Vision Res. Vol. 16, pp. 535 to 543. Pergamon Press 1976. Printed in Great Britain.

THE FUSION ILLUSION[1,2]

Lloyd Kaufman and Aries Arditi
New York University, Department of Psychology, 6 Washington Place, New York, NY 10003, U.S.A.

(*Received* 24 *April* 1975; *in revised form* 20 *May* 1975)

Abstract—Four experiments were performed to test for the occurrence of perceived central fusion of vertically disparate stimuli. Two of these employed the method of Signal Detection Theory in order to measure the sensitivity of observers in discriminating disparate from non-disparate cyclofusional stimuli along the horizontal meridian. The other two experiments attempted to compare "fusion" thresholds with monocular control data. The fusion effect could not be differentiated from the limitations of monocular acuity. It was concluded that fusion is an illusion which may be attributed to the effects of suppression and failures of acuity.

When similar spatial contours are binocularly imaged at slightly disparate retinal places, the observer may report seeing but a single contour. This singleness of vision, which has come to be known as "fusion", occurs with transverse disparities of less than about 7′ of arc in central vision and may be accompanied by stereoscopic depth perception. Many theorists accept the notion that fusion, or a tendency towards fusion of disparate contours, is necessary to the occurrence of stereopsis. The fusion theories of stereopsis are described elsewhere (Kaufman, 1974).

Fusion of disparate contours also occur in the vertical retinal dimension. However, such vertical dimension fusion cannot of itself yield stereopsis. The magnitude of vertical disparity that may be fused is about 4′ of arc in central vision and may be larger with increased eccentricity (Mitchell, 1966).

The occurrence of fusion has suggested to some theorists that the spatial directions associated with retinal points are modifiable (e.g. Dodwell, 1970). Fusion, interpreted as a shifting of visual directions, would require theories of visual functioning quite different from theories which do not countenance such lability. The fact that vertically disparate contours may fuse provides investigators with an opportunity to study the fusional process without the complicating accompaniment of stereopsis.

In a typical study of fusion, Kertesz and Jones (1970) made use of the vertical disparities in stimuli such as those shown in Fig. 1a. Their careful measurements indicated that cyclorotational compensation does not occur with this stimulus. This is consistent with the results of Ogle and Ellerbrock (1946), who found that torsionally disparate contours oriented across the horizontal meridian provide relatively weak stimuli for cyclorotational compensation. Kertesz and Jones measured these eye movements with an accuracy of 0·25°, and found none even though observers "fused" lines tilted 2·5° from the horizontal. This implies the occurrence of a central cyclofusion of contours having a total angular disparity (θ in Fig. 1a) of about 5°. In a subsequent study Kertesz (1972) measured cyclorotational eye movements with an accuracy of about 1′ of arc. Despite the absence of such eye movements, total angular disparities of up to 13° were "fused". These results imply that there is a remapping of retinal points about the lines of sight of the two eyes in response to torsionally disparate lines along the horizontal meridian.

This remapping of retinal points is not unlike the displacement phenomenon reported long ago by Werner (1937). This displacement is a shifting in the visual direction to two laterally disparate elements so that the binocularly perceived element occupies a direction which is intermediate between the directions of the monocular elements when they are alternately viewed. Such displacement has been cited by Charnwood (1951) and by Sperling (1970) as symptomatic of the occurrence of central fusion. Von Tschermak

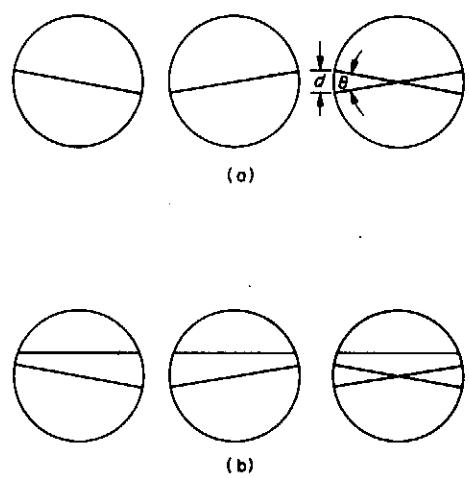

Fig. 1. (a) Typical cyclofusional stimulus. (b) Stimulus in Experiment 2.

[1] This research was supported by National Science Foundation Grant No. GB-36976. Lloyd Kaufman, Principal Investigator.

[2] *Editor's note*—Since this paper by Drs. Kaufman and Arditi deals so closely with the work of Dr. Kertesz, and raises considerable and important controversy, we have obtained an exchange of letters from these workers, and append them directly to this paper.

Seysenegg (1952) considered displacement (allelotropia) to be basic to the occurrence of stereopsis. Sperling (1970) and Werner (1937) believed that the magnitude of displacement is related to the magnitude of perceived depth. The finding of Kertesz that there is a cyclorotational form of displacement without eye movements is important evidence since previous critics of the displacement phenomenon have held that it is due to a disparity of fixation (Ogle, 1950; Pitblado, 1966; see Kaufman, 1974, for a review of displacement and of its criticisms).

In view of its theoretical importance, it is necessary to evaluate the concept of central cyclofusion. One factor which must be considered is whether or not the report of "fusion" is based upon a precise and unique criterion. In the experiments by Kertesz and his associates (Kertesz and Jones, 1970; Kertesz, 1972; Kertesz and Optican, 1974; Sullivan and Kertesz, 1975), observers merely reported the occurrence of "fusion". It is therefore impossible from the published experiments to determine precisely what was meant by "fusion" although we can make some plausible assumptions.

