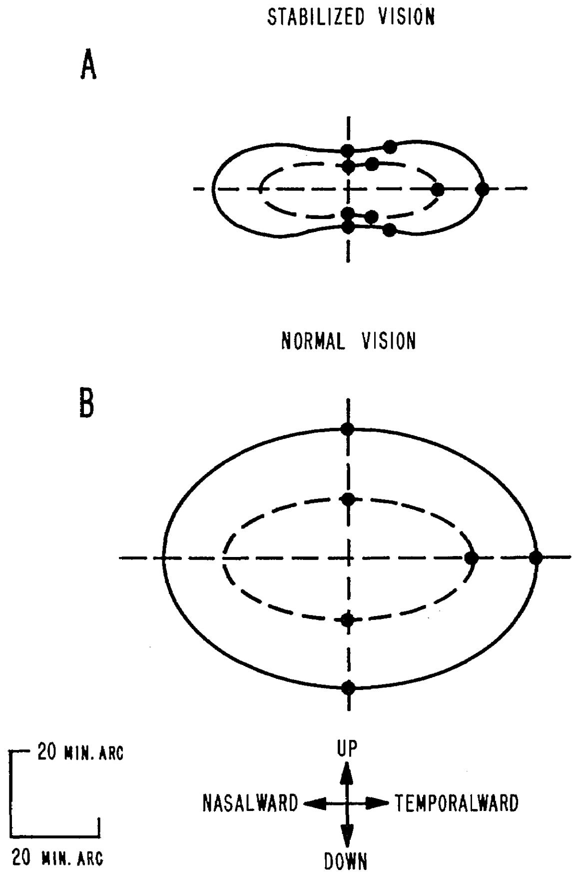

FIG. 4. Retinal areas over which fusion (dotted curve) of single line targets is possible. The solid curves show the limits at which breakaway occurs. Only points in the temporal direction have been tested; we assume that the diagrams are symmetrical about the vertical axis.

never nasalward. The results are shown in Table III for stabilized vision only. The means of these values are intermediate between those given in Tables I and II and indicate that fusion can be achieved over an elliptical area of the retina without the assistance of disjunctive eye movements [Fig. 4(a)].

The corresponding area for normal vision shows a greater tolerance of disparity [Fig. 4(b)]; this is due to eye movements, as may be seen from Fig. 5. The data for this diagram were obtained as follows: the eye movements of the subject were recorded using the method described by Byford[7]; the signals were converted to digital form at 20-msec intervals and were transmitted to a computer.[8] The computer was programmed to calculate the horizontal and vertical motions of the visual axis of each eye. The values for the left eye were then subtracted from the corresponding values for the right eye, giving the horizontal and vertical components of the disjunctive motions between

[7] G. H. Byford, Nature 184, 1493 (1959).
[8] G. D. McCann and D. H. Fender, *Neural Theory and Modeling* (Stanford University Press, Stanford, California, 1964), p. 232.

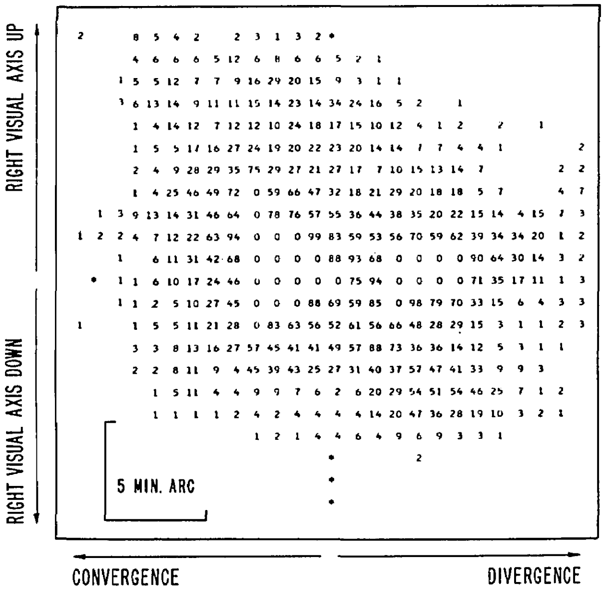

FIG. 5. Two-dimensional histogram, illustrating the motion of the right visual axis with respect to the left during a 2-min viewing period. The number printed in each cell should be multiplied by 20 to get the total duration in msec of the disparity whose value is shown by the coordinates of the cell. The zeros in the center of the diagram represent times longer than 2 sec.

