

HYSTERESIS IN HUMAN BINOCULAR FUSION: A SECOND LOOK

Thesis by
Daniel Bruce Diner

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DEDICATION

To Derek,

who put me on feet

I didn't know I had,

and

to Tina,

had you lived but six weeks longer,

you would have seen

this dream

come true.

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The work of this thesis was performed during my years as a graduate student in the Bioinformation Systems option at Caltech. I had the good fortune to work under the guidance of Professor Derek Henry Fender, a man who has won my trust, admiration, and love. Derek taught me a most valuable lesson: to use my freedom wisely.

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ABSTRACT

A study of hysteresis in human binocular fusional ranges had been performed in order to clarify the nature of the extension of Panum's Fusional Area as demonstrated by Derek Fender and Bela Julesz (1967).

Using binocular retinally stabilized images, a stimulus regime was designed to determine the size and location of Panum's Fusional Area at any given stimulus condition. This regime was employed to measure Panum's fusional area in the non-extended and in the extended conditions.

The following three results were obtained.

1. The nasalward limits of Panum's fusional area and the hysteresis demonstrated by the nasalward limits do not differ significantly from the temporalward limits of Panum's fusional area and the hysteresis demonstrated by the temporalward limits.

2. A non-transient (continually presented) stimulus will fuse over a significantly wider range with a transient (flashed) stimulus than with another non-transient stimulus. Furthermore, the range of fusion for the transient stimulus is dependent upon the non-transient stimuli that are present immediately before the transient stimulus is presented.

3. The extension of Panum's fusional area, as effected by the stimulus regime of this thesis, not only includes the recruitment of retinal locations into Panum's fusional area which are not normally in Panum's fusional area, but also includes the loss from Panum's fusional area of certain retinal locations which are normally within Panum's fusional area. For all subjects, Panum's fusional area is

shifted significantly. For some subjects, Panum's fusional area is stretched significantly. In some situations, the "zero disparity" retinal location may be lost from, and therefore not included within, Panum's fusional area.

A new definition of "corresponding retinal points" is developed from the results of this thesis.

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I. INTRODUCTION

It has been known since the mid 1800's (Wheatstone, 1838; Dove, 1841; Panum, 1858) that exact alignment of the visual axes is not necessary for single binocular perception. In other words, for a stimulus projected upon any particular location of one retina, there exists a corresponding region on the second retina, such that, when an identical stimulus is projected upon that region, the two stimuli will be perceived as one.

When this occurs, one says the two monocular images are fused into a single binocular percept. The region on the second retina over which fusion is possible for a particular location on the first retina is called Panum's fusional area. Thus, Panum's fusional area is a function of a retinal location.

For every point on each retina, there exists a Panum's fusional area on the other retina. Thus, there exists a region in space over which fusion is possible. The line through the angular center of this region is called the horopter; and a great deal is known about the horopter (Ogle, 1964). This thesis does not study the horopter. This thesis studies Panum's fusional area locally; that is, this thesis studies the dynamic aspects of Panum's fusional area for one specific point on one retina. Whether the findings of this thesis apply globally; that is, whether the dynamic aspects of the entire horopter are identical, or even similar, to the dynamic aspects of Panum's fusional area cannot be answered by this thesis.

If an image on the second retina falls outside Panum's fusional

area for an identical image on the first retina, then the two monocular images, although identical in form, will be perceived as two separate stimuli. When this occurs, the total percept of the two monocular images is a double percept, and one is said to see double.

For over 100 years, this seemed to be the story. Then in 1967, Derek Fender and Bela Julesz (Fender and Julesz, 1967) demonstrated that under certain conditions Panum's fusional area changes, and, in fact, demonstrated hysteresis.

Using binocularly retinally stabilized images, they found that when the images of two identical bars, one upon each retina and on non-corresponding regions of the two retinae, were slowly moved into corresponding regions of the two retinae and then slowly moved back to their original positions, the two images fused at one disparity and then lost fusion at a significantly larger disparity. This difference in the disparities of fusion and loss of fusion constitutes hysteresis. Their results indicate that Panum's fusional area changes as a function of its recent stimulation. They reported that Panum's fusional area was extended to include retinal locations not normally included in Panum's fusional area by the regime of stimulation they used.

This thesis attempts to duplicate part of the Fender and Julesz experiments, verifies the fact that hysteresis in fusion exists, extends the measurements of this hysteresis into retinal regions Fender and Julesz were unable to explore, measures the nature of the extension of Panum's fusional area (to determine if Panum's fusional area is stretched or shifted or whatever), and then measures the effect

on Panum's fusional area when one of the two stimuli is presented in a transient (flashed) rather than a non-transient (continually presented) manner.

It is found that a non-transient stimulus will fuse over a significantly wider range with a transient stimulus than with another non-transient stimulus. Furthermore, the range of fusion for the transient stimulus is dependent upon the non-transient stimuli that are present immediately before the transient stimulus is presented.

It is also found that the extension of Panum's fusional area, as effected by the stimulus regime of this thesis, not only includes the recruitment of retinal locations into Panum's fusional area which are normally not in Panum's fusional area, but also includes the loss from Panum's fusional area of certain retinal locations which are normally within Panum's fusional area. For all subjects, Panum's fusional area is shifted significantly. For some subjects, Panum's fusional area is stretched significantly.

II. Background

2.1 The Classification of the Binocular Percepts

There are three basic ways that two identical images, one projected upon each retina, can be perceived by the brain: diplopic (double), rivalrous, and fused.

2.1.1 Diplopia

The perception of diplopic images occurs when the two images fall upon retinal locations of such large disparity that the higher cortical perceptual centers do not consider the sources of the images to be located in the same place in space. The concept of retinal disparity is central to this thesis, and may need explanation. When the two eyes fixate any target in space, the two images of the fixated target fall, one upon each retina, at particular locations. Any other targets in the binocular part of the visual field will cast one image upon each of the two retinae. If the angle between the two images of the second target and the second target itself is measured and then this angle is subtracted from the angle between the two images of the fixated target and the fixated target itself, the "retinal disparity" of the second target with respect to the fixated target has been measured. If no fixated target exists, then the retinal disparity of any target in the binocular part of the visual field is measured with respect to the angle between the two eyes' individual perceptions of "straight ahead."

By this definition, "crossed" disparities ($\angle A_L A A_R$ in Figure 1) are negative, and uncrossed disparities are positive.

Diplopia (double vision) can be readily experienced when the optic axes of one's eyes are significantly out of alignment. To experience diplopia, you need only to push one eyeball upward gently with your finger.

2.1.2 Rivalry

The perception of rivalrous images may occur when the brain receives incompatible information from the corresponding retinal locations of the two eyes. In such a situation, the incompatible information may be confusing to the brain, and to resolve the confusion, by processes at present not well understood, the percept of one of a pair of incompatible images is suppressed. In this case, we say the images are rivalrous, and the image that is not perceived is said to have been suppressed by the image that is perceived.

Rivalry may be global; that is, the image of one eye may be completely suppressed by the image of the other eye. Rivalry may also be local; that is, parts of the two images may be suppressed while other parts of the images are not. All types of combinations may occur. It is not at all uncommon for two conflicting monocular images to yield an overall percept made up of a composite of parts of the two conflicting images, and to even include some diplopia.

As an example of the nature of rivalry, place your right hand in front of your right eye, with the base of your little finger just in front of the tip of your nose. Holding both eyes open, fixate some object about five feet away. You will be able to "see through" part of your hand (composite image). Continue to fixate the object and wiggle your little finger. You may perceive two little fingers wiggling about (diplopia). Inspect the scene with each eye alone. In this manner, you can experience some of the local properties of binocular rivalry.

The rivalry system can also alternate; that is, first the image of one eye is suppressed, and then the image of the other eye is suppressed. This alternation can also occur locally as well as globally.

2.1.3 Fusion

The perception of fused images, or fusion, is the normal percept of the healthy human visual system in the area of attention. Two identical monocular images, one upon each retina, are said to be fused when the overall binocular percept has the following three properties:

- 1) singleness
- 2) binocular depth
- 3) intermediate direction.

As an example, consider Figure 1.

The subject fixates a fixation target at location F . At location A , a dark bar stimulus target is presented. Its monocular right image (the image focused by the right eye upon the right retina) is focused by the right eye at location A_R on the right retina, and its monocular left image is focused by the left eye at location A_L on the

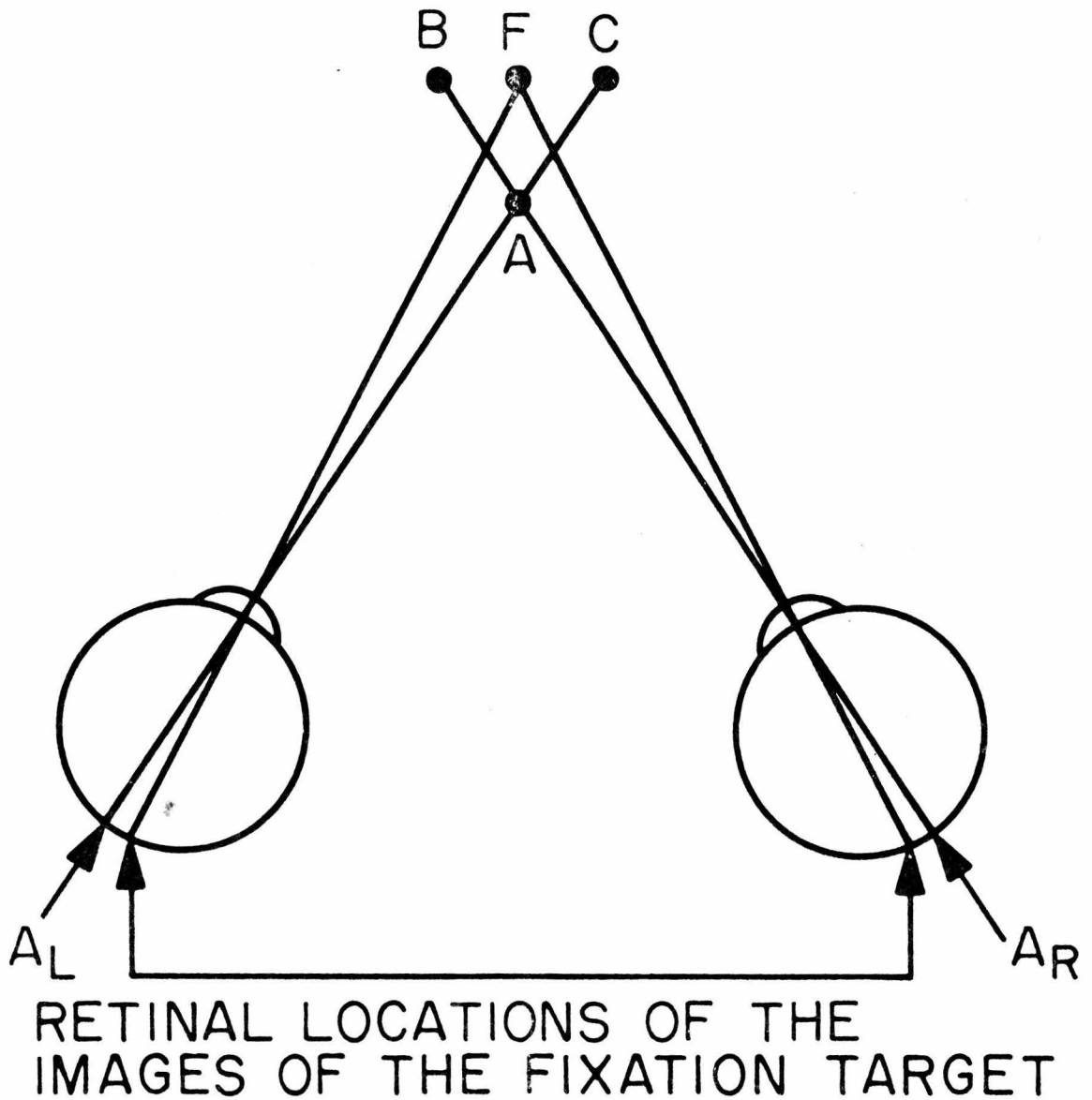


Fig. 1. The geometry of binocular vision. The two eyes fixate a fixation target located at location F. A stimulus target is presented at location A. An image of the stimulus target is focused by the left eye at A_L ; and another image of the stimulus target is focused by the right eye at A_R .

left retina. The fused percept is that of the stimulus target at location A in space.

Notice, the image of the stimulus target falls upon the same location of the left retina as would a target which is located at location C, which is to the right of the fixation target. If the right eye is closed, and other cues do not say otherwise, then the stimulus target will be perceived to the right of the fixation target. If the left eye is closed (and the right eye opened), the stimulus target will be perceived to the left of the fixation target, at location B, for the same reason. Thus if the two images are perceived as fused, the binocular percept of the fused bar will be that of one bar (singleness) located in space in front of the fixation target (binocular depth) and in the same direction, straight ahead, as the fixation target (intermediate direction). The perceived direction of a fused image is intermediate between the direction of the bar's monocular right image (to the left of the fixation target), and of the bar's monocular left image (to the right of the fixation target).

The perception of direction can be complex. The complexity arises in determining the frame of reference for the direction percept. For example, when one turns his head 45 degrees and is asked to point "straight ahead", he may point directly down his nose, or directly in front of his body, or he may select a direction based upon something in his surround. To avoid confusion, in this thesis "direction" will always mean "direction with respect to the fixation targets" or, when no fixation targets are present, "direction with respect to the center of the field of view of the experimental apparatus." The fixation targets when present, are centered upon the center of the field of view prior to the experiment.

Also prior to each experiment, the center of each field of view is adjusted by the subject to the direction of "straight ahead" for each eye.

Consider again Figure 1. Suppose the bar at location A (in visual space) cannot be perceived as fused; that is, the disparity of A_L and A_R is too large for fusion to occur. The higher cortical perceptual centers may decide that the two monocular images on the two retinæ (at A_L and A_R) are the images of two distinct bars, located in different directions (one to the left and one to the right of the fixation target). The perceptual centers conclude that, for some reason, the bar on the left cannot be seen by the left eye, nor the bar on the right by the right eye; nevertheless, there are two distinct bars. The observer will perceive a double image.

This can be experienced by holding a pen vertically at arm's length in one hand and a pencil directly in front of it in the other hand. Now, staring steadily at the pen, slowly move the pencil toward you. At some point, the pencil will be perceived as double, that is assuming you have a healthy binocular visual system. This assumption is made in all these demonstrations.

Suppose while you are seeing double, global rivalry occurs. Let us suppose the left monocular image (at A_L in Figure 1) suppresses the right monocular image (at A_R). Then, the overall percept will be one pencil, located to the right of the pen, and the pencil's depth will have to be determined by monocular depth cues (to see this, close the right eye).

In such a situation, a subject might mistakenly report the percept of fusion, and the experimenter would mistakenly measure Panum's fusional area as larger than it actually is. It is critical, therefore, that this error be minimized.

The perceived direction and the difference between the monocular depth perception and the binocular depth perception are two cues to help an observer decide whether he is seeing a binocularly fused single percept or a monocular rivalrous percept. The observer's ability to make this distinction is a critical factor in all the experiments in this thesis, and will be discussed later.

The percepts of binocular depth and monocular depth have significant differences. Monocular depth is responsible for the absolute depth perceived, using such cues as focus, size, texture, etc. Some relative depth perception is also possible monocularly, using such cues as parallax, focus (clearer objects tend to be perceived as closer), size, etc.

The main cue for the percept of binocular depth is the binocular disparity relative to the fixation target; this is strictly a relative cue. This information can only be obtained binocularly and is much more sensitive than monocular depth, allowing for very fine depth discriminations. For the rest of this thesis, the term "binocular depth" will refer to this high-acuity depth determined by binocular disparity. Adopting this convention, one may say that binocular depth is strictly relative depth.

In order to maximize the difference between monocular depth perceptions and binocular depth perceptions in the experiments of this thesis, I suppressed some monocular cues and fixed others as much as

possible by presenting the stimuli at optical infinity and holding the head of the subject still to prevent parallax cues. Under such conditions, all monocular cues signalled that all stimuli were at the same depth. However, binocular disparity still signalled the percept of depth relative to the fixation target, and therefore, relative to all the other stimuli in the visual field.

This approach would have made the percept of depth a very fine criterion for distinguishing fusion from rivalry, if not for the following: there exists a range of retinal disparities, intermediate between the disparities which yield fusion and the disparities which yield diplopia without binocular depth, at which diplopic percepts are perceived at a specific binocular depth. This range of disparities corresponds to two regions in real space called the regions of diplopic depth (see Figure 2).

Consider two monocular images, one on each retina, presented at optical infinity, such that they are perceived in diplopic depth. If rivalry occurs, the percept may be of a single image in binocular depth, but not at an intermediate direction. Thus intermediate direction is a more reliable cue than binocular depth in determining whether a single percept is truly a fused percept or a rivalrous percept of part of a diplopic depth percept.

It is not certain that rivalry of one image allows the percept of binocular depth in the region of diplopic depth. I did not instruct my subjects to report on this phenomenon, and I mention it here for future researchers to consider.

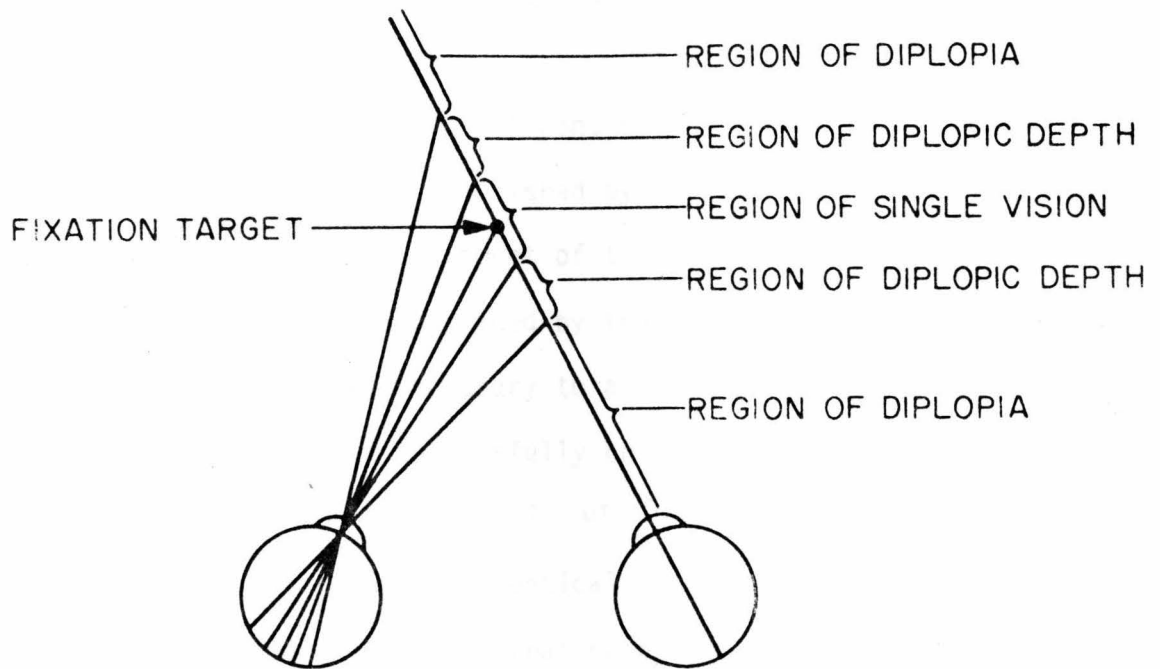


Fig. 2. The regions of binocular perception. The regions of real space are drawn and labelled in terms of the possible binocular percepts. Rivalrous phenomena are disregarded here.

Let us look at some of the experiments and some of the conclusions drawn in the study of binocular fusion.

2.2 A Summary of the Study of Binocular Fusional Ranges

Wheatstone (1838) published a description of the stereoscope. He noticed that, within a finite range of disparities, binocular stimuli of different disparities could be fused and perceived at different depths.

His work, however, did not control for eye movements; that is, the fusion might have been accomplished by vergence eye movements (movements which change the alignment of the visual axes), and the percept of depth might have been determined by the magnitude and direction of the vergence eye movements necessary to achieve fusion.

Dove (1841) first successfully untangled the effects of vergence eye movements on the measurements of fusional ranges by using flashed binocular stimuli. Identical binocular stimuli were presented for so brief a period of time that no eye movements could be made during the presentation interval; thus no eye movements could significantly shift the locations of the projected images of the stimuli on the retinae. Subjects reported whether they perceived one or two stimuli. In this manner, Dove was able to measure the fusional area in the static situation. He found a finite fusional region (not a single point), proving that exact alignment of the visual axes is not necessary to achieve a fused binocular percept (see Figure 3).