For one thing, "fusion" probably entails that the fused binocular line is perceived as single. This would follow from the assumption of Kertesz that meridionally disoriented disparate lines cause retinal points to be remapped as though the eyes had actually counter-rotated to get the lines on corresponding retinal places. It is also consistent with the widespread assumption that, in general, fused disparate lines appear as single.

Secondly, it is also implied in the papers by Kertesz and his associates that the perceived binocular line is experienced as being horizontal. This is implicit in the figure published by Wright and Kertesz (1975) which shows renditions of the "appearance" of fused stimuli. It is also consistent with the statements of other theorists (e.g. Werner, 1937) who hold that fused images are perceived as being at an intermediate lateral position relative to the positions of the half-image when seen separately—hence the term "displacement".

The third criterion occasionally employed by Kertesz is the occurrence of apparent movement of one half-images when one eye's view is occluded. This movement is sort of springing back into position of a previously "fused" line.

Each of these criteria is subject to criticism. Singleness of vision, for example, could be atributed to suppression. Many theorists (e.g. Verhoeff, 1935; Asher, 1953; Hochberg, 1964) have suggested that the reason why one does not always see double images is because one of these images is suppressed. Crossed binocular lines are in fact very good stimuli for inducing binocular rivalry since suppression spreads from the point of intersection of contours over distances which may be as large as several degrees of arc (Kaufman, 1963).

The criterion of horizontality is also not a unique determinant of fusion. A line perceived in isolation and tilted but a few degrees from the actual horizontal may not be discriminably different from what the observer thinks the horizontal may be. Unless he can compare the "fused" line with an actual horizontal line, the observer could be mistaken in his judgement of horizontality.

The criterion of movement is also not conclusive. If one or both lines are partly suppressed by binocular rivalry, then the occlusion of one eye could easily lead to the impression of apparent movement.

Finally, since the criteria to be employed by the subject were never explicitly stated, it is conceivable that he may have been trying to utilize multiple criteria in his judgement. Under some circumstances this could make discrimination tasks very difficult to perform. Thus, the appearance of "fusion" could well have been due to a failure to discriminate between a situation in which lines were on disoriented retinal meridians and the idea the subject may have had in his mind about the appearance of a line which was in fact imaged at corresponding horizontal retinal meridians.

All of these, and other considerations to be mentioned later, led us to the notion that a proper test for the occurrence of central fusion would allow an observer to compare disoriented lines such as those employed by Kertesz with identical lines having no disparity. If it is correct that central cyclofusion results in the perception of a single horizontal line, then such a fused line should not be discriminably different from a stimulus in which the same lines are not tilted at all. If such discrimination can be made then we must say either that "fused" disparate lines differ monocularly in some as yet undefined way from other "fused" lines falling on corresponding retinal meridians, or that fusion (construed to be the result of displacement) may not even exist. We shall return to these possibilities after describing some experiments in which the capacity to discriminate between such stimuli was studied.

EXPERIMENT 1

This first experiment employed the methods of Signal Detection Theory (Green and Swets, 1966) to determine the sensitivity of observers to differences between two stimuli which were exactly alike except that in one case the tilted lines (as in Fig. 1a) had a small total angular disparity and, in the second case, the total angular disparity was zero. Thus, the observer was required to discriminate "centrally fused" disparate lines from "binocularly superimposed" non-disparate lines.

Method

The stimuli used in this experiment were similar to those illustrated in Fig. 1a except that a small fixation point was provided at the intersection of the binocular lines. The stimuli were produced by a function generator (Wavetek Model 116) which supplied sinusoidal waveforms (1 kHz) to the X axes of two oscilloscopes (Tektronix 5103). The same waveforms were applied to the Y axes of the two oscilloscopes. The resulting Lissajou patterns were straight lines whose slopes were determined by the ratio of gains of the X and Y amplifiers. The X axis gain was kept constant. For two observers the Y axis was 1/80th that of the X axis and, for a third observer, it was 1/70th that of the X axis. When stereoscopically viewed the total angular disparity (θ) of the stimuli provided to two observers was 1·43° and 1·64° for the third observer. These total angular disparities are much smaller than the values at which "fusion" occurred in Kertesz' threshold experiments to be reported below. Thus, these stimuli would, if seen alone, be reported as fused.

The disparate stimuli described above were to be discriminated from the same stimuli having a zero disparity. This was accomplished simply by removing the signals to the *Y* axes of the oscilloscopes.

The oscilloscope screens were placed 42 in. from the eye and at right angles to each other and their images superimposed in a partially silvered mirror. Since the image from one oscilloscope was seen as a reflection in the beam splitter, the tilted line was equal and opposite in orientation to the tilted line viewed directly through the beam splitter, thus producing optically superimposed lines similar to those illustrated in Fig. 1a. Both oscilloscopes were covered with polarizing filters oriented 90° out of phase. With his forehead placed firmly against a rest, the observer viewed the optically superimposed images through polarizing filters oriented so that one eye saw one oscilloscope screen and the other eye the other oscilloscope screen. The screens were viewed in a totally dark room and the fixation point was visible as a dark spot at the intersection of the dichoptic lines.