the two visual axes at 20-msec intervals. Finally, the results are displayed as a 2-dimensional histogram showing the total time, during a long viewing period, for which any given value of disparity (both horizontal and vertical) might occur as a result of spontaneous eye movements—colloquially, the diagram shows how one visual axis wanders with respect to the other. If this diagram is considered as a bivariate normal distribution, the standard deviation is about 8-min arc in the horizontal direction and 7-min arc in the vertical. This would account fully for the difference between the fusional limits for normal and stabilized vision. The breakaway limits are rather larger, especially in the vertical direction; we speculate that once captured by a fused pair of images, the visual axes can be pulled up or down by some 10-min arc more than in the horizontal direction.

EXPERIMENT NO. 2. RANDOM-DOT STEREO TARGETS

Method

This experiment had the same design as for Experiment No. 1, but the target material consisted of a binocular pair of random-dot patterns as described by Julesz.[4] Each pattern was composed of a 100×100 array of square-shaped picture elements, black or white with equal probability (Fig. 1). The entire pattern subtended 3.43 deg in the visual field and each picture element was a little over 2-min arc square; in these highly textured patterns, they were just at the limit of resolution; some subjects could perceive the individual picture elements, others only clumps of them. The left and right patterns were identical, that is, they would superpose exactly, except for a 40×40 square in the center. This center square was also identical but was moved two picture elements towards the left in the right-hand pattern and two picture elements toward the right in the left-hand pattern, as if it were a solid sheet. This arrangement has been shown to generate the perception of depth displacement of the central square out of the background (with an equivalent vergence of about 8-min arc) without the participation of monocular cues.

Results

In normal vision, the targets could be adjusted to fusion and stereopsis as was seen and described previously[4]; depth could also be perceived in stabilized vision[9] even though the subject could no longer fuse the targets by disjunctive eye movements. This is not novel, for the tachistoscopic experiments of Julesz[10] indicated this.

The perception of depth, like many visual acuities, is subject to periodic fading and regeneration in stabilized vision. It may be noted, however, that the fading refers to the perception of stereopsis and not to the random dots; at adequate contrast these did not fade. However, it was found that the frequency of the cycle from clear vision through loss of the depth perception and back to the stereoscopic perception depended to some extent on the fixation point chosen by the subject. For example, some subjects reported that even with normal vision they could make the perception of depth fade out and return in a manner analogous to the effects normally associated with stabilized vision, by fixating the center of the 40×40 square very carefully. This was most apparent with patterns for which the central square subtended 2.0 deg or more but seemed to be impossible in normal vision with patterns of the size used in this work, in which the central square subtended only 1.37 deg. In stabilized vision this effect is much more pronounced and occurs even with the small patterns, provided that the fixation point used by the subject is at the center of the square. In order to

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[9] Subject G was unable to obtain more than fleeting glimpses of the stereoscopic effect in stabilized vision despite considerable training. Most subjects can examine a considerable area of a stabilized image with high acuity even though they cannot shift their line of regard over the target. This area is usually elliptical, subtending about 2 deg horizontally by 1 deg vertically; outside of this area, acuity in stabilized vision falls off rapidly. Subject G does not have this faculty; his area of high acuity in stabilized vision is at most 20-min arc wide; thus very rarely is he able to resolve a sufficient number of picture elements belonging to the central square and some belonging to the surround at the same time a condition which appears to be necessary for perception of the stereoscopic effect. Subject G showed normal stereopsis with line targets in normal and in stabilized vision, and also with random-dot targets in normal vision.

[10] B. Julesz, J. Opt. Soc. Am. 53, 994 (1963).