Panum's fusional area is defined as a function of one retinal point. That is, for a stimulus projected on the point on the right

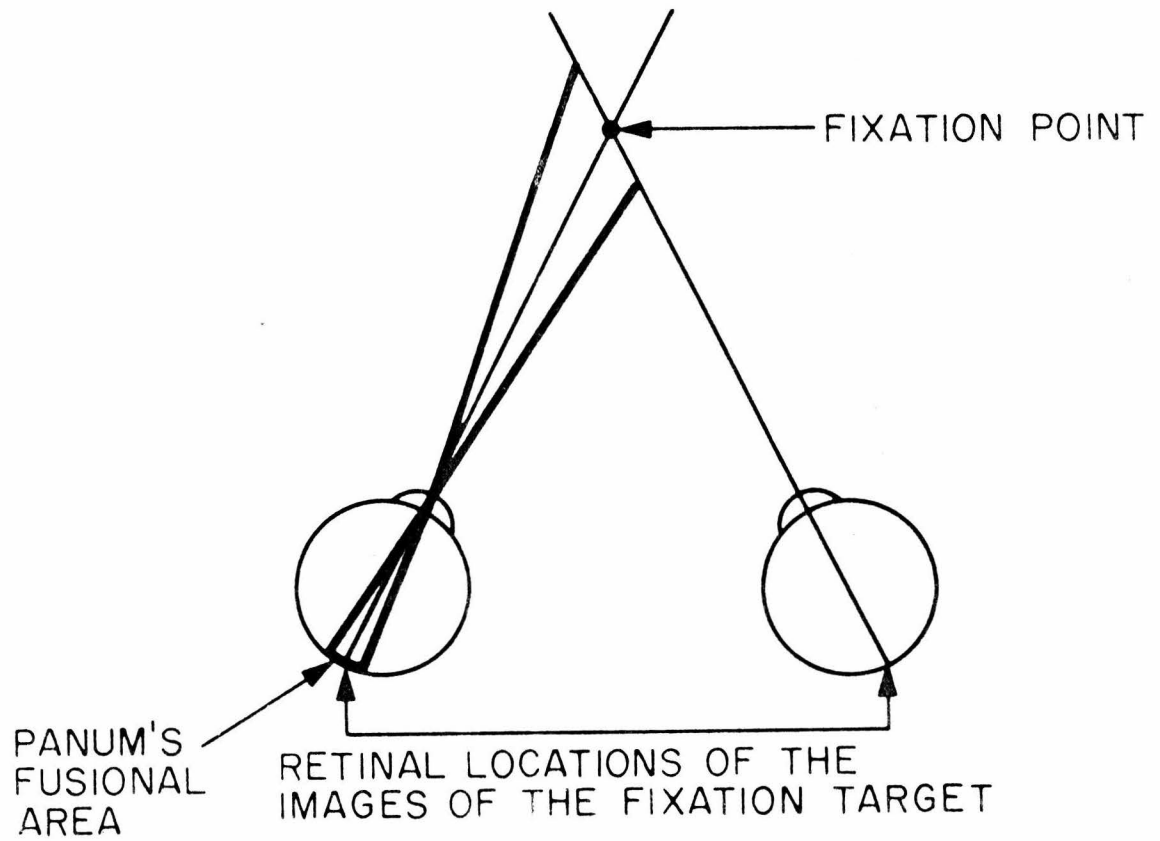


Fig. 3. Panum's fusional area. The two eyes fixate a fixation target. Panum's fusional area for the point designated on the right retina is the region of points on the left retina between the heavy, dark lines.

retina (designated by the arrow), there exists a region on the left retina (limited by the two heavy dark lines) such that, when an identical stimulus is projected upon that region, the two stimuli will be fused.

Panum (1858) researched and published a description of the fusional phenomena, and the fusional area was named after him. Ditchburn and Ginsborg (1952), and also Riggs, Ratliff, Cornsweet, and Cornsweet (1953) independently developed a technique known as retinal stabilization of visual images. To appreciate the nature of retinally stabilized images, we must first consider the dynamics of the human oculomotor system.

The direction of gaze of the human eye is in constant motion. For a classification of the micro-movements of the human eye, see Beeler (1965). It is important to recognize that, except possibly under extremely good fixation, a point source of light at infinity will constantly project photons onto different retinal locations as the direction of gaze constantly changes.

In order to study the interactions between a particular location on the left retina and a particular location on the right retina, a method must be employed which guarantees that the images of the stimuli will fall upon only those particular retinal locations. The method employed by Dove (1841), flashing the stimuli, has one major disadvantage; the dynamic properties of the binocular interactions cannot be studied. To study the dynamic properties of the binocular interactions, it is necessary to be able to present stimuli which move in a controlled manner over particular retinal locations. In order to

do this, it is necessary to short-circuit the effect of eye movements on the site of retinal stimulation.

By a clever optical method, Ditchburn et al. (1952) and Riggs et al. (1953) were able to move the projection of the stimulus light entering the eye in exactly the same manner that the direction of gaze moved. They attached a small mirror to the eye by use of a tight-fitting scleral contact lens and, by reflecting the projected stimulus light off this mirror before the light entered the eye, the mirror served as an optical lever. With the proper supporting optics, they were able to project the image of a stimulus onto a particular set of retinal receptors, and, within the range of their apparatus, keep that image on those same receptors no matter how the direction of gaze moved. Neither system was perfect, but modern versions of the system can be relied upon to limit retinal motion of an image to within one or two minutes of arc for eye movements of up to three degrees in magnitude.

Beeler (1965) describes in detail the method of stabilization of retinal images. Figure 4 (copied from Fender and Julesz, 1967), shows the left channel of the apparatus used in both the work of Fender and Julesz and this thesis. When shutter S_1 is closed and shutter S_2 is open, non-stabilized images are focused upon the retina; when shutter S_1 is open and shutter S_2 is closed, only stabilized images are focused upon the retina.

There are three ways a stabilized image can be moved upon the retina: rotation of the prisms P , rotation of mirror M_1 , and motion of the target in the target plane. Prior to each experiment, the prisms P are rotated by the subject to adjust the center of the field

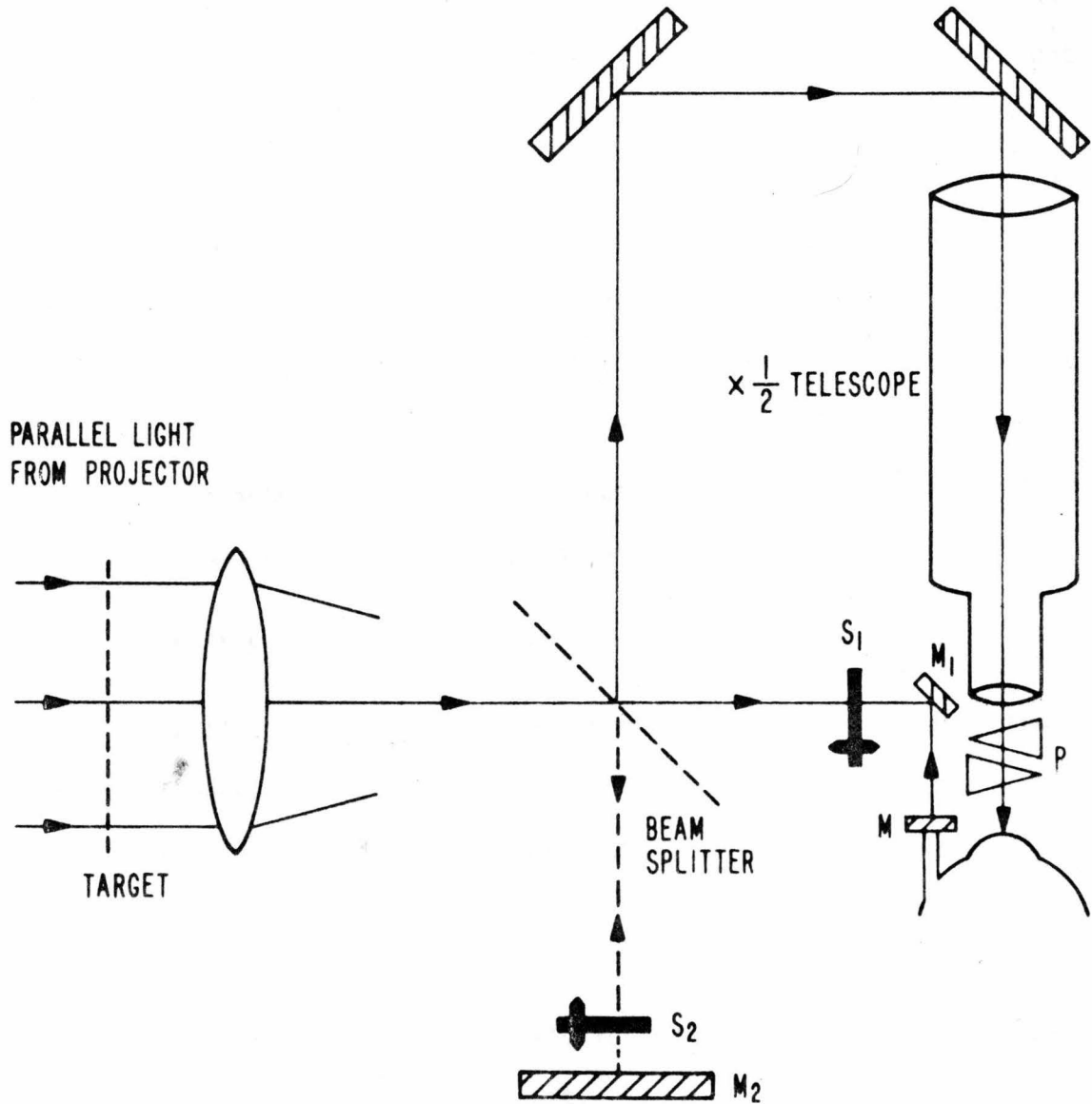


Fig. 4. Left-eye component of equipment for producing binocular retinally stabilized images. Parallel rays enter from a projector at the left. (Copied from Fender and Julesz, 1967).

of view of the telescope to the perceived direction of straight ahead. Prior to each experiment, mirror M_1 is rotated about the vertical and the horizontal axes to place the stabilized image onto the starting position. During each experiment, the target is moved in the target plane by the experimenter to produce controlled motion upon the subject's retina.

Derek Fender and Bela Julesz (1967) used the method of retinal stabilization of images to study the dynamic properties of Panum's fusional area. By using two retinally stabilized images, one projected upon each retina, they were able to vary the disparity of the two images in a controlled manner, and measure the effects of their stimulation regime on Panum's fusional area.

2.3 The Work of Fender and Julesz

"Extension of Panum's Fusional Area in Binocularly Stabilized Vision" (Fender and Julesz, 1967) stands as a landmark in the study of binocular fusion. Using binocularly stabilized retinal images, this paper concluded that Panum's fusional area is plastic, and in fact, demonstrates hysteresis.

It also concluded that Panum's fusional area is strictly dependent upon the stimuli used to measure it.

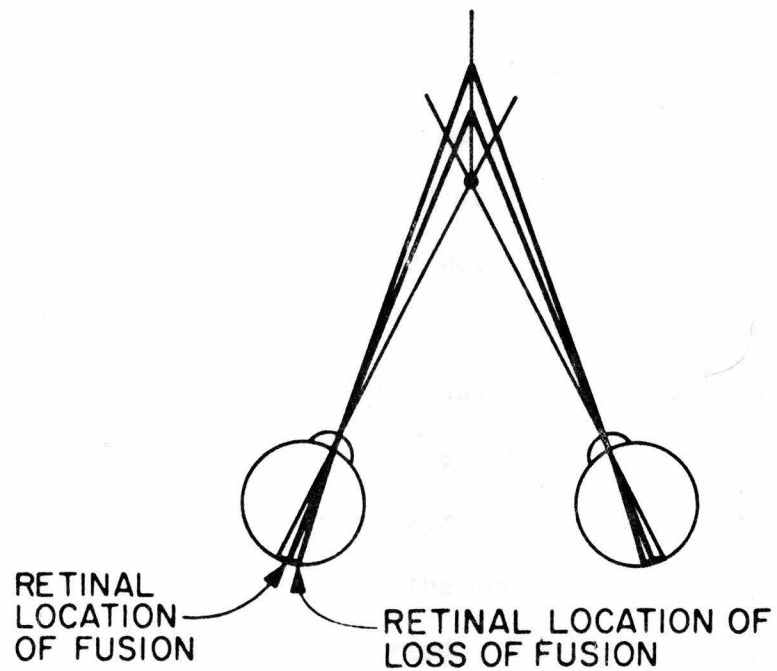
Fender and Julesz measured Panum's fusional area in the following manner. One image of a pair of fusible images was projected in a retinally stabilized manner upon each retina. The subject adjusted these stabilized images by moving the stabilized images across his retinae until each stimulus appeared to be "straight ahead". The

subject moved the stabilized images across his retinae by adjusting a mirror M_1 which reflected the stimulus light onto the mirror mounted upon the scleral contact lens.

Upon completion of this adjustment, which was the final adjustment the subject made, the two images were fused. The two stimuli were then drawn slowly into the temporalward visual fields by the experimenter, until they were perceived by the subject to "break apart." The actual retinal disparity was recorded at the instance of breaking apart. The two images were next moved in the reverse directions (towards the center) until the subject reported fusion of the two images. This retinal disparity was also noted. The images continued to be moved towards the center until they were again at the retinal disparity originally determined by the subject to be exactly overlapping and exactly straight ahead. The motion of the images was reversed, and the process repeated many times.

The surprising result was that the retinal disparities at which fusion occurred and the retinal disparities at which fusion was lost (break was perceived) were significantly different. Loss of fusion occurred at greater disparities than did fusion. Thus Panum's fusional area demonstrates hysteresis.

The fusion and breakaway disparities were found to be vastly different for two types of binocular stimuli. The first type of binocular stimulus consisted of identical dark bars ($13' \times 60'$ arc) on light backgrounds. These bars fused, for the typical subject, at 42 ± 10 min arc and lost fusion at 65 ± 14 min arc, (see Figure 5).



RETINAL STABILIZED IMAGES

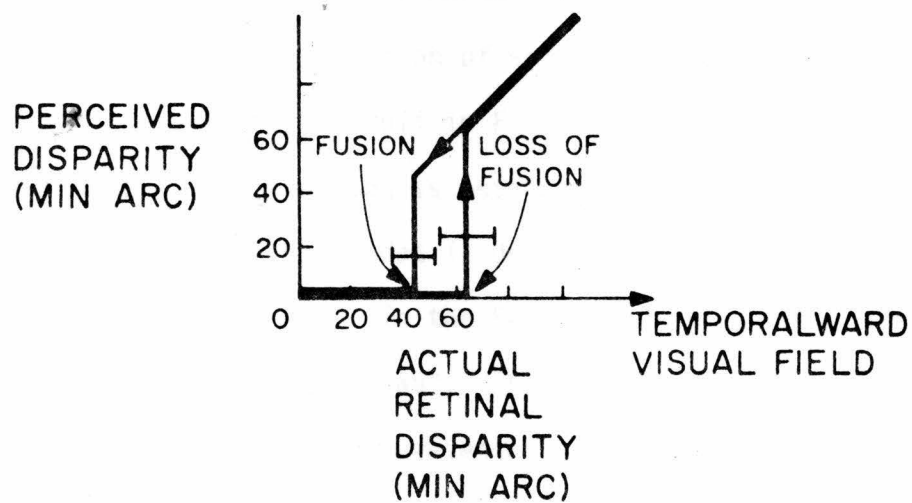


Fig. 5. Hysteresis in binocular fusion, as measured by Fender and Julesz. Perceived disparity is presented as a function of actual retinal disparity of the stimulus. Perceived disparity of fused images is zero. The stimulus was a pair of retinally stabilized images of dark bars (see text for details).

The subjects were asked to report how far apart the stimuli appeared when they were not fused. This task was made easier by the presence of tick marks at various disparities in the light background of the stimuli. When the stimuli appeared fused, the perceived disparity was zero; that is, there was no space perceived between the two stimuli. However, when the two images were not perceived as fused, the subjects reported the disparity correctly; that is, perceived disparity was equal to the actual retinal disparity.

NOTE: The data of Fender and Julesz, as presented in Figure 5, have been smoothed by me to eliminate the confusion which might arise from a contaminating factor they reported. The contamination arose when the dark bar stimulus on one retina attempted to fuse with the tick marks on the other retina.

The results of these experiments were presented as a graph of perceived disparity as a function of actual retinal disparity and can be seen for the dark bar stimuli in Figure 5.

In Figure 5, a convention is established. Although no fixation targets exist, a large black dot is drawn where a fixation target might otherwise be present. In the Fender and Julesz experiments, both eyes looked "straight ahead". Therefore the optic axes were parallel. For the sake of convenience, the eyes are drawn in a converged position. The convention, for the rest of this thesis, is as follows: the large black dot shall represent the point of intersection of the optic axes when they are parallel to each other. This is consistent because all images in the Fender and Julesz

experiments, and in this thesis, were presented at optical infinity. When fixation targets were presented, they were presented optically at this point.

The second type of binocular stimulus was a Julesz stereo pair (Julesz, 1960). Each stimulus consisted of 100×100 2-min-arc squares which were generated by computer to have each square pseudo-randomly black or white with equal probability. The two stimuli were identical except for a center region of 40×40 squares which was shifted 2 box widths (4 min arc) horizontally in the nasalward visual direction. When such stimuli are fused, one perceives the 40×40 region floating in depth in front of the background.

For the same subject reported above, the random dot stereo pair fused at a disparity of 6 ± 4 min arc, and broke apart at a disparity of 120 ± 18 min arc (see Figure 6).

Thus the conclusion that Panum's fusional area is stimulus dependent.

The third major find of the Fender-Julesz experiments is that the fusional extension process is time dependent. The time dependence was measured in two ways. The first method for measuring time dependence of fusion was to vary the velocity at which the disparity of the stimuli was increased and decreased. The results of this work revealed that the extension of Panum's fusional area (that is, the difference between the disparity of fusion and the disparity of loss of fusion) was greatly dependent upon the velocity of disparity increase and specifically, the slower the velocity, the larger the extension of

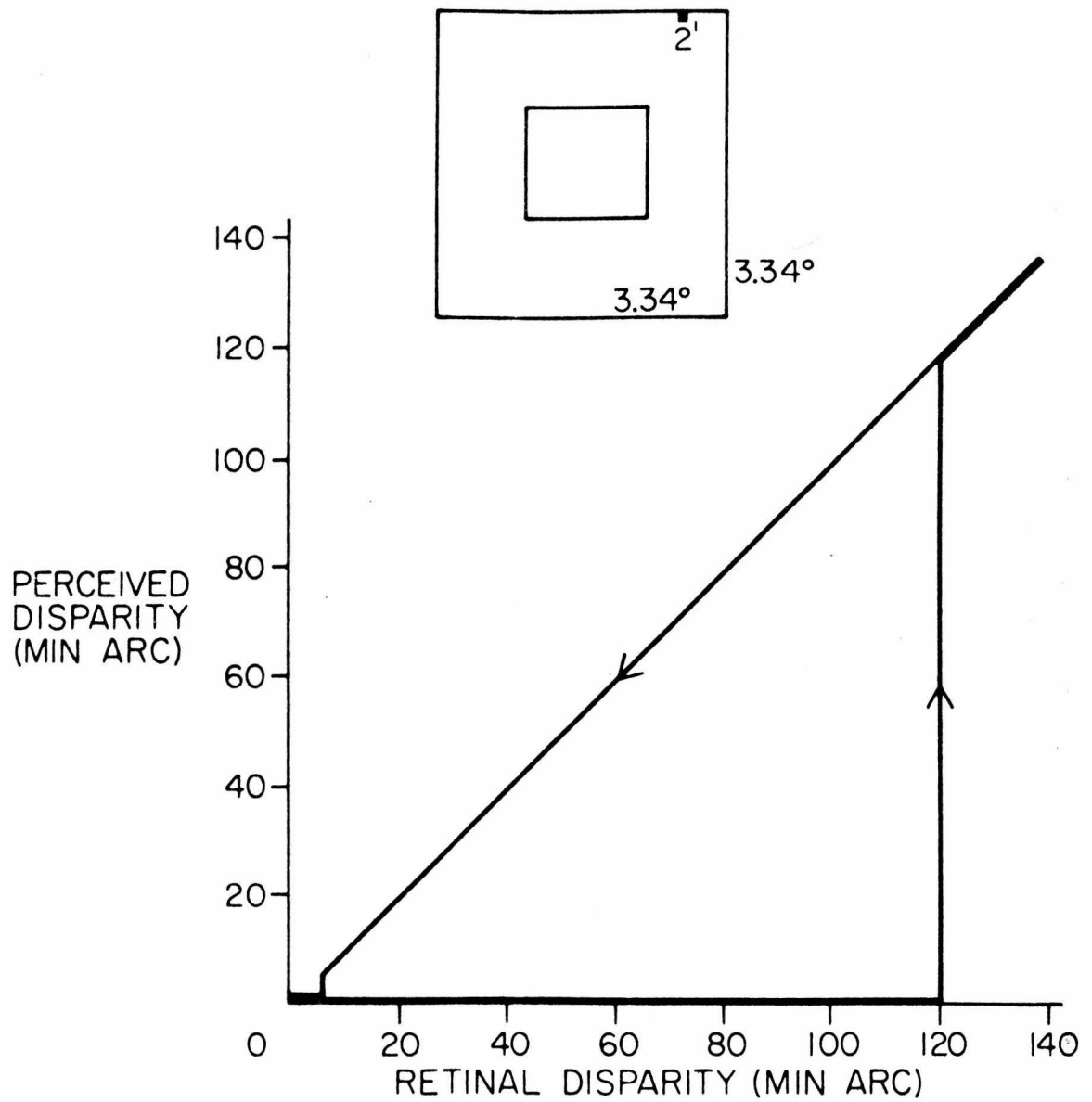


Fig. 6. The extension of Panum's fusional area as measured by Fender and Julesz (1967) for a Julesz stereo pair (top diagram) presented in stabilized vision.

