Oculomotor Effects upon Binocular Rivalry*

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Summary. Binocular rivalry was generated by projecting dissimilar Julesz-type patterns to each eye. The minimum angular width of the patterns needed to observe rivalry was measured at four retinal eccentricities for two simulated viewing distances: 200 and 20 cm. The angular width needed to just detect rivalry was up to 50% greater for the 20 cm viewing distance as compared with the threshold width measured at 200 cm. This increased tolerance for rivalry for near fixation was inversely proportional to the change in apparent size. The results suggest that the lateral geniculate nucleus is the site of size-scaling or "zooming".

For some time, it has been known that convergence or accommodation can influence the apparent size and apparent distance of an object (Helmholtz, 1910; Heinemann *et al.*, 1959; Leibowitz and Moore, 1966; Foley, 1967). Such changes in apparent size are often observed when the members of a pair of stereo images presented to each eye are interchanged, thereby altering disparity and convergence (Wheatstone, 1852). These size changes are truly due to influences associated with binocular mechanisms, for there are no other cues available when the effect is observed with after-images in the dark. As convergence is altered, both the size and the apparent distance of the after-image will change[1]. Thus, in some manner, the oculomotor system appears to be able to exert a neural influence over the perception of size and distance, thereby changing the metric for visual space. The object of this study is to localize the approximate site in the visual system where the metric for visual space may be altered by accommodation or convergence.

Before proceeding further, however, an important distinction must be recognized: The effect of accommodation and convergence of immediate concern is not the same as the classical size-constancy phenomenon, which is based largely upon contextual cues available in a well-structured visual environment (Leibowitz and Moore, 1966; Julesz, 1968). The true effects of oculomotor adjustments upon apparent size are at most

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1 Changes in depth with convergence are best observed by using two after-images, each formed by two bleaching lights placed at different distances.

a factor of $4\times$ in magnitude when all contextual cues to size and depth are eliminated. These effects of the oculomotor influences are thus an order of magnitude less than the classical size-constancy phenomenon[2]. To distinguish between the classical size-constancy phenomena which are based principally upon monocular cues and context, and the oculomotor effects on size observed when contextual cues are eliminated, the latter will be called "zooming". Thus, the "zoom illusion" represents the changes in apparent size which are correlated with convergence and accommodation, *with no contextual cues to depth or size available*. The object of this study is to determine the approximate site of "zooming" in the visual system.

As a first step toward isolating the site of the zooming operation, it is convenient to determine whether this operation precedes or follows the first site of binocular interaction. The prior evidence is scanty. For example, even though zooming does affect figural after-effects (Sutherland, 1961), acuity (Aubert, 1865; Biedermann, 1927; Freeman, 1932; Luckiesh and Moss, 1941; DePalma and Lowry, 1962), areal summation (Richards, 1967) and CFF (Harvey, 1968), the site which provides the limiting constraints for these tasks cannot yet be accurately localized. Even the evidence for stereoacuity is somewhat ambiguous, because increasing the convergence does not always yield a monotonic decrease in acuity over the complete range of natural fixation distances (Amigo, 1963). Perhaps the most suggestive data previously available are measurements which may reflect the size of Panum's area. For example, an increase in Panum's area would explain the increasing tolerance for fixation disparity observed as fixation distance is reduced (Hoefer, 1906; Ogle, 1950). In Hoefer's experiment, the magnitude of fixation disparity necessary to account for his data increased from 3.9 min of arc at 50 cm to 13.4 min at 15 cm. An examination of fixation-disparity curves taken at different distances or with different spherical corrections suggest similar increases for near fixation. Furthermore, possible alterations in Panum's area are indicated by variations in horopter settings, where the mean angular error markedly increases as the fixation distance is reduced (Ogle, 1950). Part of this effect may be due to the previously

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2 For example, the Holway and Boring (1941) data show approximate constancy with a rich contextual environment for measurements from 3 to 35 meters. This range for contextual cues is further extended to 30 cm by the results of Harvey and Leibowitz (1967). On the other hand, McCready's summary (1965) of the data of von Holst (1955) and Heinemann *et al.* (1959) shows that when contextual cues are reduced, the amount of "size-constancy" expected over the range of ∞ to 10 cm is only about $4\times$ for the average observer. My own observations using two pinpoints of light in the dark (thereby eliminating all contextual cues) found the greatest amount of "zooming" to be $2.8\times$ from 200 to 25 cm for one subject in a total of twenty-five examined.

mentioned decreases in acuity. Nevertheless, such increases in the variability of the horopter settings suggest that the areal limits for stereopsis have also increased as convergence is increased, thereby implying that the effects due to convergence must take place at or before the level of disparity detectors in the cortex.