TABLE IV. Disparity at which random-dot stereoscopic patterns fuse or separate.

Visual condition	Subject	Horizontal disparity Fusion point (min arc)	Horizontal disparity Breakaway point (min arc)
Normal	N	160±20	180±25
Stabilized	N	6± 4	120±18
Normal	B	153±30	166±34
Stabilized	B	10± 6	137±25

Visual condition	Vertical disparity: Left target up Fusion (min arc)	Left target up Breakaway (min arc)	Right target up Fusion (min arc)	Right target up Breakaway (min arc)
Stabilized	1±1	18±1	9±1	23±1

standardize the viewing condition and to minimize spontaneous fading of the depth effect, the subjects were instructed to view one corner of the center square formed by the stereoscopic effect during the setup procedure; if necessary, their eye movements were recorded to insure that they were doing this. The subjects were then allowed to view this arrangement and to make small changes of the positions of the retinal images until a stable stereoscopic effect was formed. Target disparity was then introduced slowly by the experimenter during the periods for which the depth effect was perceived; otherwise the procedure was as described in the previous experiment.

With increasing disparity, the failure of the stereoscopic perception and of fusion of the two images occurred simultaneously, and the two targets were seen to separate. The results of this experiment are given in Table IV and are shown in Fig. 6. These results are in broad agreement with the results obtained for the single line, but it is noticed that the targets can be pulled apart by a much larger amount, exceeding 2 deg, before fusion is lost. On the other hand, the targets do not re-fuse until they are moved very close together, within about 6-min arc.

The results reported in the preceding experiments are qualitatively similar: targets presented with zero disparity are seen as one fused image; if they are then moved gradually into disparate positions, the images remain fused until some limiting disparity is reached. At this limit, the two images break apart perceptually, and are seen separately in their disparate positions. Further increase of the disparity merely causes the images to appear to move further apart. If, however, the disparity is reduced below the limit, re-fusion does not occur until some much lower limit is reached. The targets then form a single fused image once more, and this percept is maintained until the real disparity is reduced to zero. If we consider the situation near the maximum-disparity limit, we have the following sequence; just below the limit the images appear to be fused, at the limit they break apart, but then, if the

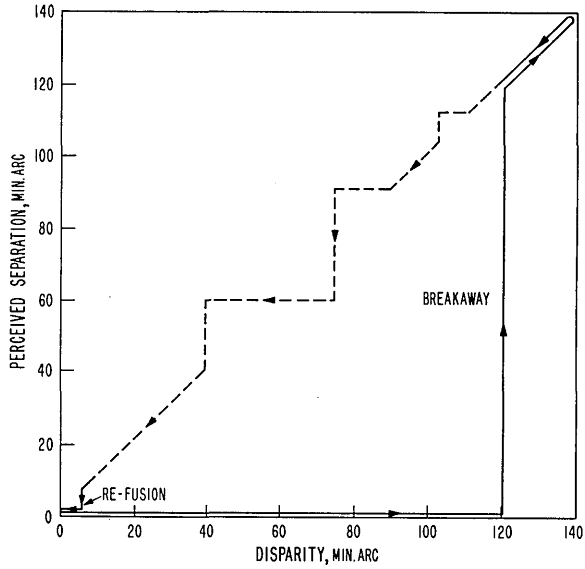

FIG. 6. Breakaway and fusional limits for random-dot stereo patterns moved into horizontal disparity; stabilized vision. Dotted region as in Fig. 3, except that transient fusion now occurs between small groups of picture elements which happen to have high correlation between left and right images.

disparity is immediately reduced to its former value, the images remain apart although previously they were fused at this disparity. The converse effect occurs near the lower limit. Further, we can find some target disparity between these two limits at which the images are perceived with zero disparity (that is, fused) if the setting has been approached from smaller values of disparity, but they are seen as separated if the setting is approached from larger values of disparity. This lagging of effect (magnitude of perceived disparity) behind cause (retinal image disparity), irrespective of the sign of the change in the cause, is another example of hysteresis in the classical sense.