Panum's fusional area. They found that velocities slower than one min arc/sec disparity change did not increase the extension of Panum's fusional area. For velocities faster than about 8 min arc/sec disparity change, no extension of Panum's fusional area was observed.

They also found that there exists a maximum disparity for which fusion is possible. This, of course, is the limit of the extension of Panum's fusional area with disparity changes of velocity one min arc per sec or slower. These are the values reported for the typical subject above, and shown in Figure 6.

The second method Fender and Julesz employed to measure the time dependence of the fusional process was the method of occlusion. A pair of retinally stabilized images were presented in exact alignment, and were slowly pulled into the temporalward visual direction (as above). At various disparities, the motion of the stimuli images on the retinae was halted, and both images were occluded by closing shutters S_1 on both sides of the apparatus for a period of time. The images were then re-presented at the same retinal locations at which they were last presented, and the subject was asked to report whether or not the two images were fused.

If, upon re-presentation, the two retinal stabilized images were not fused, they would not fuse in the five seconds the subjects were allowed to view them. However, depending on the duration of the occlusion, and the disparity, the stimuli might re-appear either fused or unfused.

If the re-presented images were perceived as fused, Panum's

fusional area was still in the extended state. However, if the re-presented images were not perceived as fused, Panum's fusional area was not in the extended state.

The occlusion experiment measures how long Panum's fusional area will remain in the extended condition for various disparities (or, equivalently, the decay rate of the extension of Panum's fusional area for various disparities) and this particular binocular stimulus. The results are presented in Figure 7.

Figure 7 can be understood as follows. When Fender and Julesz occluded the random-dot stimuli for 10 msec, the subject perceived the re-presented stimuli as fused only if the retinal disparity of the two monocular images was less than or equal to $38 \text{ min arc} \pm 5 \text{ min arc}$. If, however, the stimuli were occluded for 800 msec, the subjects perceived the re-presented stimuli as fused only if the retinal disparity of the two monocular images was less than or equal to $12 \pm 3 \text{ min arc}$. The two tails of the graph point toward the following observed phenomena. There exist disparities too large ever to be fused (left tail); and (within Panum's fusional area) a 6 min arc disparity (or less) will fuse spontaneously, despite infinite occlusion time (right tail).

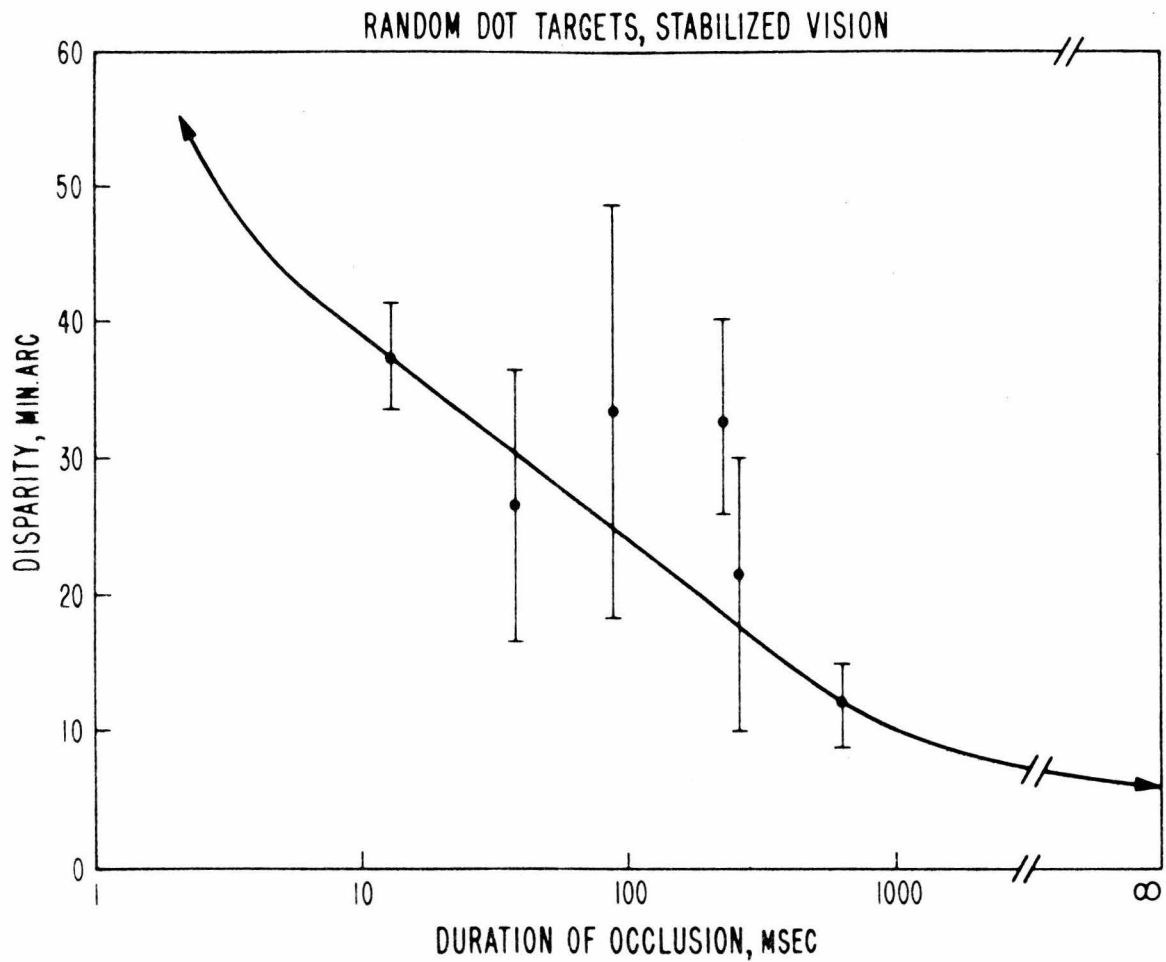


Fig. 7. Time-dependence of the extension of Panum's fusional area as measured by Fender and Julesz. The maximum disparity that would permit re-fusion of a random-dot stereo pair of retinally stabilized images after both images had been occluded is presented as a function of the duration of the occlusion (in msec). (Copied from Fender and Julesz, 1967).

2.4 A model of binocular fusion

Nelson (1975) published a model of the binocular visual system which summarizes nicely many of the ideas of the earlier models, particularly those of Julesz (1971) and Sperling (1970), and which effects the results of Fender and Julesz.

Nelson focused his attention upon the binocular disparity detector system as the basis of his model. A binocular disparity detector is a cortical cell which fires most vigorously for binocular stimuli of a specific disparity. Binocular disparity detectors have been found in cat cortex (Barlow, Blakemore, and Pettigrew, 1967), and also in monkey cortex (Hubel and Wiesel, 1970). Nelson states that the tuning curve for disparity is extremely sharp; a retinal disparity detector may fire vigorously for one disparity, and be silent for all disparities 10 min arc larger or smaller.

Nelson then proposes two properties for the binocular disparity detectors:

- 1) Retinal disparity detectors of similar disparity tunings facilitate each other, and
- 2) Retinal disparity detectors of dissimilar tunings inhibit each other; the more dissimilar the disparities, the weaker the mutual inhibition.

Nelson describes fusion of images of non-zero disparities as the dominance of those particular disparity detectors over all other disparity detectors, and loss of fusion as the recapture of dominance by the zero-disparity detectors. The recapture is possible because all the detectors have a tonic firing rate, and the number of

detectors decreases with the magnitude of the disparity. The zero disparity, according to Nelson, is the disparity to which the most units are tuned. The disparity detectors which signal a particular disparity, according to Nelson, can gain dominance over all other disparity detectors if the disparity detectors which signal that particular disparity are stimulated strongly enough to silence the other disparity detectors.

Panum's fusional area, according to Nelson, is the range of disparities corresponding to the disparity detectors which will gain dominance if stimulated.

In order to explain hysteresis in Panum's fusional area, Nelson proposes that the mutual inhibition between the disparity detectors is recurrent; that is, as one cell inhibits a second cell, it decreases the inhibition of the second cell upon itself.

The model works as follows. As fused stimuli move slowly onto retinal regions of greater disparity, the disparity detectors which signal the stimuli's current disparity are dominant. These detectors are inhibiting the many other disparity detectors, which are thus no longer able to inhibit the now dominant disparity detectors or any other disparity detectors. The dominant disparity detectors and the detectors of similar disparities which the dominant detectors facilitate, are thus able to fire more vigorously than before this release from inhibition. This will allow even more inhibition of even other disparity detectors, effecting even more release from inhibition to the currently dominant disparity detectors, and of course, the detectors of similar disparities. This, plus the

proposal that similar disparities facilitate each other, will allow disparities slightly larger than the currently dominant disparity, if stimulated, to fire more vigorously than otherwise possible; so the fused stimuli will remain fused as they stimulate these slightly larger disparities. If the fused stimuli increase their retinal disparity slowly enough, this process will have time to prepare the detectors of the next slightly larger disparity, and Panum's fusional area may be extended to disparities which normally cannot dominate the system.

Fusion can be extended, according to Nelson, only as long as the currently dominant disparity is able to inhibit the zero-disparity detectors strongly enough to prevent their regaining dominance. When fusion has been extended to a disparity tuning such that either too few detectors exist for that disparity, or that the inhibition from each of those disparity detectors is too weak, the zero disparity detectors regain dominance, and the extended fusion is lost.

Nelson explains that the random dot stereograms used by Fender and Julesz were able to extend Panum's fusional area to larger disparities than were the dark bars, by proposing that the facilitation of identical disparities occurs between disparity detectors that are stimulated by neighboring retinal receptors. The large area of the retina stimulated by the random dot stereo pair (3.34° on each retina) enabled an even greater facilitation of the currently stimulated detectors, and thus an even greater extension of Panum's fusional area.

Although Nelson's model has not been proven, I shall discuss my work in terms of it.

2.5 Discussion of the work of Fender and Julesz

One of the major problems an experimenter encounters when presenting a subject with retinal stabilized images is the foveation reflex. Whenever a stimulus is presented anywhere in the visual field other than on the fovea, the visual system responds by turning the eyes to "look at" the stimulus. This is the foveation reflex.

However, a retinally stabilized image cannot be relocated on the retina by making an eye movement. The retinally stabilized image will remain on the same retinal location despite the eye movement (within the accuracy of the stabilizing system). In non-stabilized conditions, a stimulus would remain on the same retinal location during an eye movement only if the stimulus moved in the same direction as the eye rotation, at the same velocity, and at the same time. Thus the brain interprets a retinally stabilized image as an image dancing about in space. A subject can see his own eye movements by observing the apparent motion of a retinally stabilized image.

Consider now the case of a retinally stabilized image projected slightly to one side of the central fovea. Supposing the stimulus is perceived to be left of straight ahead; the eye rotates toward the left to foveate the stimulus. The stimulus is perceived to move to the left. The eye attempts to foveate the stimulus again by again turning to the left. The stimulus again is perceived to move to the left. Foveation again, and the chase is on.

This is a hopeless chase, which will not stop until either the subject overcomes his foveation reflex or until the direction of gaze

moves outside the range of the retinal stabilization apparatus.

Each experimenter must devise his own method to overcome what I shall call the stabilized foveation problem. Each experiment will be limited by the restrictions, if any, that the experimenter's method imposes upon the experiment.

Fender and Julesz overcame the stabilized foveation problem by taking advantage of the fact that the human visual system cannot diverge the eyes beyond a certain angle.

Fender and Julesz thus presented their experimental targets in the subjective straight ahead direction and moved them slowly and symmetrically in the temporalward visual fields.

The two main limitations of this method on the experiment were as follows. First, they were unable to present any targets in the visual nasalward fields, and second they were unable to move one target alone in any direction.

The first limitation, the inability to work in the nasalward visual fields, they discussed, and they carefully reported their results as having been measured only in the temporalward visual fields.

The second limitation, the inability to move the retinally stabilized image of one target on one retina while holding the retinally stabilized image of the other target still on the other retina, they mentioned briefly, and performed no experiments in this condition. I would like to draw attention to this point, because I feel it is important. Careful examination of the theoretical significance of this point reveals that Fender and Julesz never truly measured an extension of a Panum's fusional area.

In light of the above discussion, for the duration of this thesis, when discussing the results of Fender and Julesz, I shall speak of the extension of fusional ranges and not of the extension of Panum's fusional area.

III. THE WORK OF THIS THESIS

3.1 Problem definition

Fender and Julesz reported that Panum's fusional area was extended by the regime of stimulation they used to include retinal locations not normally included in Panum's fusional area.

Can a true Panum's fusional area be so extended, and, if so, does this extension include the loss from Panum's fusional area of certain retinal locations which are normally within Panum's fusional area? If so, what is the extent of this loss of retinal locations from Panum's fusional area, and what is its overall effect on the size and location of Panum's fusional area?

3.2 Equipment

The equipment used in this thesis is the same equipment used by Fender and Julesz and described by Beeler (1965) with the following differences.

- 1) The targets are now moved by stepping motors which are controlled by a PDP-11/20 computer dedicated to the running

of the experiment and the collecting of the data. The stepping motors are geared to step the stimuli one-quarter min arc per step. If both stimuli are moved in a symmetric manner, the total disparity change per step is $\frac{1}{2}$ min arc.

2) The eyepiece lens of the left channel of the apparatus was found to have a focal length of 44.5 cm, whereas the eyepiece of the right channel has the correct focal length of 40 cm. This does not affect the quality of the stabilization, but does affect the magnification of the left image, making it slightly smaller than the right image. Also, it may have affected the monocular depth percept of the left image, but this was not noticed. Unfortunately, this equipment error was discovered after Subject 1 had left Caltech, and there was no way to re-collect data on him. Subject 2 had completed all but the last of the experiments to be described below. Thus, the decision was made to complete the experiments with the improper left eyepiece lens.

I adjusted and checked the equipment periodically, adjusting the stabilization to within an accuracy of one, or at most, two percent. Thus, in a 100 min arc sweep of the calibration telescope, placed in the location where the subject's eye is normally placed, the stabilized image moved usually less than one minute arc, and rarely, if ever, more than two minutes arc.

The magnification difference between the two channels was noticeable (and estimated by both subjects to be from 2-10%) but did not prevent fusion of stimuli. Random-dot stereo patterns easily yielded

depth in non-stabilized conditions, and many non-stabilized as well as stabilized experiments were conducted with this apparatus as it is; no noticeable problems arose.

However, this difference between the two channels is reported, as it may be relevant to future researchers.

3) Our lenses were sucked tightly to the eye with 24 cm negative pressure of artificial tear solution. This tighter fit may have improved the quality of the stabilization over that of Fender and Julesz. It may also have caused poorer acuity by impairing the blood flow to the ciliary body.

4) In most of my work, the visual field was restricted to 150 min arc. This restriction was necessary to prevent the subject from seeing such spurious information as the edges of the slides.

In the Fender and Julesz work, the visual field was about 6° , which allowed the subject to see the edges of the slides, and perhaps use them as additional cues to fusion.

Each subject was fitted with two moulded scleral contact lenses by Dr. Solon Braff of El Monte, California. I then mounted each lens with a stalk holding a first surface mirror and a pinlight. The mirror served as the optical level necessary for stabilization. The pinlight was used to measure the eye positions (see Williams, 1977).

Each lens was mounted with a suction apparatus (see Williams, 1977).

3.3 Methods

3.3.1 The method used to overcome the stabilized foveation problem

The method used to overcome the stabilized foveation problem was to present the subject with two identical, non-stabilized fixation

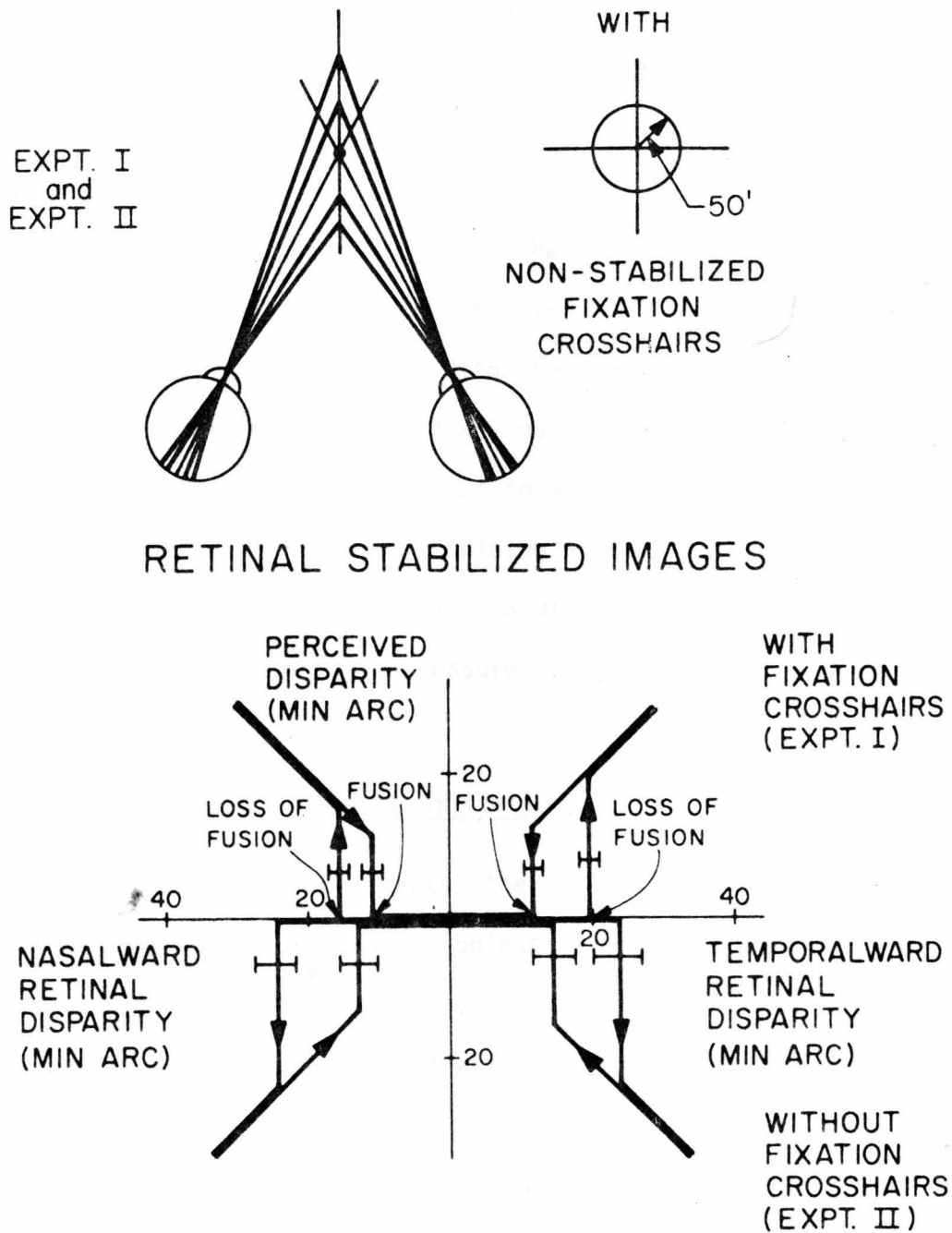


Fig. 8. Hysteresis in binocular fusion as measured in this thesis. Use of non-stabilized fixation crosshairs enabled subjects to overcome the stabilized foveation problem. Nasalward as well as temporalward visual fields were measured. The error bars show the 95% confidence intervals of the mean. Data are for Subject 1.

crosshairs with a 50 min radius ring (see Figure 8). The subject saw one crosshair with each eye, and initially adjusted the apparatus so that the two crosshairs overlapped exactly and fused in the subjective straight ahead position.