However, a more conclusive demonstration that the zoom operation resides at or before the level of "disparity detectors" would be to show that zooming may affect binocular rivalry. Binocular rivalry appears when each eye is presented with different patterns, such as horizontal lines to one eye and vertical lines to the other. The sensation is an alternation between the conflicting inputs to each eye, which interact dynamically in an antagonistic manner often with the appearance of lustre. These binocular contrast effects are assumed to occur at the first site in the visual pathway where the signals from each eye interact, presumably in area 17. Some quantitative properties of these rivalrous effects have been stated recently by Kaufman (1963) and Levelt (1965). The relative spatial dimensions and configurations are most important parameters. Obviously, once maximum rivalry has been obtained for two different patterns in the left and right eyes, then making the patterns more and more similar will weaken the rivalrous effects. In particular, if the patterns seen by both eyes are similar except in one small region, then this region of difference can be made sufficiently small so that no binocular rivalry can be observed. The dependent variable in the following experiments is this minimum area, analogous to Panum's area, over which two monocular patterns must differ before binocular rivalry can be observed. Of interest is whether this minimum area will be altered when convergence or accommodation are changed. If convergence alone will alter the minimum area needed to see binocular rivalry, then the site for zooming would have to be at or precede the site of binocular interaction[3], which is presumably in area 17 where binocular units are found in primates (Hubel and Wiesel, 1968; Marg et al., 1968).

In order to examine this possibility, the tolerances for detecting rivalry between two different monocular patterns were measured for two fixation conditions: 200 and 20 cm, at various retinal eccentricities. These tolerances for rivalry were then compared with changes in apparent size observed under the same conditions.

Method and Apparatus

Fig. 1 shows the Julesz-type pattern (1963) made from zip-a-tone, which was used to produce binocular rivalry. If this figure is viewed so that each pattern is

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3 This conclusion is stronger than is logically warranted, and is made for simplicity of exposition. The statement is true only if the criterion for detecting rivalry is not altered. This possible objection will be discussed later after the changes in the areal tolerances for rivalry are correlated with the changes in apparent size.
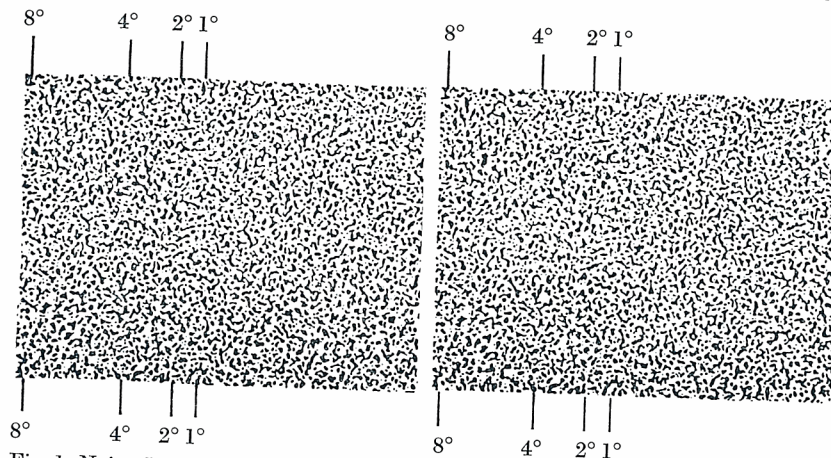
Fig. 1. Noise pattern used to generate binocular rivalry. The lines indicate fixation positions at 1, 2, 4 and 8° from the rivalrous border