The two lines in the display were arranged so that they would intersect exactly at their centers. This was done with the polarizers removed from the apparatus. With the polarizers back in place the dark adapted observer viewed the oscilloscope screens one eye at a time through a neutral density filter which attenuated light by 2 log units. The intensity of the viewed oscilloscope screen was adjusted until the threshold for detection of the line was found. This was done independently for each eye and then the filter was removed so that the subject could compare the alternately viewed stimuli to insure that they had equal apparent luminance. Thus, the luminances of the two lines were set so that they would each be 2 log units above threshold.

The experiment consisted of a total of 100 trials. On 50 of these trials the observer was presented with lines tilted so that they has a small total angular disparity. These trials were called "signal trials". The lines used in the other 50 trials were not tilted. These lines were both horizontal and with bifoveal fixation maintained on a fixation point, they were imaged on corresponding horizontal retinal meridians, i.e. they had no disparity. Trials on which these lines were presented are called "noise trials". The noise and signal trials were intermixed to form a random sequence. The subject responded to each trial with a number, from 1 to 5, to indicate his judgement as to whether he had seen a "signal" stimulus or a "noise" stimulus and his confidence in that judgement.

All trials had a duration of 700 msec and were separated from each other by a period of from 5 to 10 sec. The observer was instructed to maintain a fixation on a central fixation point which was aligned with the center of the 2·1° dia visual display. Between trials this fixation point was superimposed on small brilliant points of light located exactly on the centers of both displays. When fixation was achieved the observer actuated a switch which caused the stimulus lines to replace the points of light in the displays.

Fixation was aided by the small brilliant binocular luminous spots present at the fixation point between trials because of the formation of an after-image which was easily kept in line with the fixation point during the 700 msec period of a trial.

Two of the observers used in this experiment were the authors of this paper. The third observer was totally naive as to the purpose of the experiment.[3]

[3] For the naive observer JB in Experiment I, the fixation point consisted of small circles which bisected the lines in each half-image. These were also generated as Lissajou patterns. Care was taken to insure that the stimulus lines transversed the diameters of these small circles.

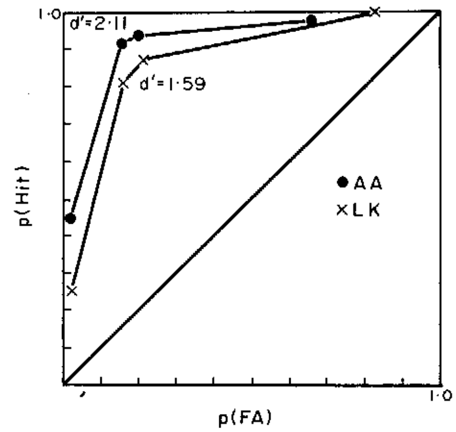

Fig. 2. ROC curves for Experiment 1.

Results

The results of the experiment are very clear. Two observers, JB and AA were able to discriminate between the signal and noise trials with $d' = 0{\cdot}61$ for JB and $d' = 2{\cdot}11$ for AA. Both of these subjects were required to discriminate between disparate lines having a total angular disparity of 1·43° and non-disparate horizontal lines. The third subject, LK, was able to discriminate between the lines with $d' = 1{\cdot}59$. The ROC curves shown in Fig. 2 are from the data obtained from observers AA and LK. They are approximately symmetrical and indicate that the assumptions of Signal Detection Theory were reasonably satisfied. Observer JB used only two of the five available categories of judgement, "2" and "4", and therefore did not provide sufficient information for the construction of the ROC curve. Yet the data do show that he is able to make the discrimination. Thus, all of our observers could discriminate total angular disparities that are at least as small as the values used in the experiment.

Using stimuli similar to those employed here, Kertesz and Jones found the threshold of fusion to correspond to total angular disparities of about 5°. The fact that our observers were sensitive to much smaller total angular disparities indicates that the method of limits used to measure such thresholds is not sufficiently sensitive. Signal detection methods, on the other hand, establish that observers are far more sensitive to small disparities than would be indicated by Kertesz' data.

To obtain some idea of the actual retinal disparities involved in these experiments it would be well to reconsider the fact that the total angular disparity (θ) is independent of the viewing distance of the observer and also of the lengths of the lines employed. The actual retinal disparity between the end-points of the lines (*d* in Fig. 1a), however, is dependent upon both the viewing distance and the lengths of the lines. This vertical disparity in the Kertesz stimulus which was fused with a total angular disparity of 5° was about 29′ of arc. In our stimulus with the total angular disparity of 1·43°, the actual maximum retinal disparity was about 1·53′ of arc. The stimulus having a total angular disparity of 1·64° had an actual disparity measured at the ends of the lines of 1·76′ of arc. These values are the maximum actual vertical retinal disparities in the displays. All other vertical disparities are smaller the closer they are to the intersections of the two lines, where the disparity is zero. These tiny vertical disparities are not much larger than the limitations of monocular resolution.

This experiment shows that the human observer can discriminate between stimuli having very tiny vertical disparities and stimuli which have no vertical disparities. Such discrimination should not be possible if the retinal points are remapped as a result of central cyclofusion.