Previous work on Panum's area has given us a very detailed account of one end only of this hysteresis cycle, considered as a static phenomenon. We believe that binocular fusion is a dynamic process, continually changing to allow for motion of objects in the visual space, changes of fixation, body motions and spontaneous eye movements. Disregard of this fact makes it very difficult to elucidate the mechanisms underlying binocular fusion.

EXPERIMENT NO. 3. TIME DEPENDENCE OF FUSION

The purpose of this experiment was to test the time dependence of the fusional processes.

In normal vision, the motions of the eyes are not perfectly correlated; this results in a constantly varying amount of binocular disparity. It is a puzzling fact that this fluctuation of disparity does not affect stereopsis. The errors of convergence or divergence

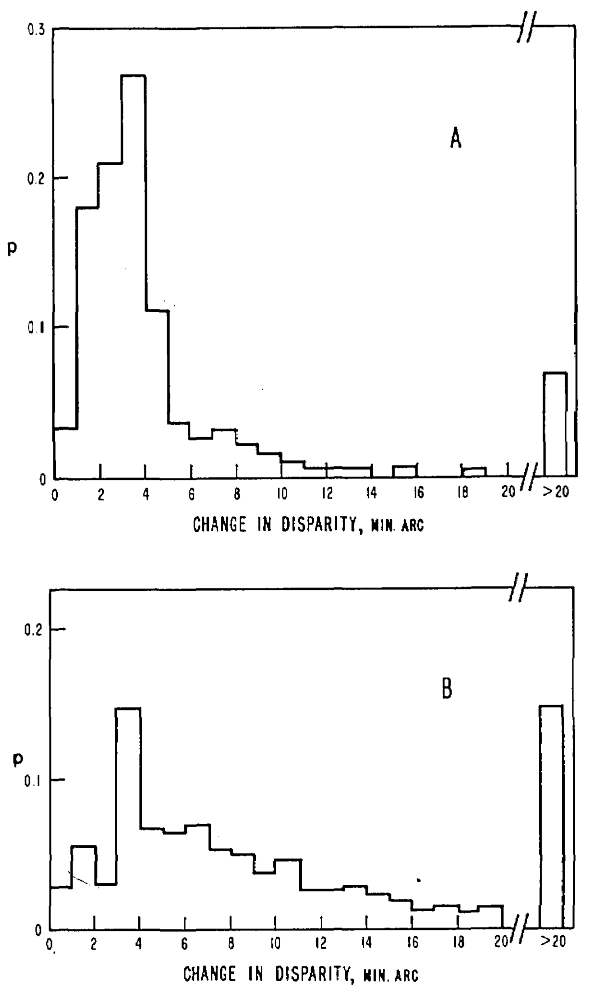

FIG. 7. These histograms show along the ordinate the probability, p, that a spontaneous saccade causes a change in vergence (and hence of image disparity) of magnitude shown along the abscissa. Upper diagram, pinhole target viewed binocularly; lower diagram, random-dot stereo-pair targets. This diagram refers to subject G.

caused by the drifting component of eye motion developed at slow rates, of the order of 1-min arc per sec. The previous experiments have demonstrated that error rates such as these can be compensated adequately by the hysteresis process which preserves the cortical registration. On the other hand, the saccadic components of eye movement cause convergence or divergence errors which are much larger than those caused by slow drifting motions. These errors develop in a very short period. The duration of a spontaneous saccade is at most 40 msec; nevertheless, even experienced visual observers do not detect loss of fusion or perceptual changes during saccades.

The distributions of errors of disparity caused by saccades when a pinhole or a random-dot stereoscopic pattern is viewed binocularly for a period of 2 min are shown in Fig. 7. These histograms were obtained as follows: The eye movements of the subject were recorded and transmitted to a computer as described previously. The computer was programmed to identify saccades by noting any displacement of the visual axis of either eye greater than or equal to 3-min arc occurring in a 40-msec interval. The corresponding displacement of the other visual axis was then calculated; these two vectors were then combined to give the absolute value of the change of disparity caused by the saccade. This value is displayed as the abscissa in Fig. 7. The diagrams show that the probability that any saccade changes the disparity by 3-min arc or more in 40 msec is 0.57 when a pinhole is viewed and 0.89 for a random-dot pattern.[11] Some saccades produce changes greater than 20-min arc.