The advantage this method gave the experimenter over the method used by Fender and Julesz to overcome the stabilized foveation problem is quite significant. With the crosshair method, any retinal locations can be stimulated and any motion regimes employed. Thus, the method allows the experimenter to move a retinally stabilized image across one retina, while holding a second retinally stabilized image fixed on the other retina. In other words, a true Panum's fusional area can finally be measured. Nasal visual fields can also be tested.

3.3.2 The quality of the stabilization

Throughout all experiments, the subject was instructed to fixate the centers of the crosshairs (unless otherwise stated in the text). Two sources of unwanted image movement upon the retinae exist:

- 1) Errors in the optical adjustment of the stabilization system, and
- 2) Slippage of the scleral contact lens upon the surface of the eye.

The optical adjustment is checked by a calibration telescope. The "stabilized image" is focused upon a calibrated reticule mounted in the calibration telescope and placed in the location where the subject's retina would be if the subject were in the apparatus. A mirror on the calibration telescope is placed in the location where the mirror on the subject's contact lens would be if the subject were in the apparatus. The stabilization apparatus is adjusted until the angular motion of the

stabilized image on the calibrated reticule is less than one percent of the angular rotation of the mirror on the calibrating telescope. Under such conditions, unwanted image motion on the subject's retina will be less than one percent of the magnitude of the subject's eye movements. Since the subject is fixating a non-stabilized fixation target, his eye movements will be significantly less than 100 min arc, and the unwanted image motion on his retinae will be less than one min arc.

My control for lens slippage was as follows: consider a stabilized image of a dark bar on a light background. Suppose that image were to slip. The subject would then perceive a three-part bar due to after-image effects. Now suppose the image slipped to the right. Then, the rightmost part of the image would be a dark bar projected upon a region of light adapted retina, yielding the percept of a very dark bar. The leftmost part, however, would be a light region of the background projected upon a region of dark adapted retina, thus yielding the percept of a very bright bar. The rest of the bar would be projected upon retina adapted for it, and would appear to be intermediate in intensity.

To control for lens slippage, the subject would make 50 min arc saccades and look for the three-part bar. The experimenter would decrease the suction on the lens until the subject reported the three-part bar. The experimenter would note the amount of suction and then increase the suction until the subject could no longer see the three-part field. For the subjects reported in this thesis, 12-15 cm

negative pressure was more than sufficient to prevent the three-part bar percept. All experiments were conducted with 20-24 cm negative pressure. The three-part bar percept is quite vivid, and image slippage of 1-2 min arc could easily be detected.

3.3.3 The duration

When a subject became weary, his eye movements would become unsteady, and the experiment would be stopped. Otherwise, the maximum length of any experiment was determined by safety factors. No subject was allowed to wear a contact lens under suction for longer than 45 minutes in any one day, because prolonged suction can disrupt the blood flow to the cornea, causing clouding of the cornea and possible irreversible damage.

3.3.4 The stimuli

The stimuli were 13 min wide by 60 min tall high-contrast dark bars on a light background, identical to the bars reported as stimuli by Fender and Julesz. Vertical disparities were always kept as close to zero as possible, the disparities presented and measured were all horizontal disparities.

Figure 9 (top) shows what the subjects saw in each eye, and (below) the percepts of fusion and diplopia. Rivalry would yield the percept seen by the single eye that was successfully suppressing the other eye.

3.3.5 The experimental procedures

To begin an experiment, the subject placed both lenses onto his eyes and 24 cm negative pressure of artificial tear solution was

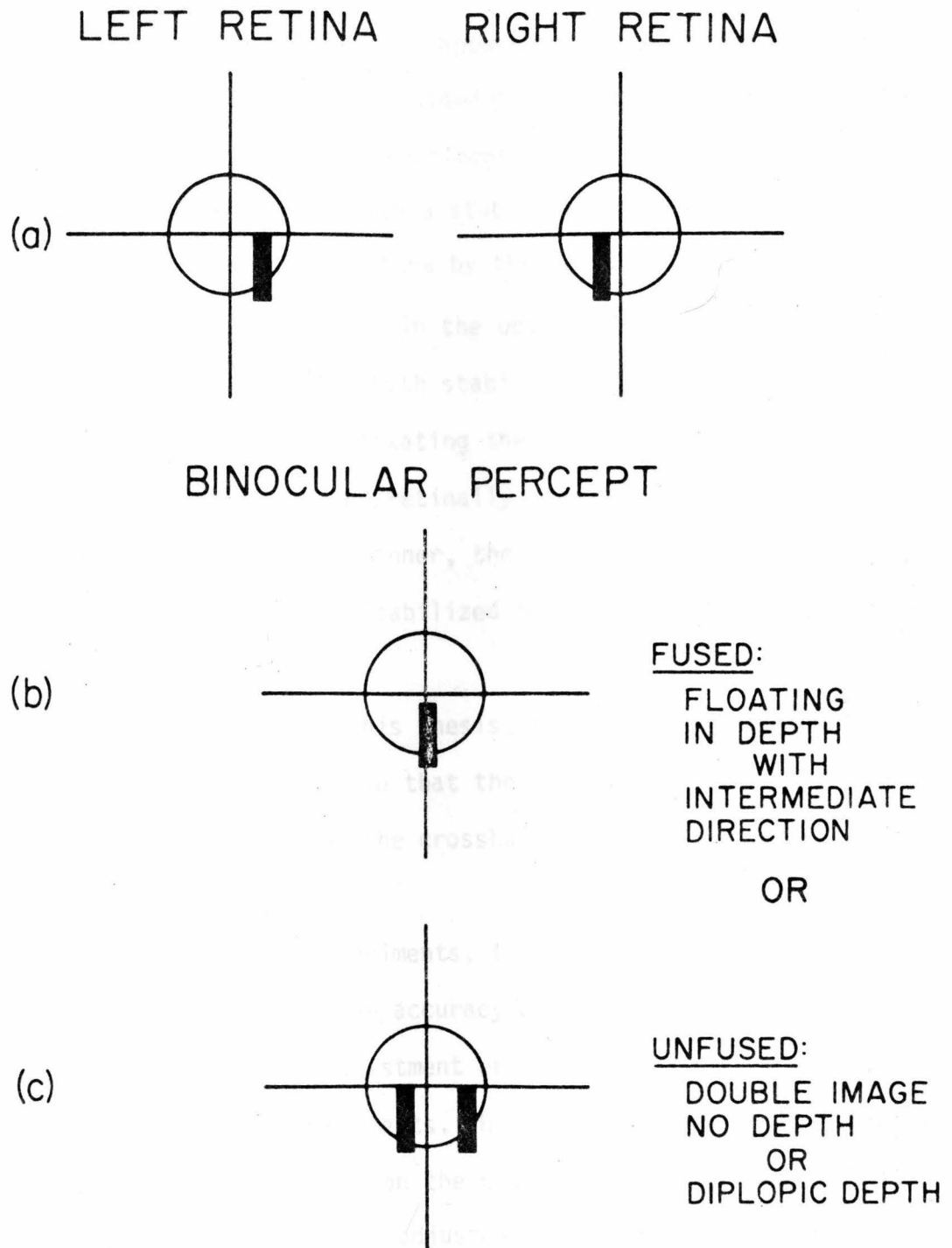


Fig. 9. The stimuli of this thesis and the possible percepts:
 (a) each monocular percept, also the rivalrous percepts, (b) fusion,
 and (c) diplopia.

applied. The subject entered the apparatus by biting on a bitebar and leaning into a headrest, both moulded to fit him, and mounted to keep his head immobile during the experiment.

Each eye was presented with a stabilized image which the subject was able to move across his retina by the horizontal and vertical rotations of mirrors M_1 placed in the optical paths of the apparatus (see Figure 4). He adjusted both stabilized images onto pre-determined locations of his retinae by fixating the centers of the non-stabilized crosshairs, and adjusting the retinally stabilized images with respect to the crosshairs. In this manner, the subject was able to accurately adjust the locations of the stabilized images to within about two min arc.

In all experiments of this thesis, the subjects adjusted the retinally stabilized images so that the tops of the bars were level with the horizontal line of the crosshairs. Thus all work was done in the lower visual fields.

In the first three experiments, the subjects adjusted the bars to peripheral locations with an accuracy of about 3 min arc. The data processing corrected for adjustment errors.

In the final two experiments, the subjects adjusted the stabilized images so that they centered on the crosshairs horizontally. This increased the accuracy of the adjustment to about one min arc. The data processing did not correct for adjustment errors, but did verify the accuracy of the adjustment.

The subject indicated when he had finished adjusting the

stabilized images; then the experimenter signalled the computer, which moved the stabilized images in a controlled manner upon the retinae.

The subject was instructed to push a button to signal when he perceived loss of fusion and to release the button when he perceived fusion. He was also frequently instructed to push and release the button when the stimuli reversed direction. The latter task, being surprisingly difficult at low stimuli velocities, served to measure the subject's response time. The experimenter knew when the motors actually reversed direction, and both subjects usually responded within one-half second. Thus both subjects' response times for the fusion-loss of fusion task were estimated to be below one half second. All data were adjusted for a one-half second response delay.

Whenever the subject pushed or released the button, the locations of all targets, measured by potentiometers accurate to one or two minutes arc, were presented by the computer to the experimenter, both on a cathode ray tube screen and on teletype hardcopy. The experimenter copied the locations from the cathode ray tube into a data book, and later computed the retinal disparities at which fusion was perceived and lost.

As a second check, data were recorded on magnetic tape and processed later on a PDP-11/45 computer. The measurement of eye movements was done in many of the experiments, and these data were recorded only on magnetic tape.

The recording interval for the magnetic tape data was 25 msec. No micro-saccade could be missed, because the eyes cannot jump to one location, and then jump back to the first location, in less than 25 msec. This precaution was necessary to ensure that the measurements of the disparities which elicited and lost fusion were not contaminated by factors perhaps critical to the experiment, such as large eye movements.

For Experiments No. 4 and No. 5, a third check was employed. The computer kept count of the motor steps taken, and these data were compared to the potentiometer output.

3.4 Preliminary experiments

3.4.1 Training

The subjects were first trained to overcome the foveation reflex by fixating the center of the crosshairs, and next trained to establish criteria to distinguish between rivalry and fusion.

Training consisted of having the subjects fixate the crosshairs while adjusting two stabilized bars to locations 35 min arc into each nasalward visual field. When the bars were fully adjusted, the experimenter signalled the computer, which moved the bars symmetrically (and at a constant speed) until both were 35 min arc into the temporalward visual fields. This completed one "sweep" across the target range. The computer then reversed the directions of motion of both bars and returned them (at the same speed as before) to the original locations, completing a second sweep. At this point, the computer repeated the above process. The experimenter controlled the number of sweeps of the targets, and the target speed.

The subject practiced maintaining fixation on the centers of the crosshairs and signalling, by button push, both when he had achieved the percept of fusion and when he had lost the percept of fusion. This constituted Experiment No. 1.

Eye movements of the subject were monitored by the method described by Williams (1977), to determine how well the subject was fixating the crosshairs.

After four to ten days, both subject and experimenter felt that training was sufficient and that reliable data could be collected.

All subjects found it easier to learn to overcome the foveation reflex when each target moved across the retinae at 1 minute arc per second; (that is, a total disparity change of 2 minutes arc per second). Slower motion was tediously boring, and faster motion made it difficult to avoid tracking. Data were therefore taken at this velocity of disparity change until subjects felt confident they could perform well at 1 minute arc per second total disparity change. A control was then performed at 1 min arc/sec total disparity change for Subject 1. The results were not significantly different, showing that 2 min arc/sec disparity change was quite satisfactory. Considering that 2 min arc/sec disparity change was more comfortable to the subject, and twice as much data could be taken daily, all following experiments were performed at 2 min arc/sec disparity change.

3.4.2 Experiment No. 1

The stimulus of Experiment No. 1 was the stimulus of the training period; that is, one retinally stabilized image of a dark bar 13' wide by 60' tall projected onto each retina. The subject fixated non-stabilized crosshairs (described above) and adjusted each retinally stabilized image upon his retinae until each bar was centered 35' arc nasalward of the center of the fixation crosshair, and until the top of each bar was level with the horizontal line of the crosshair. The experimenter signalled the computer when the adjustment was completed. The two retinally stabilized images were then moved by the computer, into the temporalward visual fields at a speed of 1 min arc/sec

each, causing a total disparity change of 2 min arc/sec between the two bars. When the two bars reached 35' arc temporalward of the center of the fixation target, the motion of the bars was reversed.

The subject was instructed to signal by button push, as quickly as possible, whenever the two separate bars were perceived to fuse, and whenever the fused bars lost fusion. The data of Experiment No. 1 consisted of the records of the stimulus locations at the time of the button pushes.

The results of the first experiment can best be described in two ways:

1) The graph of Figure 8, which is an extension of the method of data presentation of Fender and Julesz, and by

2) Table 1a, which presents the four disparities of interest.

The results of the experiments are as follows:

1) Subject 1 perceived fusion at 12 ± 1 min arc temporalward disparity and 11 ± 1 min arc nasalward disparity. He lost fusion at 19 ± 1 min arc temporalward disparity and at 16 ± 1 min arc nasalward disparity.

2) Subject 2 perceived fusion at 11 ± 1 min arc temporalward disparity and 10 ± 1 min arc nasalward disparity. He lost fusion at 16 ± 1 min arc temporalward disparity and at 17 ± 1 min arc nasalward disparity.

The results of Experiment 1 for Subject 3 are qualitatively different from the results for Subject 1 and Subject 2. Subject 3, it should be noted, has a vertical tropia of about 1 diopter, which can be overcome by muscular effort. Subject 3 has stereo vision, at

least for crossed disparities and for uncrossed disparities. Subject 3 claimed to possess the ability to fuse diplopic stabilized retinal images by volition. I attempted to measure this phenomenon, but was unable to.

Due to a tragedy in Subject 3's family, Subject 3 was unable to continue as a subject in these experiments. The only data I was able to obtain from Subject 3 are the data of Experiment No. 1.

I must also mention that all data collected from Subject 3, unlike any of the data collected from Subject 1 or Subject 2, were collected while the Digital Equipment Corporation PDP-11/20 laboratory computer was out of order. The experimental conditions for Subject 3 differed from the experimental conditions for Subject 1 and Subject 2 in the following ways:

- 1) Subject 3 controlled the target motion by means of a toggle switch,
- 2) Subject 3 was instructed to stop the target motion for several seconds whenever the percept changed from fusion to diplopia or from diplopia to fusion.

This instruction was given for two reasons:

- 1) Data were collected from one of the target location potentiometer pots with a one-channel Nesco Instruments, Inc. Graphic Recorder Model JY 110-2. Upon the record of the target location, the experimenter marked the subject's perceptual reports with a felt-tipped pen. By having the subject halt the target at locations of perceptual changes, the experimenter could get a more reliable estimate of the exact target location when the perceptual change occurred.

2) Subject 3 reported two 8 to 12 min arc ranges (one nasalward and one temporalward) of disparities over which the percepts of fusion and diplopia alternated in time. Subject 3 reported that during the diplopia (and when the targets were not being moved), the bars remained a constant distance apart. The subject also reported that the transition from the diplopic percept to the fused percept was experienced as "the two bars jumping to an intermediate position, almost midway between" their original positions. Subject 3 appeared to be able to distinguish this alternation between fusion and diplopia from an intermittent rivalry.

The data of Subject 3 are presented in Table Ib, in the following manner. Subject 3 reported "solid fusion", "fusion-break", or "solid break" at the onset of the perception. Thus when the percept of fusion gave way to the alternation of the percepts of fusion and break, the subject reported "fusion-break". When the alternating percepts gave way to constant diplopia, Subject 3 reported "solid break", etc. In Table Ib, "F", "F-B", and "B" are used to represent "solid fusion", "fusion-break", and "break". The arrow above the letters represents the direction of motion of the bar presented to the right eye in visual space. Thus, \overleftarrow{F} means the temporalward disparity of fusion for the two bars, because if the right bar fuses while moving toward the left, it must be in the temporalward (left) visual field.

Subject 3 perceived solid fusion at 17 ± 2 min arc temporalward disparity, and 17 ± 1 min arc nasalward disparity. Subject 3 perceived solid break at 28 ± 2 min arc temporalward disparity, and 31 ± 2 min arc nasalward disparity.

Table Ia

Mean disparities of fusion and break for Subjects 1 and 2

Conditions		Disparity (\pm standard error of the mean) in min arc				
Experiment Number	Subject Number	Nasal Break	Nasal Fusion	Temporal Fusion	Temporal Break	Number of Trials
1 Both Targets Move	1	-16 \pm 0.8	-11 \pm 0.8	12 \pm 0.8	19 \pm 0.8	33
	2	-17 \pm 0.9	-10 \pm 0.8	11 \pm 0.9	16 \pm 0.7	23
Crosshairs						
2 Both Targets Move	1	-25 \pm 1.5	-13 \pm 1.3	14 \pm 1.6	23 \pm 1.6	13
	2	-21 \pm 0.9	-9 \pm 0.9	10 \pm 1.1	21 \pm 0.9	20
No Crosshairs						
3a Right Target Moves at 2 min arc per second	1	-21 \pm 0.8	-8 \pm 0.9	9 \pm 0.5	15 \pm 1.0	18
	2	-15 \pm 2.1	-10 \pm 1.2	11 \pm 0.8	16 \pm 1.0	20
3b Left Target Moves at 2 min arc per second	1	-17 \pm 0.8	-12 \pm 0.9	13 \pm 0.8	19 \pm 0.7	23
	2	-16 \pm 1.4	-9 \pm 0.8	10 \pm 1.0	14 \pm 0.9	19
3c Right Target Moves at 1 min arc per second	1	-17 \pm 0.9	-11 \pm 1.5	12 \pm 0.6	16 \pm 0.9	8

Table Ib

Mean disparities of fusion and break for Subject 3

B = break, F = fusion, F-B = onset

of alternation of fusion and break

Arrow pointing leftward = converging motion

Arrow pointing rightward = diverging motion

Data for Experiment No. 1

N = number of trials

Both targets moving - crosshairs present

\leftarrow B	F \rightarrow B	\leftarrow F-B	F \rightarrow	\leftarrow F	F \rightarrow B	\leftarrow F-B	B \rightarrow	N
-31	-25	-22	-17	17	16	25	28	10
\pm 1.7	\pm 1.5	+ 1.5	\pm 1.5	\pm 1.7	\pm 1.8	\pm 2.0	\pm 2.2	

In order to look for hysteresis in Subject 3's fusional range, it is best to look for hysteresis in the location of the region of alternating percepts. In the temporalward visual fields, as the stimuli bars move toward the center, the region of alternating percepts is located between 17 ± 2 and 25 ± 2 min arc disparity; in the temporalward visual fields, as the stimuli bars move away from the center, the region of alternating percepts is located between 16 ± 2 and 28 ± 2 min arc. No significant hysteresis was measured in Subject 3's temporalward visual fields. However, in the nasalward visual fields, there is significant hysteresis in the location of the region of alternating percepts; it moves from between -17 ± 1 and -25 ± 1 min arc disparity to between -22 ± 2 and -31 ± 2 min arc disparity.

Subject 1 and Subject 2 showed hysteresis significant beyond the 95% confidence limits (determined by the Student t-test) in both the temporalward and nasalward visual directions. For Subjects 1 and 2 nasalward hysteresis and temporalward hysteresis were not significantly different.

Experiment No.2 was designed to determine the effect of the crosshairs on the hysteresis.

3.4.3 Experiment No. 2

When the subjects felt sufficiently well-trained in the experimental regime of Experiment No.1, I removed the crosshairs. The subject was instructed to fixate the center of the visual field and respond as in Experiment No. 1.

Both subjects found this task grossly simplified by fixating

a speck of dust visible on the optics. Note that this is either a monocular cue, or a very weak binocular cue (as compared to the heavy lines of the crosshairs).