EXPERIMENT 2

This second experiment was designed to test the hypothesis that even finer discrimination of disparities can be made if the observer has available horizontal reference lines in the field of view while he is attempting to detect disparate stimuli. Such a stimulus is illustrated in Fig. 1b which contains tilted lines similar to those of Fig. 1a and, 0·5° of arc above them, a pair of horizontal lines. If an observer is asked to fixate a point located at the centers of the tilted lines and to report when the fixated lines appear to be different in doubleness, straightness or orientation from the nearby horizontal lines, then he should be able to do this more accurately than he could if the reference horizontal lines were not present. Thus, on half of the trials the truly horizontal lines were presented and on the other half, slightly tilted lines were presented. The observer was required to say if the presented lines differed in any of these ways from the reference line. Otherwise the procedure was identical to that of Experiment 1. The test stimuli were also identical, i.e. two subjects were exposed to total angular disparity of 1·43° and one observer to a total angular disparity of 1·64°.

Results

Observer JB was able to discriminate disparate from non-disparate lines ($\theta = 1{\cdot}43°$) with $d' = 2{\cdot}25$. Observer AA had an infinite d' when required to make the same discrimination, i.e. his false alarm rate dropped to zero. Observer LK, however, made the discrimination with $d' = 1{\cdot}00$ when the value of θ was 1·64°.

It could well be that the decline in d' for observer LK was due to a practice effect since this experiment was actually performed prior to Experiment 1. Since observers AA and JB also were used first in Experiment 2 and exhibited greater sensitivity with the presence of a comparison line the results are supportive of our hypothesis.

One argument which may be raised here, is connected with the findings of Sullivan and Kertesz (1975) who identified a phenomenon knows as "effort of fusion". They found that if two half-fields are "fused" then simultaneously presented horizontal lines will appear as double. This suggests that the fusion of angularly disparate lines results in a remapping of the entirety of both retinals so that the horizontal axes are functionally no longer horizontal. If this were true our horizontal line could become apparently disparate whenever the observer fuses actually disparate or tilted lines. This could make the discrimination easier to perform. It should be noted, however, that none of our observers ever reported seeing a tilting or distorting of the horizontal reference line which was located about 0·51° above the test lines.

In both Experiments 1 and 2 the observers were aware of the fact that correct detections of the signal stimuli were associated with clear perception of doubling, tilting, or distortion of the test line. These phenomena would be evidence against the proposition that our results were due to the detection of some hypothetical "effort of fusion".

EXPERIMENT 3

In this third experiment we utilized the threshold technique to study central cyclofusion. One motivation in reporting this experiment is to show that with the threshold technique it is possible with our apparatus to obtain results comparable to those obtained by Kertesz and his associates. A second motivation is to illustrate how the addition of a comparison line similar to that employed in Experiment 2 will also serve to lower the "fusion" threshold even when the method of limits is employed. Finally, in this experiment we compare directly monocular acuity for differences between the horizontal comparison line and the tilted test line using the same psychophysical method.

Method

The apparatus used in this experiment was identical to that employed in the previous experiments with the following differences: The voltage applied to the Y axes of the two oscilloscopes was adjusted continuously by the experimenter in the increasing or decreasing direction until the observer reported either the occurrence of "fusion" or its disruption. Thus, during an experimental trial the signals applied to the Y axes were reduced slowly, thereby reducing the tilt of the test lines. The observer reported when he could no longer perceive a difference between the test line and what he believed a single horizontal test line would look like. When the comparison line was present he reported when he could no longer discriminate the difference between the test line and the comparison line. After recording the Y axis voltage (as indicated by a Ballantine true r.m.s. meter) the experimenter then gradually increased the voltage until the subject reported that he could detect a difference. This procedure was repeated a total of 10 times in each direction.

Four observers served as subjects in this experiment. The two sophisticated observers were exposed to three viewing conditions while the two naive observers, GP and FB, were, in addition, exposed to a condition similar to that employed by Kertesz and Jones, i.e. no comparison line was present. The major difference between this stimulus and the one employed in Kertesz' experiments and in our Experiment 1 is that no fixation point was employed. All observers were free to scan along the lengths of the test lines which were about 2·1° of arc in length. We shall discuss the possible problems created by this departure in procedure later.

The same naive observers and the authors of the paper served as observers in another condition in which the comparison line was present (Fig. 1b). Again, no fixation point was employed, in part because we wanted the observers to be free to look back and forth between the test and comparison lines. It was assumed that if the test lines were fused so that they appeared to be identical to non-disparate comparison lines, then this should be revealed when an observer viewed both lines under identical conditions.

Finally, all four observers viewed each half-field monocularly. In the two monocular conditions the observers viewed the oscilloscope screens as before but the images were absent from one screen or the other. In both monocular conditions the test and comparison lines of a given half-field were present and the observer had to respond when he could see no difference between the two or when he could just detect a difference, depending upon the direction of change of the angle of tilt. In the monocular conditions the thresholds for differences in tilt were measured. In the binocular condition with the reference line the observers were responding in terms of any perceived differences between the reference and test lines. In the binocular condition without the reference line the observers were merely instructed to report when the isolated test line appeared as single and horizontal, or when it no longer appeared to be single or horizontal.

All observers were also given a crude test for eye dominance. In this test they were required to read letters when different matrices of letters were presented to the two eyes in a stereoscope. If an observer had a pronounced tendency to read the letters in one eye's half-field it was agreed that that eye was dominant.

Finally, it should be noted that in this experiment the room was dimly illuminated as compared with the totally dark room of the first two experiments reported here. The reason for this was that we wanted a visual framework available so that the observer would be more likely to maintain the correct vergence for the 42-in. distance of the display. It was assumed that the visible peripheral framework would serve to anchor the fixation distance.