seen by separate eyes, then the right-hand half of the combined pattern will rival — largely in the form of a shimmering or binocular lustre. On the other hand, the left side of the combined display, being identical in each pattern, will fuse easily and will remain stable. Because of the random nature of the display, the pattern appears the same regardless of which eye is dominant. Only the shimmering or lustre distinguishes the rivalrous area on the right from the non-rivalrous, left-hand side of the display. In practice, the patterns shown in Fig. 1 were projected onto a polarized screen by a Compco stereo projector, with polarization axes at 45 and 135°. Each pattern was seen independently by each eye by placing polaroid goggles over the eyes. The luminance, as seen without the polarizers, was 100 ft.-L. The subject sat with his head resting on a chin rest, and was positioned so that his eyes were 200 cm from the screen. The overhead room lights were on, but dimmed, giving the screen a background luminance of about 20 ft.-L.

Above and below the left side of the projected pattern were lines indicating the desired regions where the subject should fixate. As shown in Fig. 1, these lines were 1, 2, 4 and 8 degrees from the rivalrous border. The task of the subject was to maintain fixation along a given (imaginary) vertical line joining a pair of the fixation cues. He was encouraged to move his eyes up and down occasionally along the fixation axis, picking another fixation speck along the imaginary line in order to minimize Troxler fading of the more peripheral portions of the stimulus pattern.

At the beginning of each trial, the entire rivalrous area was visible. With the subject fixating appropriately, the experimenter then gradually reduced the extent of the rivalrous area, from greater eccentricity to less. This maneuver was accomplished by moving an occluder which was placed adjacent to the slide itself, thereby replacing a portion of one of the projected zip-a-tone patterns by the homogeneous background illumination of the screen. As has been shown most clearly by Levelt (1965), if contours are present in one eye and a homogeneous area is seen in the corresponding positions in the other eye, then only the contours are seen, without the appearance of rivalry except near the edge of the homogeneous field. This method of eliminating rivalry can be demonstrated in Fig. 1 by placing a gray piece of cardboard over part of the rivalrous portion of the right-hand member of the pair

of patterns. (In practice, because the occluder was not exactly in the plane of the slide, the projected edge of the occluder was slightly blurred.) As the occluder is advanced, rivalry is eliminated in the outer portions of the display, and the total width of the rivalrous area can be gradually narrowed. In the experimental situation, the final position of the occluder was set by command from the subject, who was instructed to indicate the minimum width needed to just observe binocular rivalry or lustre. Generally, the occluder was brought in from the periphery at $1/2$ to 1 degree per sec until rivalry disappeared. After the disappearance, the rivalrous area was then increased in $1/2$ degree steps until the subject once again observed rivalry. Depending upon his criterion, occasionally the subject requested fine bracketing adjustments before he settled upon a final position. In each session, two such measurements were taken at each fixation position, but with a left-right reversal of the pattern and fixation positions. On successive days the polarizers were reversed, thereby causing the occluded portion to alternate between eyes. These variations yielded a total of four different measurements for each fixation position.

In order to change convergence and accommodation, rotary prisms set at 15 diopters (base-out) together with −4 diopter lenses were placed before the eyes on a trial frame. In effect, the addition of the prisms and lenses forced convergence and accommodation to the equivalent of 20 cm viewing distance without appreciably altering the retinal size of the rivalrous patterns. (In fact, there was an 8% reduction in size due to lenses being 2 cm from the pupil; all measurements have been corrected for this change.) Even though the retinal image had been essentially unchanged, the apparent size of the images, of course, was reduced by the zooming effect associated with convergence. In practice, the "near" fixation condition of 20 cm imposed by the prisms and lenses was always run either before or after the previously described distant viewing condition of 200 cm. In the latter case, the same trial frame, together with the rotary prisms, continued to be worn over the eyes, but with the lenses eliminated and the prisms set at zero diopters. Just as in the 200 cm condition (when the viewing distance was reduced to 20 cm by the prisms and lenses), four measurements were also taken: left or right fixation positions and occluding the rivalrous pattern in either the left or right eye.

Subjects

Three emmetropic observers served as subjects: WR (the author) MS (a female student), and HF (a male undergraduate). The mean interpupil distance was 6.5 cm. Because the prism settings were the same for all observers, individual variations in interpupil distance will cause the simulated viewing distances to differ somewhat from the reported values of 200 and 20 cm. However, for each observer, these departures from the nominal values will be the same for all conditions, and hence the comparisons between conditions will still be valid.