For both subjects, removal of the crosshairs had no significant effect on the disparities at which fusion occurred, but had a significant effect on the disparities at which fusion was lost. Both subjects demonstrated significantly more hysteresis without crosshairs (see Table Ia and Figure 8)

This result should be presented in the inverse manner. The presence of non-stabilized fixation targets at zero disparity does not significantly change the disparities at which fusion occurs, but does significantly decrease the magnitude of the hysteresis demonstrated by Panum's fusional area.

The model of Nelson, which utilizes inhibition of dissimilar disparity detectors, would strongly predict the above results (Nelson, personal communication).

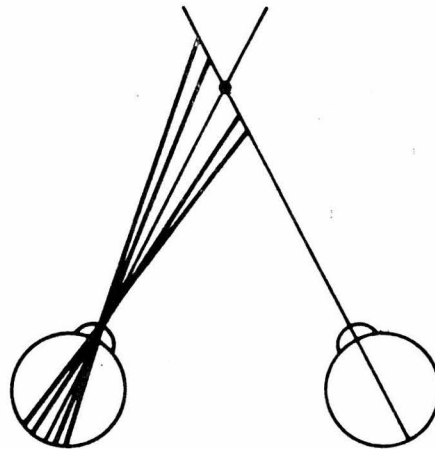
3.4.4 Experiment No. 3

Experiment No. 3 was designed to test for hysteresis in Panum's fusional area. In this experiment, the retinally stabilized image of one stimulus bar was held still on one retina, and the retinally stabilized image of the other bar was swept horizontally across the other retina (see Figure 10).

Table Ia shows that both subjects showed significant hysteresis in Panum's fusional area in both nasalward and temporalward visual directions for both eyes.

EXPT. III

WITH
FIXATION
TARGETS



RETINAL STABILIZED IMAGES

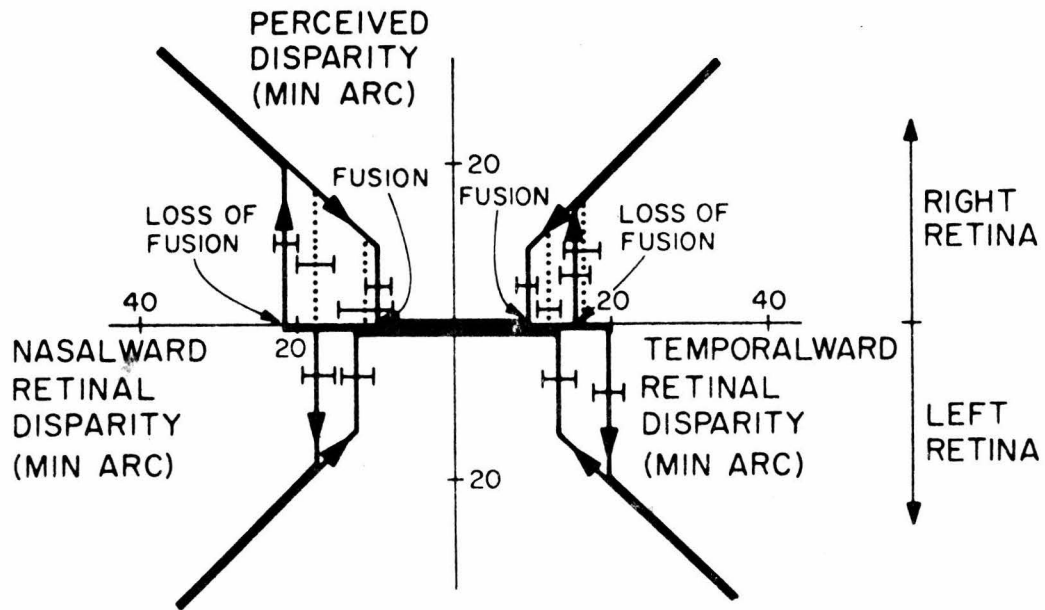


Fig. 10. Hysteresis of Panum's fusional area as measured in this thesis. Top of graph shows Panum's fusional area as measured on the right retina for a location on the left retina. Bottom of graph shows Panum's fusional area as measured on the left retina for a location on the right retina. Solid data lines are for 2 min arc/sec disparity change; dotted data lines are for 1 min arc/sec disparity change. Error bars are 95% confidence intervals of the mean. Data are for Subject 1.

Experiment No. 3a (Table Ia) shows the data for both subjects when the moving bar was presented to the right retina. Subject 1, for example, perceived fusion of the bars at 9 ± 1 min arc temporalward disparity and 8 ± 1 min arc nasalward disparity, and lost fusion at 15 ± 1 min arc temporalward disparity and at 21 ± 1 min arc nasalward disparity. Experiment No. 3b (Table Ia) shows the data for both subjects when the moving bar was presented to the left retina.

The graph in Figure 10 shows data for Subject 1 for Experiment No. 3a and Experiment No. 3c (top of graph) and Experiment No. 3b (bottom of graph).

With the sole exception of Subject I in Experiment No. 3a, there are no significant differences for either subject between the locations of fusion, or the amount of hysteresis measured in Experiments No. 1, 3a, 3b, or 3c.

In Table Ia, Experiment No. 3c data are shown for Subject I for 1 min arc/sec disparity change target velocities (also see Figure 10, dotted lines). The hysteresis is significantly smaller nasally, and not significantly smaller temporalwardly than the data collected at 2 min arc/sec disparity change. This is exactly the opposite trend one would expect if 2 min arc/sec disparity change was too fast a disparity change velocity for the hysteresis mechanism to keep up with. Thus, it is concluded that the hysteresis mechanism can keep up with a 2 min arc/sec disparity change, and that it is a legitimate disparity change velocity for these experiments.

3.4.5 Discussion of the preliminary experiments.

All three subjects of this thesis demonstrate fusional ranges significantly smaller than those demonstrated by the subjects of Fender and Julesz. This may well be within normal subject variability. However, the critical measure here is the ratio of the magnitude of the extension of Panum's fusional area and the magnitude of the non-extended Panum's fusional area. For the subject reported by Fender and Julesz, this ratio is 0.55 ± 0.06 . For my subjects (in Experiment No. 2 for the temporalward visual fields), this ratio is 0.64 ± 0.18 and 1.10 ± 0.19 . By this measure, the hysteresis I have measured is in one case comparable to, and in the other case larger than, the hysteresis measured by Fender and Julesz.

None of the subjects of Fender and Julesz reported the sensation of depth with the bar stimuli in stabilized conditions. All of the subjects in this thesis reported the sensation of depth with the bar stimuli in stabilized conditions, but in Experiment No. 2, where the crosshairs were absent, the sensation of depth was usually absent. Both Subjects 1 and 2 reported that the presence of the crosshairs were responsible for the depth sensation. Both Subjects 1 and 2 suspected that the depth sensation in Experiment No. 2, when sensed, was related to the edges of the visual fields. Considering that the visual fields in this thesis were significantly smaller than the visual fields in the work of Fender and Julesz, and that binocular depth is a relative depth, I conclude that the lack of depth sensations reported by Fender and Julesz is related to the absence of anything in the visual fields near enough to the stimuli to serve as a frame of reference for the binocular depth to be compared with.

3.5 The Nature of the Extension of Panum's Fusional Area: Experiment No.4

3.5.1 The problem

The extension of Panum's fusional area implies a recruitment of retinal locations into Panum's fusional area which are not normally in Panum's fusional area (see Figure 11). Does this mean that Panum's fusional area is increased in magnitude by the extension, or does the extension of Panum's fusional area include a corresponding loss from Panum's fusional area of certain retinal locations which are normally within Panum's fusional area, so that the overall magnitude of Panum's fusional area remains unchanged? If the first case is true, Panum's fusional area is "stretched" by the extension: if the second case is true, Panum's fusional area is "shifted" by the extension.

In Figure 11, three possible ways that Panum's fusional area may be altered by the extension process are shown. When a bar is held fixed on one retina and a second bar which is fused with the first bar is slowly moved across the second retina, the "leading edge" (on the side of the direction of motion) of Panum's fusional area is moved on the second retina in the direction of the motion to include the region of retina over which Panum's fusional area is extended. What happens to the trailing edge of Panum's fusional area?

In Figure 11b, the trailing edge does not move, and Panum's fusional area is stretched. In Figure 11c, the trailing edge moves in mirror symmetric fashion with the motion of the leading edge, and Panum's fusional area is stretched without changing its center location. In Figure 11d, the trailing edge follows the leading edge, and the

EXTENSION = STRETCH OR SHIFT?

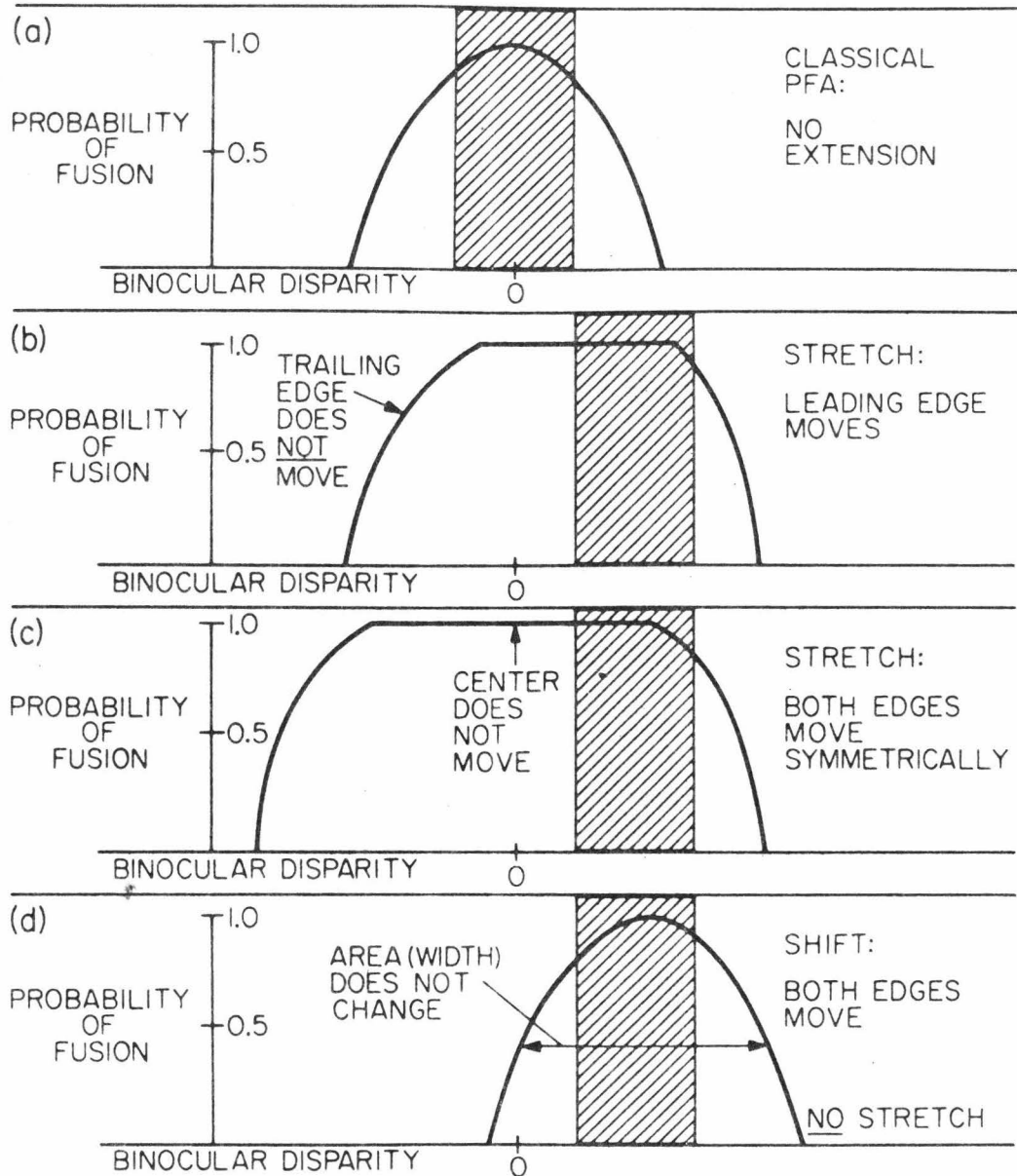


Fig. 11. The nature of the extension of Panum's fusional area. Panum's fusional area is represented as a probability of fusion curve for a range of binocular disparities. The striped region represents the bar on one retina and is centered above the value of the binocular disparity between it and the bar on the second retina. Figure 11a represents Panum's fusional area in the non-extended state; Figures 11b, c, and d represent three possible ways Panum's fusional area might be altered by the extension process.

magnitude of Panum's fusional area does not change; Panum's fusional area is shifted, but not stretched.

For the duration of this thesis, a "shifting of Panum's fusional area" will refer to a significant change in the location of both the center and the trailing edge of Panum's fusional area.

In order to test the nature of the extension of Panum's fusional area, I have designed a method which enables me to measure the probability of fusion for any given retinal disparity at any given experimental condition.

3.5.2 The method

The subject was presented with the two non-stabilized crosshairs, one to each eye. He adjusted the apparatus so that the two crosshairs overlapped exactly and fused in the subjective "straight ahead" direction. The subject was instructed to fixate the centers of the crosshairs.

The stimuli were the 13' by 60' high-contrast dark bars on a light background; this time, however, three retinally stabilized images of bars were used.

The first bar was presented to the left eye and the subject adjusted it to appear in the "straight ahead" position. Throughout the experiment, this bar remained at this location, with the following exception: every 250 msec, the bar was stepped one min arc, one time to the left, and the next time to the right. Thus the bar "jiggled" back and forth in the one minute arc region of the left retina perceived as "just left of straight ahead". This bar will be

called the "jiggling bar", or the "jiggling target".

The second bar was presented to the right eye. This bar was adjusted to the "straight ahead" position of the right eye. During the experiment, this bar moved back and forth across a 50 to 60 min arc range, centered on the straight ahead position. This bar moved at a speed of two min arc/sec. This bar will be called the "quasi-stationary bar".

The third bar was placed in a second stimulus channel on the right side of the apparatus. This channel was set up so that if the first right channel was visible, the second right channel was not, and vice versa. The "on" and "off" times of the channels were well below visual threshold. The subject, therefore, was always presented with one visible channel in the right eye. Each channel had one bar present, thus the subject was always presented with one retinally stabilized image of a dark bar on the right retina. The left eye was always presented with the jiggling bar, thus one image of one bar was always present upon each retina.

The third bar was presented to the right eye, and was adjusted by the subject into the straight ahead position. The two right channels were then alternated and further adjustments were made until no apparent motion was visible between the two bars in the right channels. The second right channel was then turned off, leaving the first right channel on. Thus, the "quasi-stationary bar" was visible, but the third bar was not.

Now it is possible to test whether any location on the right retina is within Panum's fusional area for a location on the left

retina, or not, at any instant. As the quasi-stationary bar moves in the temporalward visual direction, the third bar is invisible. When the quasi-stationary (q.-s.) bar reaches a particular location well within the extended region, the first right channel is shut off and, simultaneously, the second right channel is turned on. The second channel remains on for a brief 160 msec "flash" interval. The q.-s. bar is now invisible, and the third bar (which has been placed beforehand by the computer to stimulate a particular retinal location) is visible. This third bar will be called the "transient bar".

If the subject perceives the transient bar as fused with the jiggling bar, the location of the transient bar is within Panum's fusional area. If, however, the subject perceives two distinct bars during the flash, the location of the transient bar is not in Panum's fusional area. The 250 msec "rest" period of the jiggling bar, and the 160 msec "visibility" period of the transient bar are synchronized such that, during the 160 msec "visibility" period of the transient bar, the jiggling bar does not move.

It is essential in such a test not to allow the visual system time enough to alter Panum's fusional area; therefore after 160 msec, the second right channel is shut off, and the first right channel, simultaneously, is turned back on. Only one such presentation is made in each sweep. The q.-s. bar, which is now visible, continues to move, undisturbed by the changing of the channels. The subject reports his perception in the following manner:

- 1) "Single" -- if he is certain he saw "only one bar during the flash"

- 2) "Two" - - if he "probably saw only one bar during the flash",
- 3) "Three" - - if he is "not sure"
- 4) "Four" - - if he "probably saw two bars during the flash",
- 5) "Double" - - if he is certain he saw "two bars during the
"flash".

The subject also responds by psychophysical button push when the q.-s. bar and the jiggling bar fuse and break fusion. If the flash occurs before fusion or after the break, the subject reports "little early", "early", "little late", or "late" as is appropriate. At the end of each divergent sweep, the transient bar is reset to a new location, the q.-s. bar is reversed, and a similar test is made in the converging direction.

By repeatedly presenting the transient bar at several key disparities (with respect to the jiggling bar), I was able to measure the probability of fusion at each of the key disparities (see Figure 12). In Figure 12, for example, six out of the ten times that the quasi-stationary bar (moving to the right across Subject 2's right visual field) was replaced (while moving through the retinal location of zero-disparity) by the transient bar (at the -10 min arc disparity), Subject 2 perceived the transient bar as fused with the jiggling bar.

3.5.3 The controls

Several controls are necessary if such an experiment is to be meaningful.

First of all, the method of Experiment No. 4 is a new measure

of Panum's fusional area, and, therefore, in order to see the effect the extension of Panum's fusional area has upon its range, Panum's fusional area must be measured in this manner both in the extended and in the non-extended states. To motivate this, consider that a transient bar may be a stronger stimulus to a binocular disparity detector than a non-transient bar, and thus the Panum's fusional area measured in this manner may be larger than the Panum's fusional area measured with two non-transient bars. For each direction of motion of the q.-s. target, two critical locations of the q.-s. target must be tested; that is, one well within the extended region (see Figures 13 and 15) and one in the non-extended region (see Figures 12 and 14).

Four critical locations (two for each direction of motion) of the q.-s. bar were fed into the computer. (NOTE: a location of the q.-s. bar and a binocular disparity of the q.-s. bar and the jiggling bar are the same parameters within the limit of the 1 min arc range of the jiggle. Therefore, the two phrases will be used interchangeably in the following discussions).

The four critical locations were the diverging control disparity (Figure 12), the diverging test disparity (Figure 13), the converging control disparity (Figure 14), and the converging test disparity (Figure 15). The two control disparities were the zero disparities (except for Subject 1's converging control disparity which was set at -2 min arc to adjust for the asymmetry measured in his extended fusional ranges in Experiment No. 3a). The two test disparities for Subject 1 were 14 min arc beyond the control disparity in each

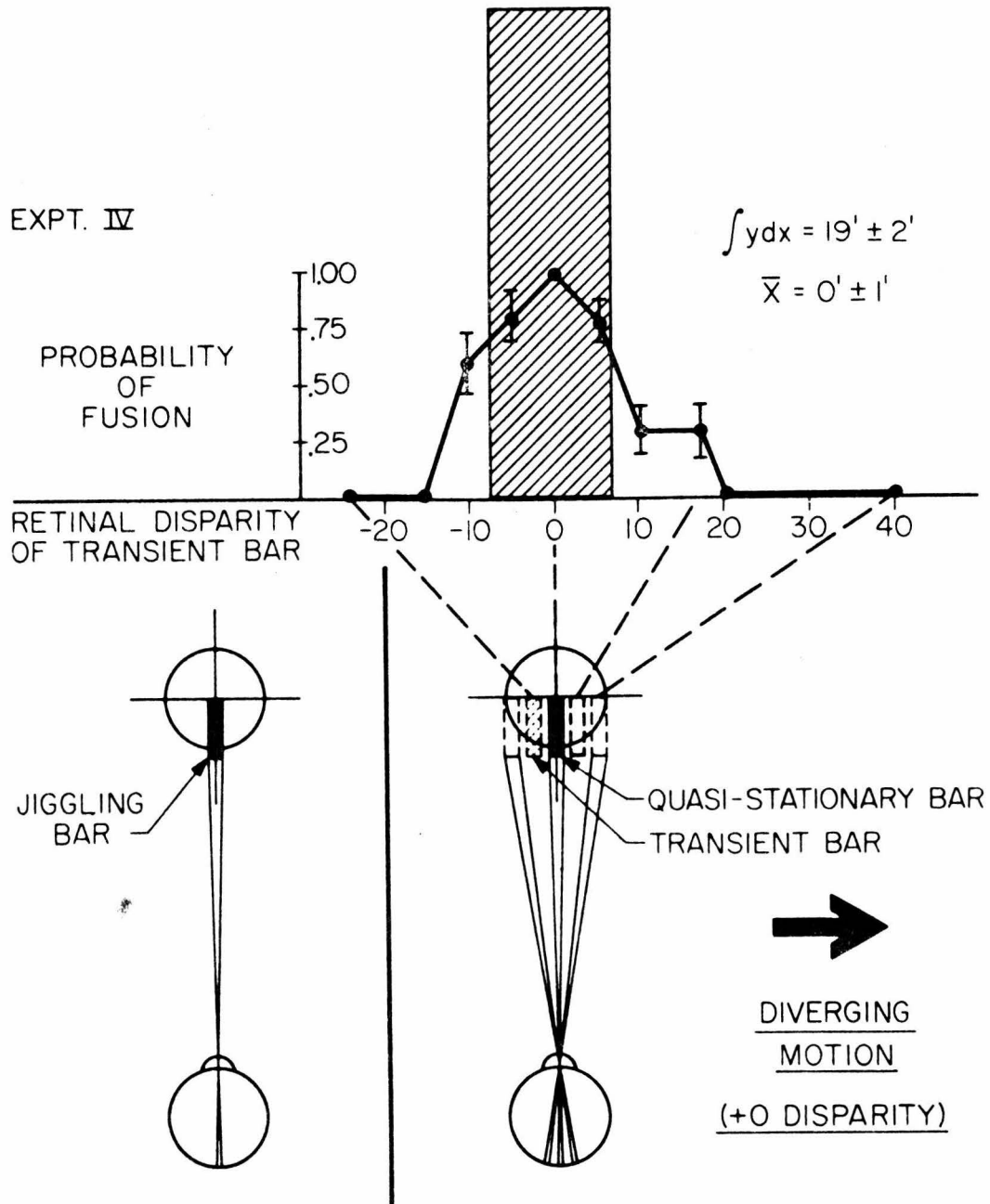


Fig. 12. Experimental method employed to measure probability of fusion as a function of retinal disparity for the stimulus condition of a quasi-stationary bar moving in a diverging direction through the zero disparity. The transient bar replaces the quasi-stationary bar for a brief interval at one of the dashed locations. The striped region represents the quasi-stationary bar and is centered above its disparity at the time of the presentation of the transient bar. Data are for Subject 2.