Large binocular-disparity changes during saccades may be compensated by a number of processes: the cortical registration demonstrated by the previous experiments may be able to follow rates of change of disparity up to 500-min arc per sec, or the cortical projection of the retina may be rezeroed after each saccade, as suggested by Beeler.[12] The following experiment tests the first of these hypotheses.

Method

Vertical-line targets and random-dot targets were used as in the earlier experiments. The targets were carried on linear-motion electromagnetic transducers, and each could be moved horizontally through angles up to 100-min arc. For these experiments the duration of the motion was 30 msec. The motion was slightly underdamped, permitting about 8% overshoot in the step motion of the target. This is characteristic of the motion of the visual axis during a spontaneous saccade.

Initially the targets were adjusted to fusion by the subject; the transducers were then energized and pulled the targets apart in a temporalward direction through a known small angle. The subject pressed a key whenever he lost fusion. At intervals of 5 sec, the targets were returned to coincidence, remained there for 5 sec and then were moved apart again.

Results

Vertical Line Targets in Normal Vision

All subjects reported that if only one line was moved through distances smaller than about 15-min arc there was no loss of fusion, but that the fused pattern moved in the direction of the moving line. If both lines moved, the fused line appeared to be motionless. In this case fusion was not lost for motion less than 30-min arc total disparity, but for values of disparity greater than

[11] The actual binocular parallax in these targets was 8-min arc, so some of these saccadic changes of disparity may have been purposeful. The probability of a saccade changing the disparity by less than 5-min arc or more than 11-min arc is 0.65.

[12] G. W. Beeler, Ph.D. thesis (California Institute of Technology, 1965).

this there is a transitory loss of fusion. The unfused period becomes longer with larger disparity until a disparity is reached at which fusion is no longer possible. These results are illustrated in Fig. 8. It is noted that, outside of the region in which fusion is not lost, there is a range of disparities for which fusion can be re-established in 1 or 2 sec; but then a sharply defined limit is reached beyond which fusion is not possible.

Vertical-Line Targets in Stabilized Vision

The results of this experiment are also shown in Fig. 8. Qualitatively, the outcome is similar to the results in normal vision, but the permissible image movement for maintenance of fusion is much smaller. However, it is noticed that re-fusion is always possible within the region of hysteresis reported in the first experiment. The fusion limit for subject N in this experiment was 35-min arc; this is consistent with the value of 42±10 min arc recorded in Table I, especially since the subject was allowed only 5 sec during which the targets could re-fuse. Note that in this case the limits of the range of fusion are approximately the same for subjects G and N, although their performances in normal vision were rather different.

Random-Dot Targets in Normal Vision

Phenomena strictly analogous to those reported for vertical-line targets were reported when random-dot targets were viewed; there is a transitory loss of fusion and of depth perception but both are re-established after a short interval. The results are given in Fig. 9.

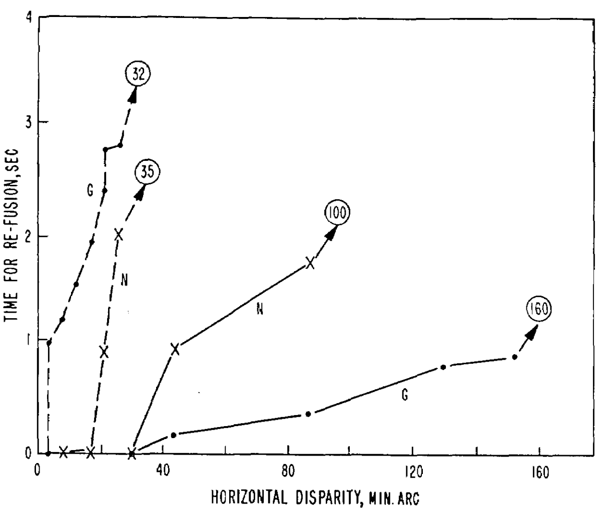

FIG. 8. This diagram compares the performance of subjects G and N. Vertical-line targets were pulled rapidly apart after fusion and the time for re-fusion was measured. Solid lines, normal vision; dashed lines, stabilized vision. The encircled number at the end of each curve gives the maximum disparity at which re-fusion could be achieved.