Results

Before turning to the results of the experiment itself it is important that we report on the eye dominances of the subjects.

One subject, FB exhibited no pronounced dominance since he read equal numbers of letters from each eye's view. It is worth noting that this subject reported himself to be a recovered strabsimus patient who, as a child, had corrective surgery and orthoptic treatments. He has good stereo acuity as evidenced in his service in other experiments. Moreover, FB has a high degree of voluntary oculomotor control since he can noticeably converge or diverge at will even when visual stimuli are ignored. Subject LK was pronouncedly right-eye dominant. Subjects AA and GP were both strongly left-eye dominant. All had good stereopsis.

The results of this experiment are summarized in Table 1 which contains the mean values of $\theta/2$, where θ is the total angular disparity at which fusion is achieved. The values of $\theta/2$ are employed so that we might compare the monocular and binocular results. Also provided are the standard deviations (S.D.) about each threshold value.

The threshold total angular disparity for subject GP when he viewed the simple stimulus lacking the reference line was 5·13°. This result is comparable to the results reported by Kertesz for this type of stimulus. Similarly, the corresponding threshold for FB was 4·27°, a value which is also commensurate with the range of those found in the earlier experiments. Thus, the fact that a fixation point was not employed or that the experimental area was illuminated did not result in a threshold less than that found by Kertesz who used both a fixation point and a visually isolated stimulus.

When a reference line was present observer GP had a significantly smaller threshold ($P < 0{\cdot}01$, $t = 3{\cdot}20$) than when the reference line was absent. Although observer FB's threshold was also smaller with the reference line present, the magnitude of the difference was not statistically significant. Perhaps, the presence of the reference line can help some observers make the discrimination in a threshold experiment but it may not help other more experienced observers. In any event, all threshold values obtained without the reference line and with the reference line are substantially larger than were the total angular disparities detected by the observers who used the discrimination method of Experiment 1. It should be further noted that AA and LK who served in the first two experiments, demonstrated "fusion" at total angular disparities which were close in size to the disparities they could easily detect as not fused in Experiment 2.

The comparison of the thresholds obtained binocularly and monocularly with the reference line is particularly interesting. Observer GP and AA are both strongly left-eye dominant by the rivalry test. Monocular data obtained with their left eyes is comparable to their binocular data. The differences between these data are not statistically significant. Observer LK is strongly right-eye dominant and his right eye's data is comparable to his binocular data.

Observer FB is the only one of four observers who gave evidence for fusion. The left eye's monocular threshold is significantly less than the binocular threshold ($P < 0{\cdot}01$, $t = 5{\cdot}488$) and the right eye's threshold is also significantly smaller than the binocular threshold ($P < 0{\cdot}05$, $t = 2{\cdot}808$). The actual difference between his average monocular performance and his binocular performance is 0·96° Since this is half the total angular disparity, FB may have been capable of fusing a total angular disparity of as much as about 2°. This corresponds to a maximum disparity of 2·14′ of arc. In view of the fact established in Experiment 1 that an observer's criterion can affect a judgement such as this, it is plausible to assume that FB could have given us these same results merely because he utilized a different criterion in the monocular case as compared with the binocular case. Thus, the "fu-

Table 1. Mean thresholds and standard deviations (S.D.) of "central cyclofusion" ($\theta/2$)

Condition Observer	Binoc. and no ref. line		Binoc. and Ref. line		Monoc. LE		Monoc. RE	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
GP	2.565°	0.241°	1.339°	0.189°	1.115°	0.065°	0.870°	0.160°
FB	2.135°	0.084°	1.985°	0.203°	0.865°	0.274°	1.185°	0.168°
LK			0.689°	0.148°	1.128°	0.193°	0.636°	0.145°
AA			1.002°	0.095°	0.928°	0.134°	0.752°	0.059°

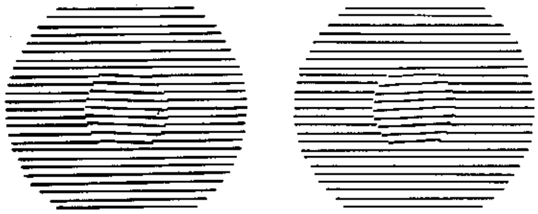

Fig. 3. See text (after Kertesz and Optican, 1974).

Table 2. Mean thresholds for "fusion" with identical (binoptic) stimuli for the two eyes and for disparate (dichoptic) stimuli in seconds of arc

Observer	Dichoptic threshold	Binoptic threshold
FB	28.26"	23.35"
LK	39.79"	39.79"
AA	21.91"	20.26"

sion" measured here must remain suspect. We are now investigating the relation between monocular and binocular judgemental criteria.

EXPERIMENT 4

Kertesz and Optican (1974) utilized a stimulus similar to the one shown in Fig. 3. While they did not explicitly define the criterion of fusion that their subjects were to employ in this experiment, they did indicate in a figure that the fused product of binocularly viewing the stereogram should look like a set of unbroken uniform horizontal lines. While vernier acuity is extraordinarily precise, and should serve as a monocular cue indicating that the inner region of the binocularly viewed display is segregated from the outer region, these authors proposed in their figure that fusion can overcome this cue and produce the impression of a fully uniform intermediate image. Because of the report of such fusion by Kertesz and Optican we decided to utilize the essential features of their stimulus in a configuration that would allow our observers to utilize as simple a criterion as is possible in estimating the point of fusion. This also allowed us to further test subject FB who gave us some indication of the occurrence of central fusion in Experiment 3.