Results

Figs. 2, 3 and 4 show the mean settings for just detecting rivalry for the three subjects. For each fixation position, there are two sets of data points: the circles correspond to the condition with fixation equivalent to a 200 cm distance; the crosses are results for the condition equivalent to fixation at 20 cm. The ordinates indicate the minimum retinal angle needed to detect rivalry.
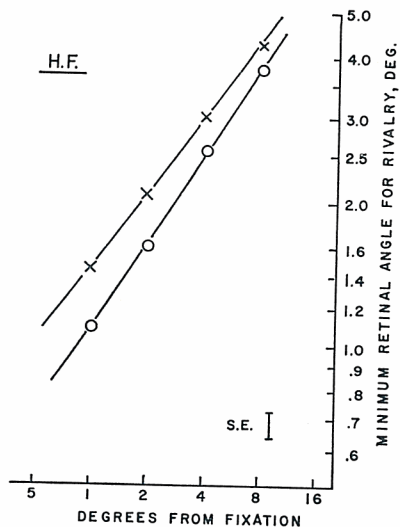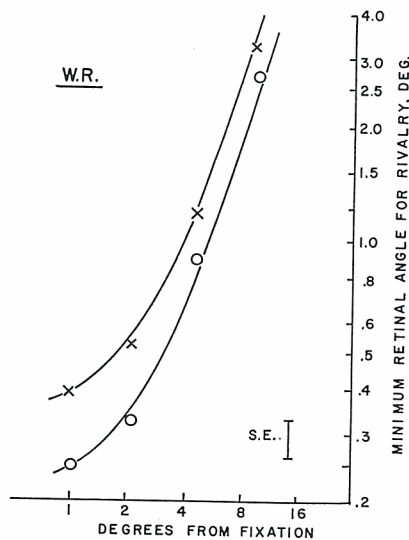
Fig. 2

Fig. 3

Fig. 2. Effect of convergence upon the minimum retinal angle needed to detect rivalry in Fig. 1. Circles: 200 cm viewing distance; Crosses: 20 cm equivalent viewing distance

Fig. 3. Same as Fig. 2; subject: WR

For all observers, near fixation increased the tolerance for rivalry as compared with distant fixation. In addition, as retinal eccentricity increases, the percentage increase in the angular tolerance for rivalry decreases, as indicated by the circles and crosses coming together as eccentricity increases in Figs. 2, 3 and 4. This decrease in the relative differences between the two fixation conditions could be due to a property of the zooming operation, whereby peripheral stimuli are less affected by zooming than foveal stimuli (see Aubert, 1865). In this case, the relative changes in apparent size when fixation distance is altered might be expected to be less as the retinal eccentricity of the stimulus increases. This possibility will be examined in a later section.

A more conservative interpretation of the effect of retinal eccentricity upon the tolerances for rivalry, however, is the possibility that one of the fixation conditions did not yield a sharp image. Even though all of the subjects reported sharp images, the differences between the two fixation conditions shown in Figs. 2, 3 and 4 are similar to the changes in contrast thresholds reported by Ogle (1961) when the retinal image is blurred. Thus, it is possible that when convergence and accommodation were forced to 20 cm, focus was not perfect and some blurring of the

retinal images may have occurred. If the contours are not sharp, then binocular contrast effects would presumably be weaker. Thus, a greater stimulus width would be expected to be necessary in order to observe rivalry if the patterns were blurred.