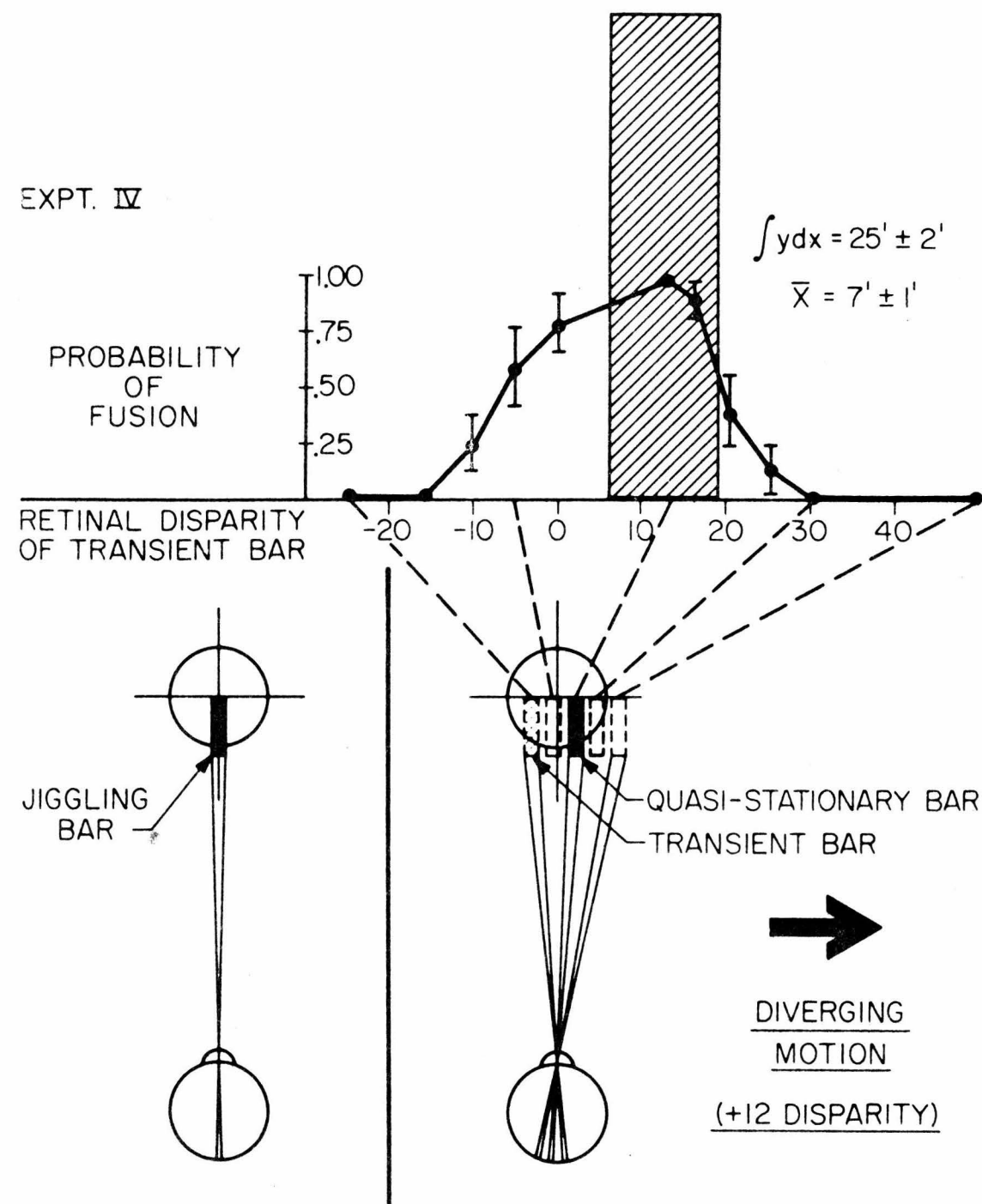


Fig. 13. Experimental method employed to measure probability of fusion as a function of retinal disparity for the stimulus condition of a quasi-stationary bar moving in a diverging direction through the + 12 disparity. Data are for Subject 2.

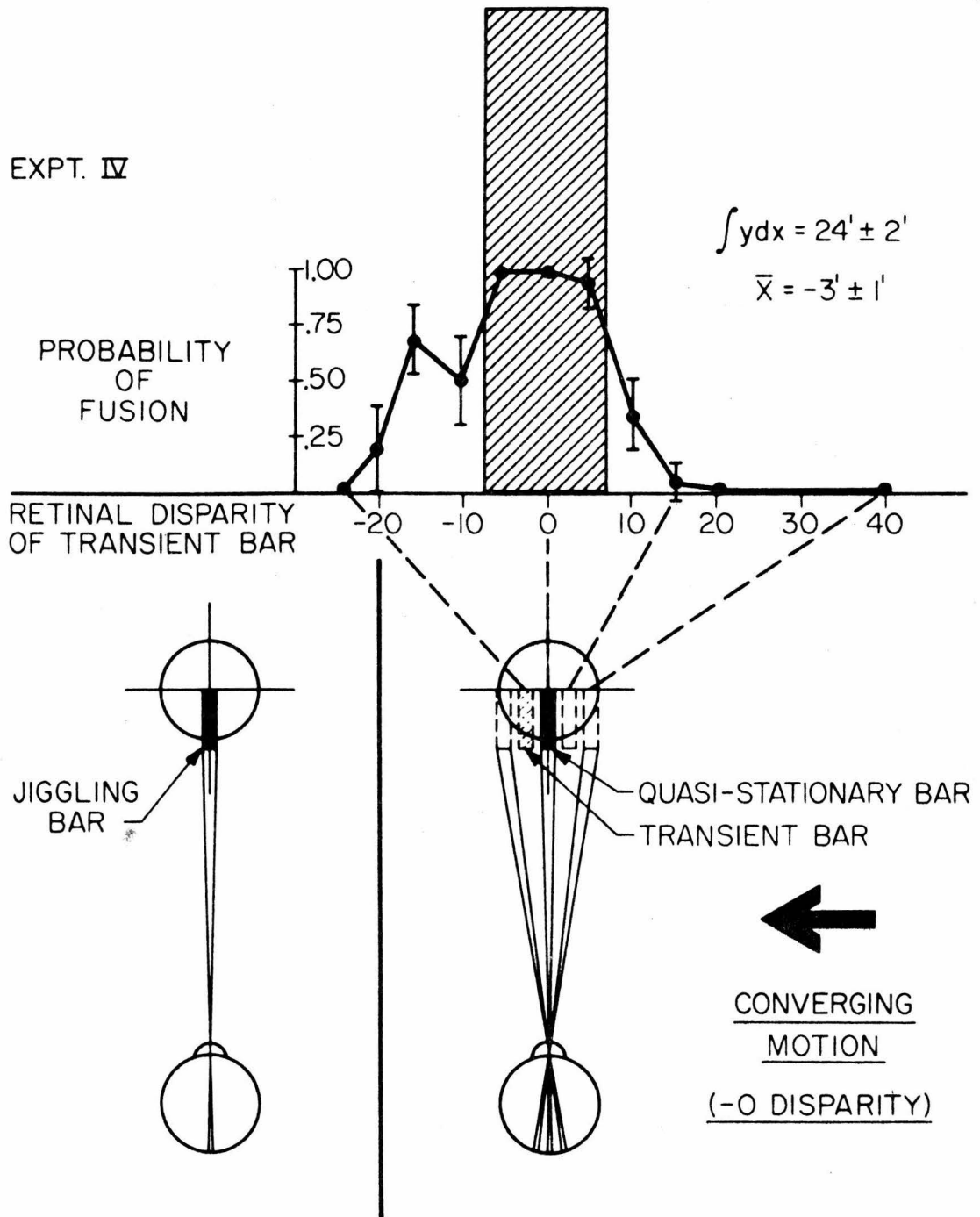


Fig. 14. Experimental method employed to measure probability of fusion as a function of retinal disparity for the stimulus condition of a quasi-stationary bar moving in a converging direction through the zero disparity. Data are for Subject 2.

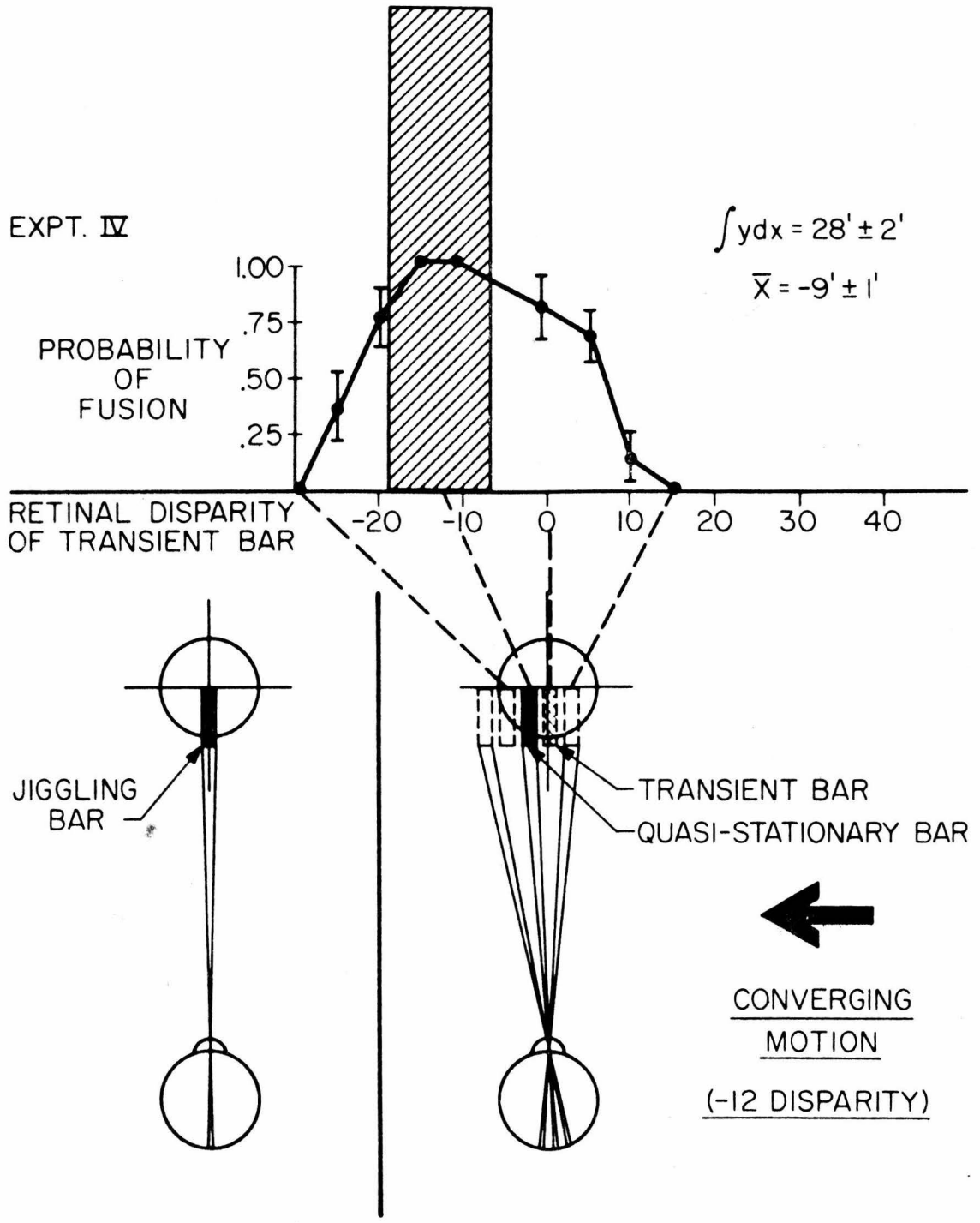


Fig. 15. Experimental method employed to measure probability of fusion as a function of retinal disparity for the stimulus condition of a quasi-stationary bar moving in a converging direction through the -12 disparity. Data are for Subject 2.

extended direction. The two test disparities for Subject 2 were 12 min arc away from the control disparity in each extended direction. For example, for Subject 1, when the q.-s. bar was diverging (moving to the right in real space) the flash might occur either when the q.-s. bar passed through the straight ahead direction (zero disparity with respect to the jiggling bar) or when the q.-s. bar passed through the location 14 min arc to the right (in real space) of straight ahead. However, when the q.-s. bar was converging (moving to the left in real space), the flash might occur either when the q.-s. bar passed through the location of -2 min arc disparity or when the q.-s. bar passed through the location of -16 min arc to the left (in real space) of straight ahead.

The second control is a control for rivalry and fading of the jiggling bar. If this bar is not visible during the flash, the subject cannot possibly see two bars and the test becomes meaningless. This is a particularly difficult problem. The jiggling bar is a retinally stabilized image, and despite the jiggle, is subject to fading, probably because only two-fourteenths of the retinal area stimulated by the bar is experiencing the on-off transient effects of the jiggle.

The stimuli of the right eye, however, are quite strong. The q.-s. bar, as previously discussed, is constantly stimulating new retinal receptors, and the transient bar usually hits all new receptors. The transient bar has a strong masking effect on the jiggling bar particularly over small disparities such as are being tested here.

In order to weaken the right stimuli so that both left and right stimuli are equally strong the right retinally stabilized images were blurred slightly. (An interesting phenomenon was observed. During the adjusting phase of the experiment, when the right stimuli were allowed to remain motionless on the retina, the bars were perceived as blurred. However, when the q.-s. target was moving and the transient target was flashed, each was perceived in sharp focus.) This slight blurring greatly reduced the "disappearance" of the jiggling bar.

The third control is a test for measuring the percept of the two right stimuli during and around the time of the flash. It is essential that no more than one bar is ever perceived by the right eye at any one time. This was tested by turning off the left channel, and viewing only the stimuli of the two right channels, both in non-stabilized and in stabilized vision. The percept was always that of one bar jumping to a new location and then quickly jumping back to its first location; never was the percept that of a second bar briefly presented alongside the first bar.

The fourth control is a test for the detectability of extraneous cues during the flash due to the flash, under binocular conditions. This was tested by occasionally flashing the transient bar in the identical location of the q.-s. bar. Both subjects reported "single" or "three" (they reported "three" when they were not sure they had seen a flash). Thus, the detectability of extraneous cues due to the flash is negligible.

In order to know how Panum's fusional area is changing, it is necessary to probe the right retina with the transient bar in many locations until one finds the "trailing edge" and the "leading edge" of Panum's fusional area for each of the four stimulus conditions being tested. For each stimulus condition (converging motion control disparity, converging motion test disparity, etc.), six "test flash locations" (where the transient bar would be presented) were fed into the computer. These test flash locations were changed until it was apparent that the leading and trailing edges of Panum's fusional area were each somewhere between three of the test flash locations for each of the stimulus conditions.

It is necessary to mention here that Panum's fusional area actually floats about the retina in these dynamic situations, and for the identical conditions, Panum's fusional area need not always be in the same place. The error bars of the data, and the raw data itself, show this quite clearly. One can, at best, find a probability that a particular retinal location is within Panum's fusional area under a given set of conditions. Anyhow, at least two test flash locations are necessary to find a leading or trailing edge of Panum's fusional area. Three test flash locations were used per edge of Panum's fusional area in order to better define these edges.

The fifth control is to insure that the subject did not know ahead of time where the transient bar would next appear, since such knowledge could bias the response. Therefore, at the beginning of each sweep, a random number generator selected the conditions of the flash for that sweep. If the subject did not see a flash at the

control disparity, he knew one would occur at the test disparity, and there is no control for this; but within that restriction, the subject was unable to predict what he would be presented with on any particular sweep. Still another possible cue to the test flash location was the sound of the stepping motor which carried the transient bar target from its last location to its next location. To control for this, the transient bar was always moved well beyond its next test flash location and then returned. This was done so that the total time in which the motor moved the transient target was constant, even if the new test flash location was the same as the old test flash location. As a control, the subject attempted to guess the next test flash location, and, under these conditions, was unable to guess accurately at all. (This control was not used for Subject I, because the extraneous cue of motor sound was not realized until after he had left Caltech.)

3.5.4 The experiment

As mentioned above, Panum's fusional area was measured by the transient stimulus method for four stimulus conditions. Figures 12 through 15 show the stimulus conditions and the resulting data for Subject 2. A comparison of the data of Figure 12 and Figure 13 will reveal the effect on Panum's fusional area of the temporalward extension of Panum's fusional area as effected by the bar stimuli and the regime in which the bar stimuli are presented. A similar comparison of the data of Figure 14 and Figure 15 will reveal the effect of the nasalward extension. A comparison of Figure 12 and Figure 14 will reveal any effects on Panum's fusional area of the direction of the motion of the quasi-stationary bar; the direction of motion is the only difference between the stimulus conditions of Figure 12 and Figure 14 for Subject 2.

3.5.5 The processing of the data

As discussed earlier, Panum's fusional area normally floats about the retina during these dynamic testing regimes. Thus, for a given set of circumstances, a particular location on the retina will have a probability of being within Panum's fusional area for a particular location on the other retina. A binomial distribution analysis of the data is appropriate.

The data of this experiment are presented as a graph of probability of fusion (that is, percent single reports) as a function of the location of the retinally stabilized image of the transient bar (see Figures 12, 13, 14, and 15).

The subjects responded on a one-to-five scale; the data, therefore, can be presented for three criterion levels:

$$\text{Strict: } \% \text{ single} = \frac{\# \text{ reports of "Single"}}{\text{total \# of reports}} \times 100$$

$$\text{Medium: } \% \text{ single} = \frac{\# \text{ reports of (Single + Two + } \frac{1}{2} \text{ of Three)}}{\text{total \# of reports}} \times 100$$

$$\text{Lax: } \% \text{ single} = \frac{\# \text{ reports of (Single + Two + Three + Four)}}{\text{total \# of reports}} \times 100$$

For both subjects, the data do not vary very much for the three criterion levels. The medium criterion was therefore used in the analysis of the data.

For each stimulus condition, a graph of the probability of fusion as a function of retinal disparity was drawn from the data. The area underneath the curve was computed, and used as a measure of the magnitude of Panum's fusional area. Next the area underneath the curve on each side of the center of the quasi-stationary bar was computed. Panum's fusional area was estimated by a rectangle with the same area on each side of the center of the quasi-stationary bar. The rationale for this is that one would like to think of Panum's fusional area as a range of disparities all of which have a probability of 1.0 of fusion.

The center of Panum's fusional area is estimated by the center of the approximating rectangle.