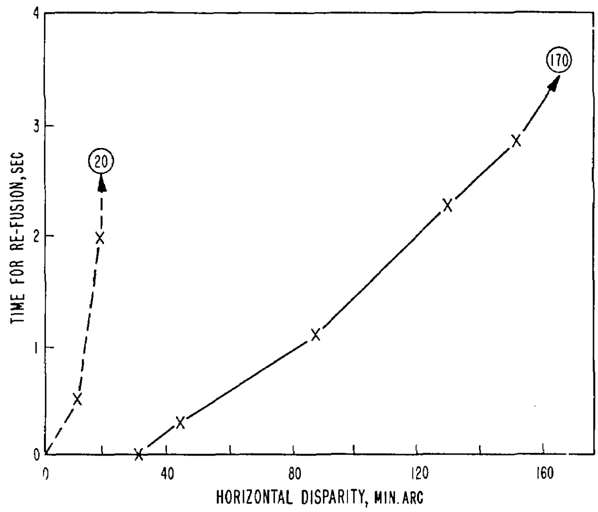

FIG. 9. Time taken by subject N to re-fuse random-dot targets after they had been pulled rapidly apart. Solid lines, normal vision; dashed lines, stabilized vision. The encircled number at the end of each curve gives the maximum disparity at which fusion could be achieved.

Random-Dot Targets in Stabilized Vision

In this case it was found that pulling the targets rapidly apart, even by amounts as small as 10-min arc total disparity in 30 msec, caused transitory loss of perception of the square. After a short period, the square could once more be perceived and seen in depth; the results are also shown in Fig. 9. The fusional limit (20-min arc) is considerably smaller than the limit of the hysteresis effect which can be achieved with slow pulling of the targets (Fig. 6).

EXPERIMENT NO. 4. DISPARITY WITH OCCLUSION

Finally, we performed the following experiment with stabilized vision. Two random-dot patterns were set up so as to be well registered and to give good depth perception. The targets were then moved slowly by the experimenter into disparate positions at a rate of 1-min arc per sec. Both targets were then occluded for short intervals ranging from about 10 to 600 msec; the interruptions occurred at random times with a mean exposure period of 1 sec. The subject was asked to signal when the central square could be perceived and seen in depth. The disparate motion of the targets was halted during the periods of occlusion and when the subject signalled that the square could not be perceived.

In this experimental condition, we found that once fusion was lost, it was never regained, although with longer exposure periods the result might be different. The subjects also reported that loss of the stereoscopic effect coincided with one of the periods of occlusion. The maximum duration of occlusion which could be tolerated without breaking fusion is an inverse function

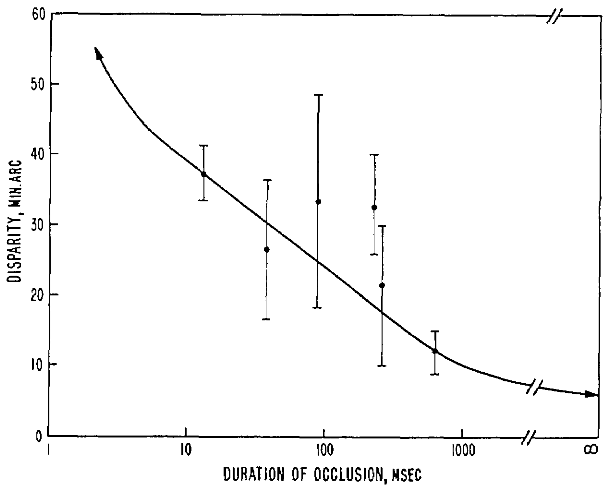

FIG. 10. This diagram shows the maximum disparity that would still permit re-fusion of random-dot stereo images after they have been occluded for a brief period.

of image disparity as shown in Fig. 10. We assume that the curve climbs to about 120-min-arc disparity at zero duration of occlusion and, from Fig. 6, that the images would be re-fused at 6-min-arc disparity, after a very long occlusion.