Blurred Images

To examine the effect of blurring upon the tolerance for rivalry, the two naive observers HF and MS were rerun with the patterns blurred an equivalent of about 1 diopter by defocusing the projector[4]. Considering that all subjects stated that the normal viewing conditions yielded sharp images, the 1 diopter amount of blurring should have been about twice as great as any detected defocusing under the normal viewing conditions (Campbell, 1957). With the images now blurred, HF was rerun at the zoomed-up conditions of 200 cm, whereas MS was rerun at the equivalent of 20 cm. Fig. 5 shows the results as a ratio of the blurred versus sharp pattern tolerances. If there were no effect of defocusing, then this ratio would remain at 1.0 for all retinal eccentricities. Values greater than 1.0 would indicate that blurring increased the tolerance for rivalry — in the expected direction as indicated by the arrows. Contrary to expectation, however, the tolerance for rivalry decreased when the patterns were slightly blurred. This effect can not be due to the changes in image size introduced by defocusing, for the next section suggests that changes in image size do not alter the tolerances for rivalry. Instead, this surprising result was apparently due to an increase in the lustre in the rivalrous areas when they were slightly defocused. One explanation for the increased rivalry is that, like some monocular Mach-bands (Charman and Watrasiewicz, 1964), binocular contrast may be heightened by replacing a step gradient with a ramp. However, excessive fixation disparity arising from the difficulty in focusing on blurred patterns may also be an important factor. In any case, because the 1 diopter defocusing reduced the tolerance for rivalry, the effect of zooming upon rivalry shown in Figs. 2, 3 and 4 cannot be attributed to a small amount of blur unless the 200 cm condition was harder to maintain than the 20 cm condition — an unlikely possibility.

Size of Pattern Texture

Still another possible uncontrolled variable which might have affected the results of Figs. 2, 3 and 4 is the size of the texture of the pattern used to generate rivalry. Clearly, as the texture becomes increasingly fine, approaching a homogeneous field, the rivalrous effects must become

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4 The equivalent amount of blur was estimated by monocularly focussing on a pencil tip placed at 67 cm and observing the blur of the pattern on the screen at 200 cm.
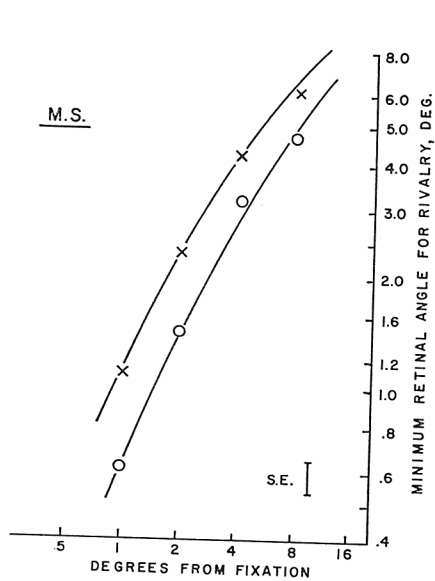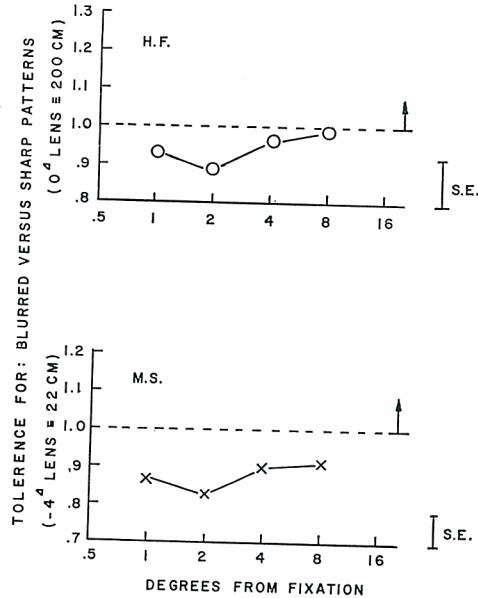
Fig. 4

Fig. 5

Fig. 4. Same as Fig. 2; subject: MS

Fig. 5. Effect of defocusing upon the minimum retinal angle needed to detect rivalry in Fig. 1. The ordinate is the ratio of the defocused to the in-focus measurements. The arrows indicate the direction that the ratio must be displaced from 1.0 in order to explain Figs. 2, 3 and 4. Contrary to expectation, defocusing made rivalry easier to detect at all retinal eccentricities

less and less. The present fine-grained pattern most probably explains why the tolerances for rivalry are much greater than the values of Panum's area measured with line stimuli. In order to determine whether or not the slight (8%) reduction in retinal image could have seriously affected the tolerances for rivalry, one series of measurements was made on HF with a new pattern which was twice as coarse as those used previously. Fig. 6 shows the result by taking the ratio between the tolerances for the coarser and normal patterns. Thus, over a 2 × range of texture size, there is no effect of a coarser pattern upon binocular rivalry. This result also suggests that the decrease in apparent pattern density induced by convergence is not the major factor leading to the increased tolerance for rivalry shown in Figs. 2, 3 and 4.