The error bars on the data points are standard deviations computed according to the statistics of a binomial distribution. The error bars on the estimates of Panum's fusional area are standard deviations computed by using the error on the data points.

The final results of these computations are presented in Table IIIa and Figure 16 for Subject 1, and in Table IIIb and Figure 17 for Subject 2. Subject 1's data are not complete, but enough exist to find some statistically significant results.

The locations of the leading and trailing edges of Panum's fusional area are presented in Table IVa for Subject 1 and Table IVb for Subject 2.

3.5.6 The results of Experiment No. 4

Consider the data of Subject 2. The data are found in Table IIb and Table IIc, and are presented in graphic form in Figure 12-15 and 17. The results are listed below. The data of Subject 1 are found in Table IIa and Figure 16.

1) The jiggling bar and the quasi-stationary bar fuse spontaneously at 5 ± 0.3 min arc nasalward disparity and 6 ± 0.3 min arc temporalward disparity. The fused bars break into diplopia at 12 ± 0.3 min arc disparity in both directions. These measurements include over 200 data points each, and will be discussed later.

2) Panum's fusional area for the transient bar and the jiggling bar is measured as 19 ± 2 min arc and 24 ± 2 min arc for the two control conditions (Fig. 17), which is significantly larger than Panum's fusional area for the jiggling bar and the quasi-stationary bar (11 ± 0.4 min arc). This difference is significant beyond the 99.9% confidence interval. (For Subject 1, the values are 29 ± 2 min arc and 14 ± 1 min arc, and this difference is also significant beyond the 99.9% confidence interval.) This may be because a transient bar is a stronger stimulus to the binocular disparity detectors than a slowly

Table IIa

Percent of transient bars perceived as fused with the jiggling bar
 as a function of binocular retinal disparity (min arc)
 for the four stimulus conditions of Experiment No. 4
 Data are for Subject 1

Quasi-Stationary Bar	PERCENT FUSED											
	Disparity (± standard deviation) in min arc											
	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25
Diverging + 0 Disparity						100	(100)	75 ± 22				
Diverging + 14 Disparity						31 ± 13	62 ± 13		(100)	100	35 ± 15	0
Converging - 2 Disparity		62 ± 13	56 ± 18			(100)	100	89 ± 11	50 ± 19		0	
Converging - 16 Disparity	25 ± 33	67 ± 27	100 (100)	100			46 ± 14	29 ± 17		0		

NOTE: Numbers in parenthesis indicate 100% fusion at the disparity of the quasi-stationary bar.

NOTE: Underlined numbers indicate fewer than three data points.

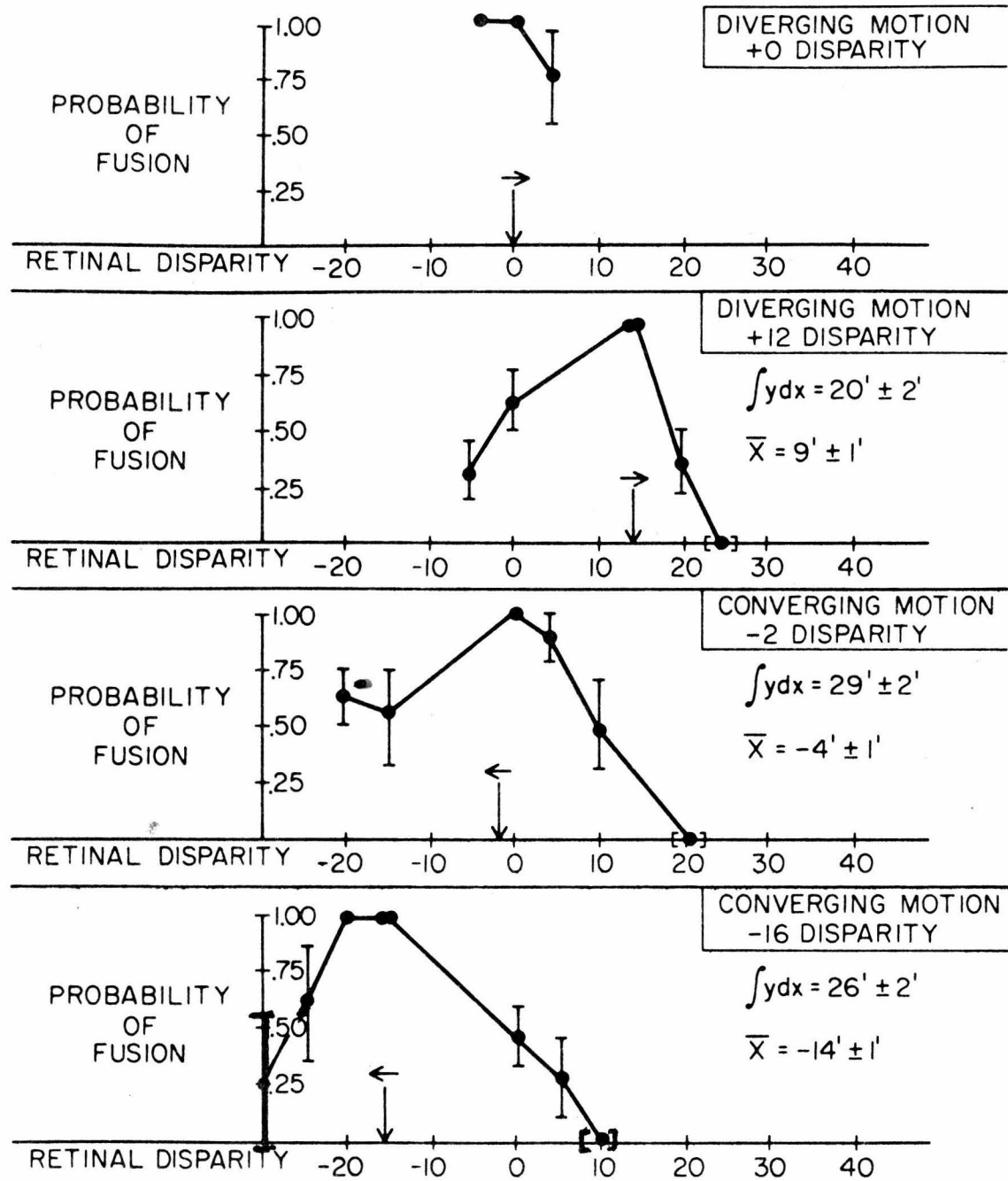


Fig. 16. Probability of fusion as a function of retinal disparity and statistics of Panum's fusional area for the four stimulus conditions of Experiment No. 4. Brackets indicate fewer than three measurements. Data are for Subject 1.

Table IIb

Percent of transient bars perceived as fused with the jiggling bar
as a function of binocular retinal disparity (min arc)
for the four stimulus conditions of Experiment No. 4

Data for Subject 2
("NO BAR" data are from Experiment No. 5)

Quasi-Stationary Bar	PERCENT FUSED										
	Disparity (± standard deviation) in min arc										
	-25	-20	-15	-10	-5	0	5	10	15	20	25
Diverging + 0 Disparity		0	60 ± 16	82 ± 10	(100)	83 ± 15	30 ± 12	30 ± 14			
Diverging + 12 Disparity			27 ± 13	62 ± 13	83 ± 12	(100)	88 ± 12	41 ± 15	13 ± 12		
Converging - 0 Disparity		20 ± 18	68 ± 14	50 ± 19	100	(100)	94 ± 9	36 ± 15	6 ± 8		
Converging - 12 Disparity	33 ± 19	75 ± 15	100	(100)	83 ± 15	69 ± 12	15 ± 11				
NO BAR		6 ± 4	69 ± 9	88 ± 5	(100)	97 ± 3	49 ± 7	5 ± 3			

NOTE: Numbers in parenthesis indicate 100% fusion at the disparity of the quasi-stationary bar.

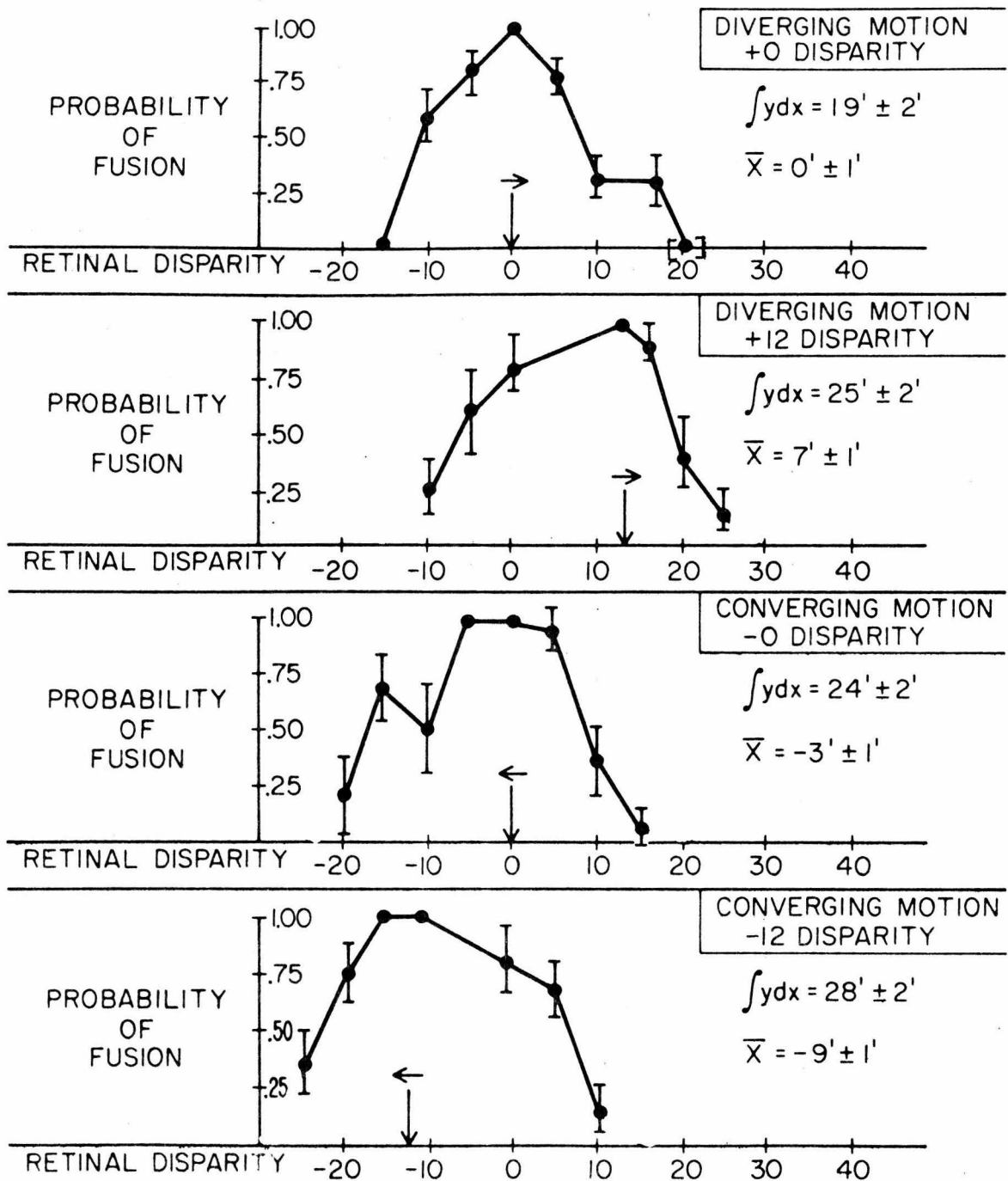


Fig. 17. Probability of fusion as a function of retinal disparity and statistics of Panum's fusional area for the four stimulus conditions of Experiment No. 4. Vertical arrows point to center of location of quasi-stationary bar. Horizontal arrow indicates the direction of motion of the quasi-stationary bar. Brackets indicate fewer than three measurements. Data are for Subject 2.

Table IIc

Mean disparities of fusion and break for Experiment No. 4
for the quasi-stationary bar and the jiggling bar

Conditions		Disparity (\pm standard error of the mean) in min arc				
Experiment Number	Subject Number	Nasal Break	Nasal Fusion	Temporal Fusion	Temporal Break	Number of Trials
4	1	-16 \pm 0.5	-7 \pm 0.4	7 \pm 0.4	15 \pm 0.5	104
4	2	-12 \pm 0.3	-5 \pm 0.3	6 \pm 0.3	12 \pm 0.3	207

Table IIIa

Area and mean (\pm standard deviation)
 in min arc of Panum's fusional area
 as measured in Experiment No. 4
 Data are for Subject 1
 for transient bar and jiggling bar

AREA

Quasi-Stationary Bar	Control	Test
	(0 Disparity)	(+ 14 Disparity)
Diverging	no data	20 \pm 2
Converging	29 \pm 2	26 \pm 2
	(- 2 Disparity)	(- 16 Disparity)

MEAN

Quasi-Stationary Bar	Control	Test
	(0 Disparity)	(+ 14 Disparity)
Diverging	no data	9 \pm 1
Converging	- 4 \pm 1	- 14 \pm 1
	(- 2 Disparity)	(- 16 Disparity)

Table IIb

Area and mean (\pm standard deviation)
 in min arc of Panum's fusional area
 as measured in Experiment No. 4
 Data are for Subject 2
 ("NO BAR" data are from Experiment No. 5)
 for transient bar and jiggling bar

AREA

Quasi-Stationary Bar	Control	Test
	(0 Disparity)	(+ 12 Disparity)
Diverging	19 \pm 1.5	25 \pm 1.7
Converging	24 \pm 1.8	28 \pm 1.8
	(0 Disparity)	(- 12 Disparity)
NO BAR	21 \pm 1	

MEAN

Quasi-Stationary Bar	Control	Test
	(0 Disparity)	(+ 12 Disparity)
Diverging	0 \pm 1	7 \pm 1
Converging	- 3 \pm 1	- 9 \pm 1
	(0 Disparity)	(- 12 Disparity)
NO BAR	0 \pm 1	

Table IVa

Edges (\pm standard deviation)
 in min arc of Panum's fusional area
 as measured in Experiment No. 4
 Data are for Subject 1
 for transient bar and jiggling bar

EDGES

Quasi-Stationary Bar	Control	Test	
	(0 Disparity)	(+ 14 Disparity)	
Diverging	no data	0 \pm 1	19 \pm 1
Converging	- 18 \pm 2 11 \pm 1	- 28 \pm 2	- 1 \pm 2
	(- 2 Disparity)	(- 16 Disparity)	

Table IVb

Edges (\pm standard deviation)
 in min arc of Panum's fusional area
 as measured in Experiment No. 4
 Data are for Subject 2
 ("NO BAR" data are from Experiment No. 5)
 for transient bar and jiggling bar

EDGES

Quasi-Stationary Bar	Control		Test	
	<u>(0 Disparity)</u>		<u>(+ 12 Disparity)</u>	
Diverging	- 10 \pm 1	10 \pm 1	- 6 \pm 1	20 \pm 1
Converging	- 14 \pm 1	9 \pm 1	- 23 \pm 1	5 \pm 1
	<u>(0 Disparity)</u>		<u>(- 12 Disparity)</u>	
NO BAR	- 11 \pm 1		10 \pm 1	

moving, continually present bar. Another possible explanation is that the presence of the two fused bars (the jiggling bar and the quasi-stationary bar) are facilitating disparity detectors of similar disparities, and increasing Panum's fusional area. Experiment No. 5 will attempt to test these two possibilities by repeating the experimental regime without a quasi-stationary bar.

3) Comparison of the graphs of Figure 12 and Figure 14 reveal the presence of "tails" in the probability of fusion. Each tail is in the direction of the disparity change, perhaps indicating that the direction of the disparity change may be a critical factor in the extension process. I focus attention on the direction, and not the disparities stimulated, for two reasons: 1) direction of disparity change is the only difference between the two stimulus conditions, and 2) in the diverging motion zero-disparity situation, for example, up until the occurrence of the test flash, no divergent disparities had been presented on that sweep. Only convergent disparities which were changing in the diverging direction had been presented.

A second possible explanation for these tails may be contamination of the data by the masking phenomena. The masking phenomena will bias the data towards higher percentages of single percepts. A bar flashed in the direction of the motion of a moving bar may well have a stronger masking effect than a bar flashed in the opposite direction.

At this point, I am unable to test this; however I do open the question for future study.

4) Panum's fusional area is significantly shifted for both subjects in both extended conditions. For Subject 2, the trailing edge shifted 4 ± 1.6 min arc (>98% significance) in both test

conditions, and the mean shifted 7 ± 1 and 6 ± 1 min arc (>99.9% significance) in the diverging and converging test conditions respectively. For Subject 1, the trailing edge shifted 12 ± 2 min arc (>99.9% significance) and the mean shifted 11 ± 1.6 min arc (>99.9% significance) in the converging test conditions. The diverging control condition data are incomplete for Subject 1, so no comparisons can be made.

5) For Subject 1, the extended Panum's fusional area is decreased in magnitude, but not significantly. For Subject 2, the extended Panum's fusional area is stretched 6.2 ± 2.2 min arc (>99.4% significance) in the diverging test condition, and 4.7 ± 2.5 min arc (>93.5% significance) in the converging test condition. (NOTE: Subject 2 has a convergent phoria of 1 diopter uncorrected and 4 diopters corrected. The scleral contact lenses are moulded with the subject's refraction correction. His immediate family has a history of eye-muscular imbalance and amblyopia. Subject 2 has a fixation disparity, discovered during this experiment, of about 2-5 min arc. Thus, Subject 2's results may well be a part of his pathology. Subject 1 has no known pathology.)

6) Panum's fusional area is extended significantly beyond the quasi-stationary bar in all cases measured. For Subject 1, the "over-extension" was 5 ± 1 min arc and 12 ± 1 min arc beyond the quasi-stationary bar; for Subject 2, the over-extension was 8 ± 1 min arc and 11 ± 1 min arc beyond the q.-s. bar (in the divergent and convergent test conditions respectively). The bar width is 13 min arc, making the over-extension about one-half to one bar width beyond the

bar itself. Though this may seem small, one must realize that these values correspond to 26, 44, 31, and 39 percent of Panum's fusional area.

7) The zero disparity retinal location is not always in Panum's fusional area. The transient bars flashed at zero disparity (± 1 min arc due to jiggle) are not always perceived as fused. This is particularly surprising when one considers that, at the moment of the flash, the non-stabilized crosshairs are fused. Two possible explanations come to mind. Perhaps the extension of Panum's fusional area is limited only to disparity detectors which are specific to stimuli similar to the stimuli used to induce the extension. (This could easily be tested by flashing various stimuli in both eyes while Panum's fusional area is in the extended condition, and measuring the location of Panum's fusional area as a function of the flashed stimuli form.) It is also possible that the subjects moved their eyes so that the non-stabilized crosshairs no longer fell upon the "zero" disparity. Unfortunately, due to the difficulty of Experiment No. 4 and the earlier conclusions that eye movements were relatively unimportant in the regimes including the crosshairs, the eye movements of the subjects were not monitored in Experiment No. 4; thus no answer can be given to this question at this moment.

In either case, the stabilized images were presented in the retinal locations of zero disparity and were not always perceived as fused (see Table V). For Subject 1, only about half ($62\% \pm 13\%$ and $46\% \pm 14\%$ for convergent and divergent test conditions respectively) of all the transient bars flashed at zero disparity were perceived as single.

Table V

Percent of zero disparity stimuli reported fused when presented during the extension of Panum's fusional area

Subject	Divergent Extension	Convergent Extension
1	62 \pm 13	46 \pm 14
2	83 \pm 12	83 \pm 14

For Subject 2, $83\% \pm 12\%$ and $83\% \pm 15\%$ of the transient bars flashed at zero disparity were perceived as fused. Therefore, no retinal disparity always signals fusion, and the notion of fixed corresponding retinal points must be re-evaluated.

It may be significant that Subject 1's transient bars were presented when the q.-s. bar was 14 (or 16) min arc disparate with the jiggling bar, while Subject 2's transient bars were presented when the q.-s. bar was only 12 min arc disparate with the jiggling bar. The further extension of Panum's fusional area for Subject 1 may be the relevant factor in his perceiving the zero-disparity transient bars as unfused with the jiggling bar more often than did Subject 2.

8) A new method has been discovered to measure the duration of the extension of Panum's fusional area after fusion is lost, and diplopia is perceived.

It was mentioned earlier that Panum's fusional area floats about the retina. Thus, on some test sweeps, the jiggling bar and the q.-s. bar will be fused when the test flash occurs, and on the other test sweeps, the two bars will not be fused when the test flash occurs. Subjects reported "early", "little early", "little late", or "late" when flashes occurred before fusion occurred or after fusion was lost. By studying the "little late" and the "late" data, I was able to estimate the decay time of the extension of Panum's fusional area.