It is instructive to compare the results of Experiments 3 and 4. When random-dot targets are pulled apart in 30 msec, a disparity of 20-min arc results in a loss of fusion for at least 5 sec. Alternatively, targets set at 20-min-arc disparity must be occluded for at least 200 msec in order to destroy fusion for 1 sec.

PERCEPTUAL CHANGES DURING PULLING

The many perceptual phenomena which occur under binocular retinal stabilization are reported elsewhere, except for the following observations which we feel belong in this article. In the following viewing conditions, disjunctive motion of the targets gives rise to the following perceptions:

Single-Line Targets

Normal Vision

Powerful impression that the line is moving toward the observer, or weak impression that it is moving away from observer.

Stabilized Vision

Stationary line, fixed in space.

Random-Dot Targets

Normal Vision

Powerful impression that the fused stereoscopic image as a whole is moving toward or away from the observer. No change of the apparent depth difference between the central square and the surround.

Stabilized Vision

Surround fixed in space, but the center square advances and grows in size as the targets are returned to the central position after temporalward pulling.

In normal vision the convergence–divergence motions of the eyes are correlated with the disjunctive motions of the targets. That convergence gives a stronger perception of apparent motion than divergence is interesting by itself, although in the equipment used for this research the target is seen at optical infinity; conflict of information between the accommodation system and the disjunctive eye-movement system may therefore be responsible for this effect. Under stabilized vision the line target appears to stay stationary in space, while for random-dot targets, which contain both a center square and a surround, the center square appears to advance in depth and grow in size whereas the surround stays stationary. The maximum increase of size was estimated by the subjects to be 30%, but immediately following this report the subject would estimate the size of the 40×40 central square as 40% of the 100×100 surround. These two cases are not strictly comparable; the line target lacks the reference plane which is provided by the surround of the random-dot pattern. Nevertheless, we have an indication that disturbing the correlation between disjunctive motions of the target and the convergence motions of the eyes causes this phenomenon.

DISCUSSION

The concept of corresponding retinal points has undergone many changes since it was introduced in 1613 by Aguilonius's notion of the horopter. The discovery by Wheatstone and Panum that fusion was possible over small but finite and corresponding "areas" of the retinae broadened the concept, since the corresponding points of the two images no longer need have the same coordinates in the left and right retinae, but merely have to be positioned within the fusional areas. The phenomenon reported in the earlier sections of this paper further changes the classical notions: According to the new idea, the recent history of the stimulation of the visual system has to be available to whatever central mechanism is responsible for binocular fusion before it can determine whether two points on the two retinae are corresponding points or not. Moreover, the context of the entire stimulation, for example the detail surrounding a given image point, has an effect on the determination of binocular correspondence. Our experiments show that two points falling on the perifoveal regions of the left and right retinae with a disparity of 2 deg may be corresponding points if they are members of a random-dot ensemble and if, prior to this amount of disparity, they were brought into alignment and then slowly pulled apart. If any one of these criteria fails, for example if the image points are not members of a dense ensemble forming a sheet of texture or have not previously been seen as fused before the onset of the disparity, the points do not function as corresponding retinal points, fusion does not occur, and stereopsis is not perceived.

These experiments reveal the dependence of the function of the visual system on the spatio-temporal characteristics of the probing stimulus. Many of the phenomena reported would have been disguised if only simple line stimuli had been used. On the other hand, some properties of binocular vision can best be examined by using line targets, since they can be perceived with one eye as well, whereas random-dot stereoscopic images do not contain any shapes which can be perceived monocularly.