Method

The stimuli used in this experiment are depicted in Fig. 4. It will be observed that if the tilted lines on the right side of this stereogram were to fuse at an intermediate position, then the fused binocular line would be horizontal and continuous with the horizontal line on the left side of the stereogram. If fixation were at the centers of the tilted lines on the right side of the stereogram, then its fusion could be called "central cyclofusion". However, with fixation elsewhere along the length of the line on the right, then fusion would simply be a fusion of the vertically disparate lines. In both cases the end result should be the same, i.e. as Kertesz and Optican demonstrate, fusion would result in the perception of a single, uniform horizontal line.

In this experiment three observers, FB, LK and AA diverged or converged their eyes to binocularly superimpose the half-images of the stereogram which were mounted on the wall of an illuminated corridor. FB and AA could do this easily but LK required the assistance of a base-in prism before one eye.

Having superimposed the stimuli, the observers were required to walk backwards away from the wall until they reached the point where the discontinuity could not be discriminated. The observer then walked toward and away from the wall several times until an average threshold distance was achieved. This same procedure was repeated when both of the observers eyes were fixated on but one of the half-fields. This provided basic acuity control data since, by hypothesis, fusion should result in perceiving a uniform horizontal line at a shorter distance from the stimulus than would be obtained if simple acuity were being measured alone.

The same procedures were repeated for observers AA and LK except that nonius markers were added to the stimuli. These markers were placed so that their vertical alignment would result in the centers of fixation being located at the centers of rotation of the tilted lines. Fusion in this case could be termed "cyclofusion".

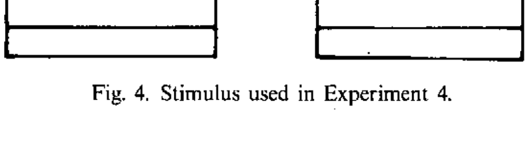

Fig. 4. Stimulus used in Experiment 4.

Results

The results of the experiment in which the nonius markers were absent are summarized in Table 2. It will be observed that these results are given in seconds of arc. The variability in the data was so minute that it does not warrant presentation. There were no theoretically significant differences between the experimental data and the control data, i.e. binocular fusion did not produce a lesser acuity for the differences between the left and right half-fields than can be predicted by basic acuity data alone.

When a nonius marker was employed observer AA had a "fusion threshold" of 26·86′ of arc. His acuity was essentially the same. Observer LK had a fusion threshold of 52′ of arc and an acuity of 53·7′ of arc. These somewhat larger values can be accounted for by the fact that the discontinuity in the line was localized somewhat peripherally when the nonius was used. Otherwise, the conclusion is the same, i.e. no fusion was evidenced in this experiment.

It could be argued with some justice that the discontinuity in the line stimulus employed in Experiment 4 is a strong monocular cue. If this cue could be processed in a channel that is parallel to the one in which binocular fusion occurs, then it would not be surprising that no evidence for fusion was found in this experiment. This same reasoning led us to reject an experiment in which we instantaneously reversed the half-images of Fig. 1a so that the line shown to the left eye was abruptly shown to the right eye while the line that had been shown to the right eye was then shown to the left eye. This was done where the disparities were half the values at which the "fusion" was measured in the same observer. All four observers detected the movement of the tilted lines when the switching occurred. This movement could not have occurred if the tilted lines were images on remapped horizontal retinal meridians since all the lines had a horizontal character, i.e. they were effectively on corresponding retinal places. However, as pointed out above, this interpretation is not conclusive because movement and binocular integration may be implemented in independent channels. The only reason for including Experiment 4 is that Kertesz and Optican had in fact performed an experiment in which similar discontinuities were purportedly overcome as a result of fusion. Now, either this occurred or it did not occur. Our evidence suggests that when such stimuli are pared down to their essentials then such an effect does not occur. It may well be that complicated stimuli containing many line elements do produce such effects but *ad hoc* hypotheses about complexity would then be required to rationalize the conflicting data.

DISCUSSION

The lack of fusion in the data of Experiment 4 is largely supported by our other experiments. Probably the most compelling experiment is the first one reported here. It is evident from this experiment that observers are capable of discriminating very slightly disparate lines, having a maximum vertical position disparity of about 1·5′ of arc, from similar lines having no disparity at all. These different sets of lines were presented at different times. It is therefore not possible to criticize this experiment in terms of the presence of a hypothetical difference between the two sets of stimuli simultaneously present in Experiment 2. Thus, nearly horizontal lines, seen in isolation and seen slightly tilted away from each other torsionally, are discriminably different from similar lines not so disoriented, even though the same lines would be adjudged to be fused in cruder threshold measuring experiments typified by our Experiment 3. It should be noted that the observers were free to scan the stimuli in Experiment 3 and would therefore be likely to have a lower threshold than would be expected with controlled fixation.