The subjects were instructed to hold down the psychophysical button whenever they perceived two bars and to release the button whenever they perceived one fused bar. (The exception to this

instruction were the percepts of the flashes, which were reported verbally, and the percepts of rivalry, which the subjects were not instructed to report.) Each time the button was pushed or released, the computer recorded the location of all targets. By comparing the location of the q.-s. bar at the time fusion was lost with the location of the q.-s. bar at the time of the test flash, I was able to determine roughly how much time had passed between the loss of fusion and the occurrence of the test flash. (I say roughly because the q.-s. target moved at two min arc per sec, and the computer outputs target position in one min arc intervals with a noise level of about one min arc).

With these rough measurements, I estimate one second \pm one half second, for the decay time of the extension of Panum's fusional area for a disparity of \pm 12 min arc. Thus, if fusion was lost about one second ago, the test flashes were usually perceived as if fusion still existed (that is, the extended condition results.) However, if fusion was lost two seconds ago or earlier, the test flashes were usually perceived as if Panum's fusional area was not extended. This agrees well with the occlusion data of Fender and Julesz.

This phenomenon is not well-quantified simply because it was noticed after the data collection was completed for both subjects. Further, this thesis does not direct itself to this question, and I only report it to let it be known that such a test is feasible.

3.5.7 Discussion of the results of Experiment No. 4

One of the major conclusions of the Fender and Julesz work was that Panum's fusional area was stimulus dependent. This conclusion was based primarily on two observations. The first observation was that in stabilized vision, the two dark bars (13 min arc wide by 60 min arc tall) fused at disparities of 42 ± 10 min arc, while the two halves of a random dot stereogram fused at 6 ± 2 min arc disparity for the same subject. The second observation was that the extension of Panum's fusional area was grossly different for the two stimuli pairs (23 min arc for the bars, and 114 min arc for the random dot stereograms.)

All my subjects, in the earlier experiments, fused the two bars between 10 and 20 min arc ± 1 or 2 min arc. After training (that is, the hundred trials of Experiment No. 4), both Subjects 1 and 2 fused the two bars at 5-7 min arc ± 1 min arc. This agrees well with the results reported by Ogle (1964) for fine threads, and also Fender and Julesz (1967), for random dot stereograms. Incidentally, by jiggling the image of the left bar, another criterion to distinguish fusion from rivalry (that of the fused percept jumping back and forth in depth) was obtained. Thus, my measurements are highly reliable.

Many differences exist between the experimental conditions of this thesis and the work of Fender and Julesz; these differences might account for the differences in our results. The differences that I feel are most likely to be relevant are the following:

- 1) The borders of the stimulus slides were not visible in my work, but were in their work.

2) My subjects were instructed to attempt to distinguish between fusion and rivalry, but Fender and Julesz (personal communication) did not pay much attention to rivalry.

3) My stimuli were moved by computer-driven stepping motors which have very different velocity and acceleration spectra than the smoother, hand-driven target motions used by Fender and Julesz.

4) My subjects were instructed to passively observe the experimental stimuli, but the subjects of Fender and Julesz (personal communication) exerted effort to try to fuse the images.

5) My subjects' scleral contact lenses were held tightly against the eyes by suction whereas no such suction was present in the work of Fender and Julesz.

These and other differences between our work exist, and future research will have to decide which, if any, were responsible for our different results.

3.5.8 Experiment No. 5

As mentioned above, Panum's fusional area for the transient bar and the jiggling bar is significantly larger than Panum's fusional area for the quasi-stationary bar and the jiggling bar. This may be because a transient stimulus is a stronger stimulus to binocular disparity detectors than a non-transient stimulus, or because the presence of the two fused bars (the jiggling bar and the quasi-stationary bar) are already facilitating disparity detectors tuned to similar disparities.

Experiment No. 5 tested the facilitation hypothesis by repeating the

experimental regime of Experiment No. 4 without a quasi-stationary bar. That is, the left eye was presented with a jiggling bar, and the right eye was presented only with a transient bar. During the interim between transient bars, the right eye was presented with a blank field which the subject had previously adjusted for luminance match to the background of the transient bar.

In this manner, Panum's fusional area was measured in the absence of disparity domain facilitation.

The results of Experiment No. 5 are presented in Figure 18 and Tables IIb, IIIb, and IVb for Subject 2, and are not significantly different from the results of the control conditions of Experiment No. 4. The edges of Panum's fusional area are -11 ± 1 and 10 ± 1 min arc for NO BAR condition (Experiment No. 5), -10 ± 1 and 10 ± 1 min arc for diverging control condition (Experiment No. 4), and -14 ± 1.5 and 9 ± 1 min arc for the converging control condition (Experiment No. 4). The area and mean of Panum's fusional area is 21 ± 1 min arc and 0 ± 1 min arc for the NO BAR condition (Experiment No. 5), 19 ± 2 min arc and 0 ± 1 min arc for the diverging control condition (Experiment No. 4) and 24 ± 2 min arc and -2.5 ± 1 min arc for the converging control condition (Experiment No. 4).

Thus a non-transient (continually present) stimulus will fuse over a significantly wider range of disparities with a transient (flashed) stimulus than with another non-transient stimulus.

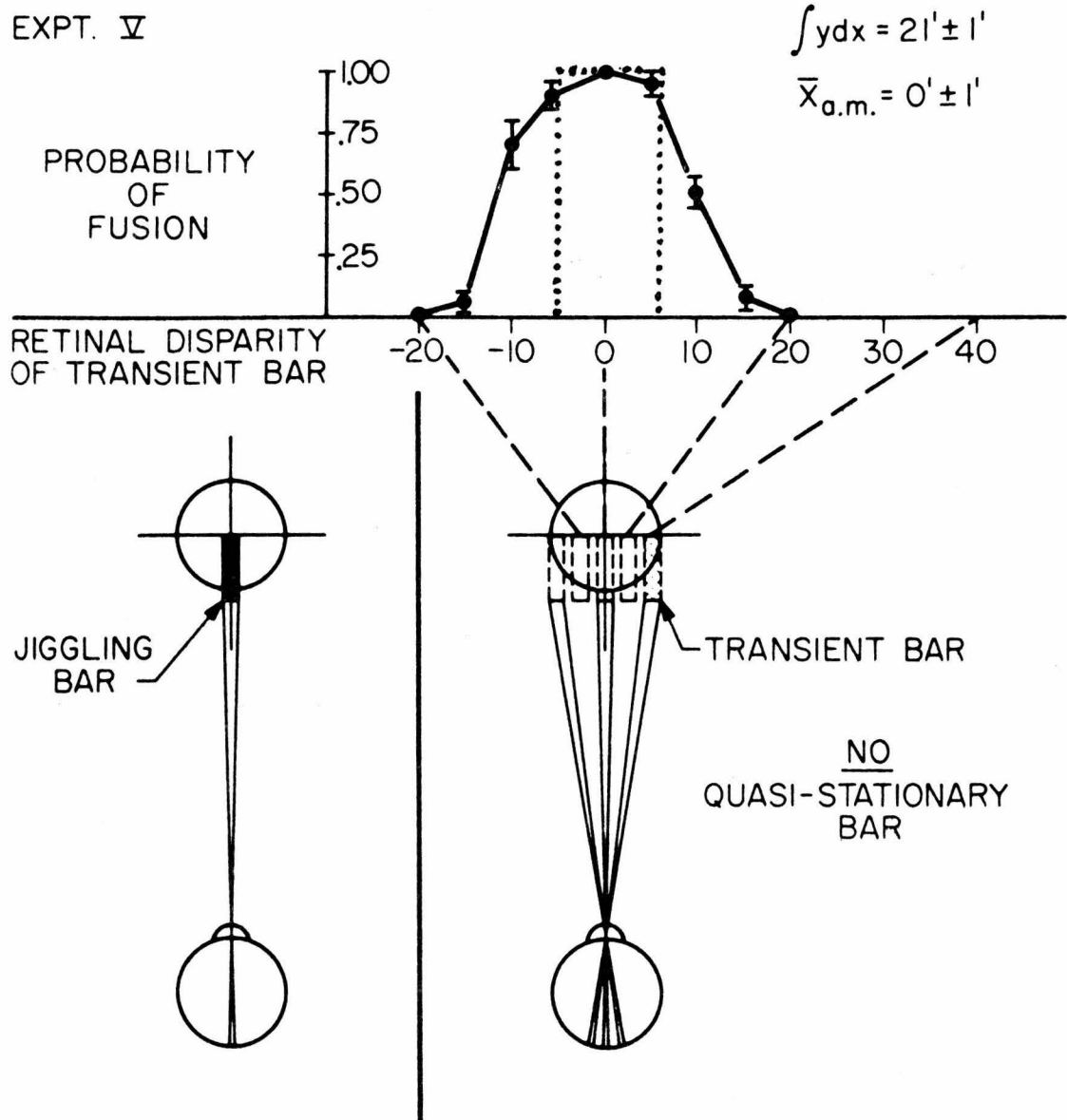


Fig. 18. Probability of fusion between a jiggling bar and a transient bar and the resulting statistics of Panum's fusional area. The dotted line shows Panum's fusional area for a jiggling bar and a quasi-stationary bar. Data are for Subject 2.

IV. TRIALS AND TRIBULATIONS

Five major problems exist in running experiments like the ones in this thesis. They are:

- 1) Equipment difficulties
- 2) Subject-related difficulties
- 3) Fading of retinally stabilized images
- 4) Rivalry
- 5) Masking phenomena

Each will be discussed briefly, and suggestions will be made to future researchers, where possible.

4.1 Equipment difficulties

The equipment necessary for retinal stabilization by the method of scleral contact lenses and an optical lever, is complex and difficult to keep adjusted. It is not uncommon for major adjustments to require one to three months to accomplish. The scleral contact lenses require about six weeks simply to be manufactured, and each subject must have an individually moulded set. They are expensive as well as uncomfortable.

4.2 Subject-related difficulties

There are three subject-related difficulties: finding subjects, training subjects, and keeping subjects. The discomfort of the contact lenses, both psychological and physical, make the selection of subjects a delicate task. One tries to find individuals dedicated

enough to vision research to persevere through several months of discomfort, and at the same time, one wants subjects who are naive. Subject naivety is normally the trait that is sacrificed.

The training of the subjects is also a delicate task. One tries to train the subjects to make subtle discriminations without educating the subjects too much about the phenomena being tested. Occasionally, the subject will misunderstand the distinctions to be made, and will report on a phenomenon different from the one the experimenter is trying to measure.

The keeping of subjects is also a delicate task. The discomfort of the lenses, personal tragedies, or major moves in life can often remove a subject from the lab just at a critical moment.

My suggestion to future researchers regarding stabilized vision experiments is to design your experiments to be quick and minimally demanding on the subjects. If this is not possible, I recommend you find a way to test the phenomena without stabilized vision. Whenever you find you cannot follow the above advice, and are determined to run a stabilized vision experiment which is not quick and easy, I strongly recommend you find individuals as capable and willing to guide you as I have found Derek Fender and Bela Julesz to be.

4.3 The fading of retinally stabilized images

Despite what people may say about high-contrast stabilized images resisting fading, I say they fade. My subjects have all experienced a good deal of fading, and as a result, have put a good deal of effort into controlling the fading of stabilized images. At this point, I can

offer two suggestions: 1) Keep your stimuli moving if possible, and 2) Attempt to train your subjects to overcome fading by volition. I have no quantitative data, but I have heard a number of subject reports, stating that the fading of retinally stabilized images can be controlled by volition. This, of course, merits further research.

4.4 Rivalry

A major limitation to the reliability of fusion experiments is the subject's ability to distinguish fusion from rivalry.

If rivalry occurs before the two bars are perceived to fuse, and the subject is fooled into reporting fusion, the error will result in an inflated measurement of the fusional area, and a resulting smaller hysteresis, than is actually present. However, if rivalry occurs just as a fused percept would otherwise break into diplopia, and the subject is fooled, a loss of fusion will be reported well beyond the break point: thus an erroneously large hysteresis.

Rivalry can therefore completely confuse the issue, and must not be allowed to do so. Criteria must be developed to distinguish fusion from rivalry. Often, the subject is the best inventor of such criteria.

For example, at fusion, Subject 2 reported a brief interval in which he could perceive the two bars "slide over one another, forming a heavy, dark bar." He could often perceive this when the bars were rivalling, as the suppressed bar would re-appear just in time for this fusion percept to occur.

Subject 1 did not see the two bars "slide over one another", but

he did develop the criterion of "the sudden formation of a solid, dark bar."

At break of fusion, both subjects reported a clear break point, where the stimuli "jumped apart."

Another suggestion is to design stimuli regimes in which a fused percept and a rivalrous percept have a distinct, visible difference. For example, by jiggling one bar and not the other, I made a fused percept that would jump back and forth in depth, whereas no rivalrous percept could do so. A second such example is to design stimuli such that the perceived velocity of a fused percept can be distinguished from the velocity of a rivalrous percept. A fused bar travels at about the average velocity of the two unfused bars. A single unfused bar travels at its own velocity. Since in all the experiments either both bars moved symmetrically or only one bar moved, perceived bar velocity was always slower for fused bars than for rivalrous bars. A sudden increase in velocity in a single bar could alert the subject to the possibility that a break of fusion had occurred and he was now perceiving only one monocular bar. This criterion, coupled with a strict attention to the other bar, often seemed to cause the other bar to reappear.

This criterion was also employed at the fusion location, but here one looked for a decrease in velocity.

If nothing else, perceived velocity was used to know when to trust a data point. If a subject felt uncertain about a data point, the experimenter noted this uncertainty, and the data point was not counted.

4.5 Masking

The masking problem is similar to the rivalry problem. The distinction I draw between masking and rivalry is that masking occurs between the transient stimulus and the non-transient stimulus, whereas rivalry occurs between non-transient stimuli. Masking was controlled in this thesis by slightly blurring the channel of the apparatus which was most likely to mask out the other channel; that is, by slightly blurring the channel which contained the transient stimulus. The data of Subjects 1 and 2, for Experiment No. 4, changed significantly when the right channel of the apparatus was slightly blurred. The data for the blurred condition are reported as the results of Experiment No. 4. When both channels of the apparatus were in sharp focus, however, both subjects reported "fusional ranges" of the most peculiar kind. The "probability of fusion" graphs were triple peaked, with their local minima located just outside the fusional range for the blurred conditions. (See Figure 19.) Many of the "fused" bars appeared to be "light and crisp" rather than "heavy and dark," and were perceived to be without binocular depth. This led the experimenter to suspect a masking phenomenon; and upon blurring of the right channel, the masking weakened, and the jiggling bar could now be seen alongside the transient bar. The transient bar, incidently, remained light and crisp, and without binocular depth.

Future experimenters who are considering using transient stimuli to measure Panum's fusional area should be advised to present the transient stimuli to both eyes, and to be wary of masking phenomena.

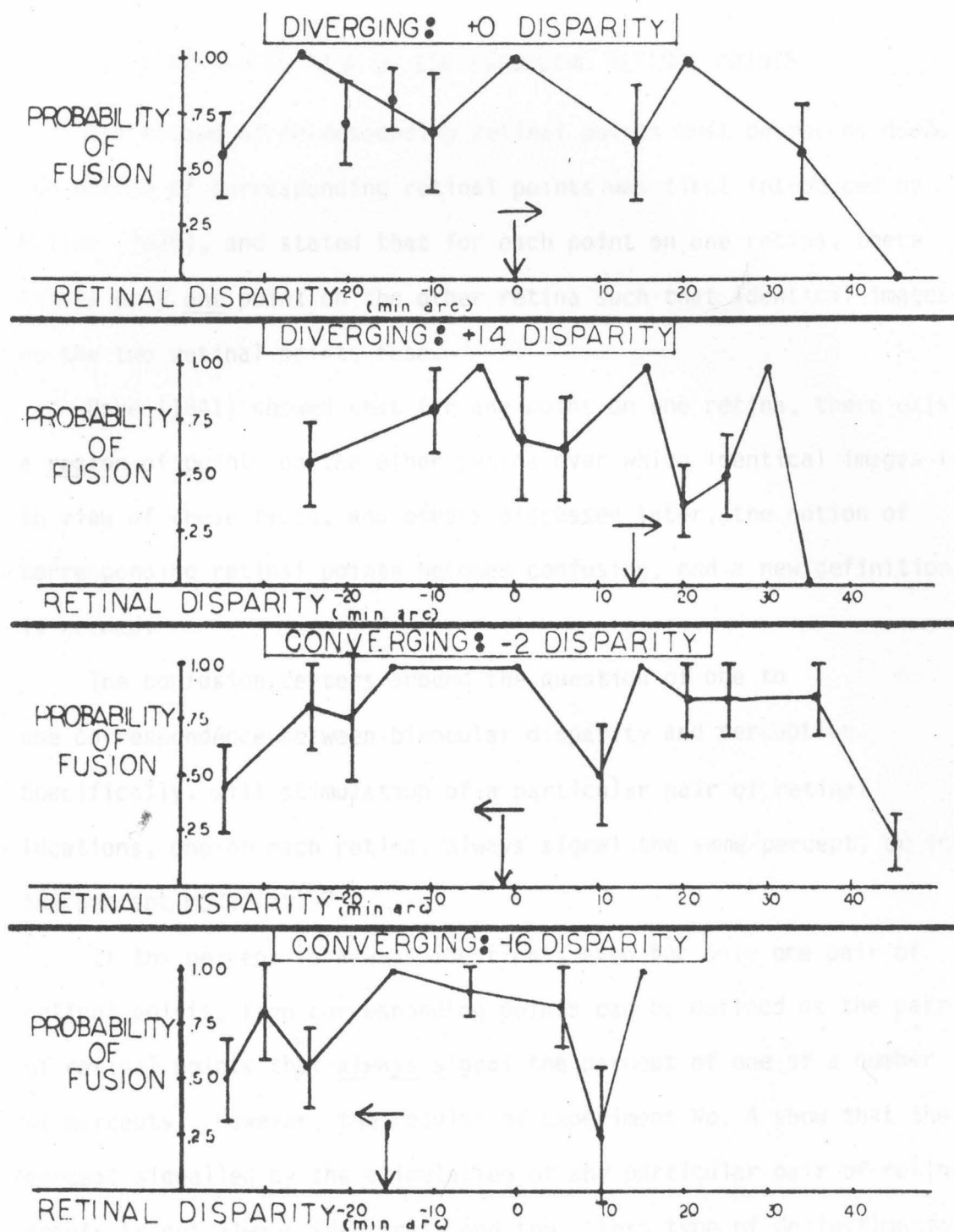


Fig. 19. Effects of masking phenomena on measurement of Panum's fusional area as measured in Experiment No. 4. Compare this figure to Figure 16, in which masking phenomena were controlled for. Data are for Subject 1.

V. A NEW DEFINITION OF CORRESPONDING RETINAL POINTS

The notion of corresponding retinal points must be reconsidered. The notion of corresponding retinal points was first introduced by Müller (1826), and stated that for each point on one retina, there exists only one point on the other retina such that identical images on the two retinal points fuse.

Dove (1841) showed that for any point on one retina, there exists a region of points on the other retina over which identical images fuse. In view of these facts, and others discussed later, the notion of corresponding retinal points becomes confusing, and a new definition is needed.

The confusion centers around the question of one to one correspondence between binocular disparity and perception. Specifically, will stimulation of a particular pair of retinal locations, one on each retina, always signal the same percept, or is the percept modifiable?

If the percept is always identical, even for only one pair of retinal points, then corresponding points can be defined as the pair of retinal points that always signal the percept of one of a number of percepts. However, the results of Experiment No. 4 show that the percept signalled by the stimulation of any particular pair of retinal points is not always identical, and thus, this type of definition fails.

Another possible type of definition of corresponding retinal points is "any pair of retinal locations, one on each retina, which have zero disparity (or some other particular disparity) with

respect to the retinal locations of fixation". The problem with this type of definition is that the angle between the retinal locations of fixation (and the fixation target) are constantly changing by amounts comparable to and often significantly greater than Panum's fusional area (Fender and Julesz, 1967).

Another possible definition of corresponding retinal locations is "any pair of retinal locations, one on each retina, upon which identical images are ever able to fuse". This definition has usefulness particularly if the following proposal is true: identical images projected upon a pair of retinal locations can produce a fused percept of the two images if and only if the two retinal locations are connected to the same binocular disparity detector.

If this proposal is true, then this final definition of corresponding retinal locations will be valuable as it brings the jargons of two areas of vision research, specifically psychophysics and neurophysiology, together.

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