Two fundamental properties of random-dot stereoscopic images emerge from these experiments: First, stabilized vision reconfirmed that these images possess a fusion region only. There is no region where the images are seen as double but still perceived in depth. Second, the ratio of disparity at breakaway to disparity at re-fusion, is 20:1 (2 deg:6-min arc) for random-dot stereoscopic images and only 1.5:1 (65-min arc:42-min arc) for vertical-line targets. This dramatic difference between the two cases gives some insight concerning the fusion mechanisms. Since the random-dot stereoscopic images are devoid of monocular shapes, the binocular correlation between corresponding areas has first to be established. It seems that this labeling of corresponding points can occur only within Panum's fusional region. We believe that the correlation process assigns the proper labels to the corresponding points; these labels can then be preserved for large retinal-image shifts provided that the disparity is less than a critical value and that the velocity of pulling is also less than a certain limit. The abrupt transitions between ordered and disordered states indicate a cooperative phenomenon requiring the near-simultaneous participation of all of the constituent elements. In our case, the establishment of fusion (correlation or labeling) and its preservation correspond to the ordered state, whereas prior to fusion and after breakaway a disordered state exists.

The strong dependence of the breakaway threshold on the previous perceptual state, whether fusion occurred or not, indicates a simple memory process. This dependence on an earlier state in our case is simply a lagging of effect (magnitude of perceived disparity) behind cause (retinal-image disparity) and we call it according to accepted usage "hysteresis" or "an hysteretic phenomenon." In our opinion this name should be assigned to all phenomena in which effect lags behind cause, and "memory" should be used for more complex information storage. For instance, the phenomenon that the break point for diplopia is always greater than that for recovery (when experimenting with prisms) is another example of hysteresis; whereas, the time necessary for aniseikonic distortions to appear after an observer puts on aniseikonic glasses might indicate a phenomenon complicated enough to be regarded as a memory process.

For a maximum hysteretic effect, a large number of elements have to cooperate simultaneously. Random-dot images are densely covered with points, each carrying information concerning image disparity, and it is reasonable to assume that stronger interactions may take place between the neural representations of ten-thousand picture elements than between the representations of a few points required to form a straight line. This might explain the small hysteresis effect obtained for lines, where only a few receptors are stimulated.

The problem of steady depth perception in spite of large and sudden disparity changes caused by vergence errors in normal vision can only partly be explained by hysteresis. We have shown that slow drifts of the order of a few min arc/sec can be adequately compensated by the labeling mechanism. On the other hand, the fast saccadic components of eye motion cannot all be compensated by this effect alone. The large differences between re-fusion for normal and stabilized vision (Figs. 8 and 9) show the importance of vergence motion of the eyes in compensating sudden errors. In the light of these results the fusional process depends at least on a convergence–divergence mechanism and on a cortical registration mechanism. The finding that random-dot stereo images can be re-fused for large shifts in normal vision (Fig. 9), without monocular form cues to assist convergence–divergence motions, indicates an intricate interrelationship between these two mechanisms.

CONCLUSIONS

The classical work on Panum's area gives a detailed account of the static aspects of stereopsis. Our experiments, in which the motions of the eyes are exactly tracked and the position of the stimulus is exactly controlled in both eyes extend this static view and emphasize the dynamic nature of binocular fusion. This changing fusional process allows for motion of objects in visual space, changes of fixation, body motions and spontaneous eye movements. Our findings suggest the existence of three different processes in stereopsis. A labeling process, which is operative in Panum's fusional region, establishes correlation between corresponding areas in the left and right images having various disparities. A cortical-registration process preserves these labels even if the left and right images are pulled apart on the retinas. In the case of random-dot stereoscopic images this pulling can be twenty times greater than Panum's fusional limit, provided that the pulling is not too fast. The third process consists of convergence motions of the eyes which compensate for large or rapid errors of disparity.

Our findings confirm that stereopsis depends greatly both on the class of stimulus used and on the history of the stimulation; therefore, stereopsis is a spatiotemporal process. If our research had been restricted to single-line stimuli, or if the convergence motions had not been controlled, many of the reported findings would have been missed. The labeling process together with the label-preserving process constitutes a phenomenon which may be a precursor of memory processes; its study may clarify how ordered states are stored in the visual system.