The simultaneous presence of a horizontal line with the test line in Experiments 2 and 3 can be criticized from the point of view of the fusional effort concept, i.e. fusion of one line leads to the doubling of the other. It should be noted, however, that so-called competing cues are always present in natural scenes in which many different disparities are always simultaneously present. Yet it is in such situations that problems arise which require theorists to postulate mechanisms like fusion. Most people do not recognize many of the double images which geometry tells us should be present in natural three dimensional scenes. It was this failure of the appearance of double images which led to the postulation of fusional areas and of the projection field of fusion theories. Thus, in anticipation of the possible criticism that our observers detected "fusional effort" rather than actual disparities between test and comparison stimuli, it is unreasonable to assert that simultaneous fusion of images with disparities of different magnitudes and of different directions does not occur, i.e. "fusional effort" occurs instead. If fusional theories are to be viable and relevant to binocular stereopsis (and this, after all, is the fundamental motive for the study of central fusion), then one had best accept the notion that such simultaneous fusion is implied by theories of fusion. If this is accepted then it is difficult to understand how "fusion" of the horizontal reference line in Fig. 1b and "fusion" of the test line in the same figure could not occur simultaneously. If such is the case, then there should be no discriminable difference between the lines when they both have disparities smaller than the so-called fusion thresholds.[4] Yet, as we have seen, at least some subjects find it easier to distinguish disparate lines from non-disparate lines when a reference stimulus is present. Of course, by itself this result would have to be viewed circumspectly because of hypothetical monocular factors to which an observer might respond independently. However, since experiments were also performed where these monocular factors were absent, the total picture is one in which fusion appears to either play no role at all or a very limited role in binocular vision.

From whence, then, does the prevalent belief in fusion arise? It has been known for at least 100 yr that fusion is not necessary for stereopsis. Helmholtz (1925), an acute observer if there ever was one, did not believe in the existence of fusion at all. Experiments by Ogle (1950) showed that it is possible to achieve valid and accurate depth perception even when double images are visible. Kaufman (1964) showed that the images in the two eyes need not be alike for stereopsis and that stereopsis can occur in the presence of patent binocular rivalry. This result was obtained by Mitchell (1970) using simpler stimuli, who also found that such "unfusable" stimuli can even initiate correct vergence changes. Yet somehow the notion of fusion and its role in stereopsis has continued to play an important role in the development of theories of binocular vision.

The very idea that the visual directions associated with retinal points are extremely flexible, e.g. fusion of total angular disparities larger than 13°, is somewhat disconcerting. It is disconcerting because we know that it is extraordinarily hard to prove that wearing a displacing prism for many hours produces more than a very small change in visual direction, as in the Gibson (1933) curvature after effect. It is doubtful if larger changes in perception due to wearing a prism are primarily visual in character at all (Harris, 1965). Yet we are ready to believe that large changes in visual direction associated with retinal points in one eye can be elicited in an instant merely by placing a disparate image in the other eye.

Such a belief is supported in some degree by observation. Classic works on perception (e.g. Boring, 1933) refer to the "fact" that the binocular object resulting from the "fusion" of the half-images of the object is unique and not simply one or the other of the half-images. Tilted lines similar to those used in our experiments and by Kertesz often appear to be "different" from the mere sum of the two optical images. Also, the stereogram published by Linschoten (in Dodwell, 1970) and reproduced in Fig. 5a has been cited as an example of the effectiveness of fusion in changing

[4] Indeed, even the simple stimuli of Fig. 1a contain a continuum of retinal disparities which vary systematically with spatial extent.

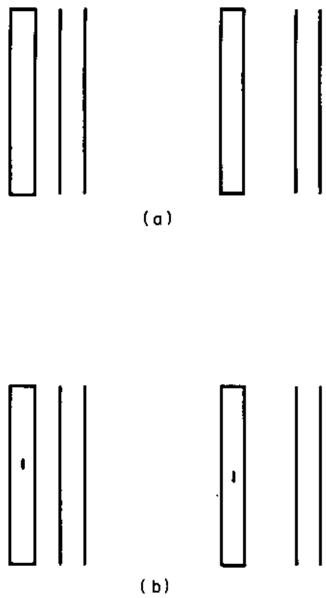

Fig. 5. The Linschoten figure.

the visual directions of lines. Rather than seeing three lines to the right of the rectangle when the rectangle is fixated, one reports seeing but two lines. This was taken by Dodwell (1970) to mean that the directions to these lines have shifted to get them onto functionally corresponding retinal places.

Electrophysiological data (Hubel and Weisel, 1970; Barlow, Blakemore and Pettigrew, 1967) also indicate that disparate images can excite common cells in the cortex and that different disparities result in the excitation of different cells. With regard to the electrophysiological data, it is evident that one cannot make strong assertions about global perceptual processes from microscopic physiological data. Such disparity detection does indeed exist but it is not proven that it is accompanied by perceptual fusion. One must distinguish between the physiological mechanisms that may be involved in the computation of depth and the subjective phenomena of fusion and doubleness of vision. Since depth may be perceived with double vision, it is obvious that disparity detection may occur in the absence of apparent fusion. If by the term "fusion" one means a physiological correlate of disparity, these phenomena should not be confused with perceptual fusion. The important point of contention here is that of the existence and meaning of sensory or perceptual fusion without compensating eye movements.

The Linschoten experiment can be understood when nonius markers are added to the stimulus, as in Fig. 5b. These markers make it evident that even when an observer thinks he is fusing the rectangles at corresponding retinal places he is in fact not doing so. The disparity of fixation which results from not fixating at the proper distance is responsible for the perception of two and not three lines. With precise alignment of the rectangles observers can see the three lines.

Disparity of fixation was cited by Ogle (1950) as the basis for another displacement phenomenon known as the Hoefer effect. He was found to be correct by Pitblado (1966) who also found displacement in Wheatstone stereograms to be due to fixation disparity. The direction and magnitude of depth in these stereograms had no relation whatever to the direction and magnitude of displacement. This is directly counter to the assertions of Werner (1937) and other proponents of the fusion theory. Also, Gestalt psychologists held that fusion is literally the result of an attractive force between disparate elements (Koffka, 1935). This force results in the fusing of the disparate half-images at a new place in depth. The amount of depth is related to the magnitude of the attractive force. This places most fusion theorists in an uncomfortable alliance with the Gestalt psychologists. The attribution of such fusion phenomena to fixation disparity served the useful role of providing an alternative to the proposition that visual directions associated with retinal points are extremely labile, even though such lability is not needed for anything we know about, e.g. depth occurs without fusion. Kertesz' contribution is that he is the first to demonstrate the possible existence of central fusion without any kind of fixation disparity.

We are proposing that Kertesz' results are an artifact of confusion and not a product of fusion. Our data indicate that results similar to those of Kertesz can be obtained when the relatively crude threshold method is employed. The more sensitive discrimination method yields quite different results; thus suggesting that fusion is due not to a failure of the subject to resolve disparities but to a failure of the method employed in its study to be sensitive enough to pick up the phenomenon in question. We are not arguing with Kertesz' eye movement data but with his psychophysics. We are also arguing against the prevailing uncritical acceptance of the concept of fusion, which, as scientists, we should recognize is badly in need of adequate definition.

REFERENCES

Asher H. (1953) Suppression theory of binocular vision. *Br. J. Ophth.* **37**, 37–49.

Barlow H. B., Blakemore C. and Pettigrew J. D. (1967) The neural mechanism of binocular depth discrimination. *J. Physiol.* **193**, 327–342.

Boring E. G. (1933) *The Physical Dimensions of Consciousness.* Century, New York.

Charnwood J. R. B. (1951) *Essay on Binocular Vision.* Halton, London.

Dodwell P. C. (1970) *Visual Pattern Recognition.* Holt, Rinehart & Winston, New York.

Gibson J. J. (1933) Adaptation after-effect and contrast in perception of curved lines. *J. exp. Psychol.* **16**, 1–31.

Green D. M. and Swets J. A. (1960) *Signal Detection Theory and Psychophysics.* Wiley, New York.

Harris C. S. (1965) Perceptual adaptation to inverted, reversed, and displaced vision. *Psychol. Rev.* **24**, 81–90.

Helmholtz H. von (1925) *Treatise on Physiological Optics* (Translated from the 3rd German edition (Edited by Southall J. P. C.). Opt. Soc. Amer. Republished Dover, New York, 1962.

Hochberg J. E. (1964) Contralateral suppressive fields of binocular combination. *Psychonom. Sci.* **1**, 157–158.

Hubel D. and Wiesel T. N. (1970) Stereoscopic vision in macaque monkey. *Nature, Lond.* **225**, 41–42.

Kaufman L. (1963) On the spread of suppression and binocular rivalry. *Vision Res.* **3**, 401–415.
Kaufman L. (1964) On the nature of binocular disparity. *Am. J. Psychol.* **77**, 398–401.
Kaufman L. (1974) *Sight and Mind.* Oxford Univ. Press, New York.
Kertesz A. E. and Jones R. W. (1970) Human cyclofusion response. *Vision Res.* **10**, 891–896.
Kertesz A. (1972) The effect of stimulus complexity on human cyclofusional response. *Vision Res.* **12**, 699–704.
Kertesz A. E. and Optican L. M. (1974) Interactions between neighboring retinal regions during the fusional response. *Vision Res.* **14**, 339–343.
Koffka K. (1935) *Principles of Gestalt Psychology.* Harcourt Brace, New York.
Mitchell D. E. (1966) A review of the concept of Panum's fusional areas, *Am. J. Ophth.* **43**, 387–401.
Mitchell D. E. (1970) Properties of stimuli eliciting vergence eye movements and stereopsis. *Vision Res.* **10**, 145–162.
Ogle K. N. (1950) *Researches in Binocular Vision.* Saunders, Philadelphia.
Ogle K. N. (1953) Precision and validity of stereoscopic depth perception from double images. *J. opt. Soc. Am.* **43**, 906–913.
Ogle K. N. and Ellerbrock V. J. (1946) Cyclofusional movements. *Archs Ophth.* **36**, 700–735.
Pitblado C. B. (1966) Displacement of half-images during binocular viewing. Ph.D. dissertation, Boston Univ.
Sperling G. (1970) Binocular vision: a physical and neural theory. *Am. J. Psychol.* **83**, 461–534.
Sullivan M. J. and Kertesz A. E. (1975) The nature of fusional effort in diplopic regions. *Vision Res.* **15**, 79–84.
Tschermak-Sysenegg A. von (1952) *Introduction to Physiological Optics* (Trans. by Boeder P.). C. C. Thomas, Springfield, Ill.
Verhoeff F. H. (1935) A new theory of binocular vision. *Archs Ophth.* **13**, 151–175.
Werner H. (1937) Dynamics in binocular depth perception. *Psychol. Monogr.* 218 (whole No.).
Wright J. C. and Kertesz A. E. (1975) The role of positional and orientational disparity cues in human fusional response. *Vision Res.* **15**, 427–430.