Apparent Size Measurements

Figs. 2, 3 and 4 show that when fixation distance is changed, then the angular tolerance for rivalry is also altered. These changes in the
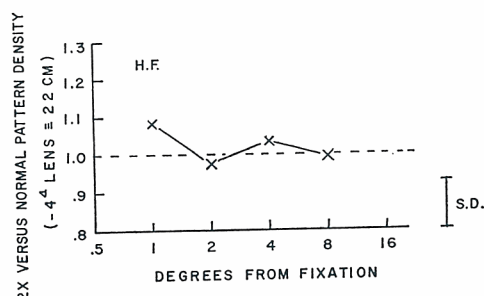
Fig. 6. Effect of pattern density upon minimum retinal angle needed to detect rivalry. There is essentially no change in the results when the pattern density of Fig. 1 is doubled

angular tolerance for rivalry do not appear the result of a blurring of the retinal images, and thus must represent an internal neural change, which is correlated with changes in convergence and accommodation. Oculo-motor adjustments are therefore found to affect two different kinds of judgments 1. apparent size (and depth) and 2. spatial tolerances for rivalry. If a single mechanism — i.e., a neural "zoom" system — is common to both effects, then the changes in the angular tolerance for rivalry should be related to the changes in apparent size observed under similar conditions.

This relationship between apparent size and the tolerance for rivalry can be visualized more clearly by considering the two rivalrous patterns in Fig. 7, seen by the retinae of the left and right eyes. Before being combined at the cortex, the neural activity associated with each of these two patterns would first pass through a zooming operation. The zoom would supposedly increase the effective size of both neural images when the eyes were diverging (DIV), whereas both neural signals would be constricted in effective display area if the eyes were converging (CON). Thus, depending upon whether the oculomotor system was in a convergent or divergent state, the display area of the neural activity projected onto the cortex would be altered. The transformed retinal images which arrive at the cortex after passing through the zoom in the convergent state would be relatively smaller in area than the same retinal images that passed through the zoom in the divergent state. These two results are depicted by the two different sizes of the combined rectangles projected onto the cortex.

Now consider that the basis for detecting binocular rivalry at the cortex is the spatial extent of the dendritic fields of the binocular units. The relevant extent of these fields should remain constant, and is represented by the bar in Fig. 7 labelled "cortical tolerance for rivalry".
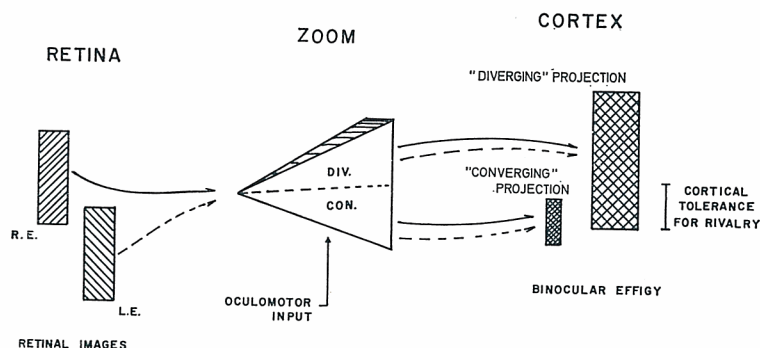
Fig. 7. Schematic diagram showing how a zoom system interposed between the retina and the cortex might alter the display areas of retinal images projected onto the cortex

Then, for the retinal images shown in Fig. 7, the cortical representations will be just at the limiting size needed to observe rivalry providing that the zoom system is in its convergent (CON) state. For this condition the height of the rectangle displayed to the cortex is the same as the tolerance for rivalry. If, on the other hand, the zoom system is in its divergent state, then the images projected onto the cortex will greatly exceed the threshold tolerance for rivalry. Thus, for a divergent state of the zoom, the retinal images must be reduced in size in order that their cortical counterparts will more closely approach the threshold for rivalry. To summarize: if the zoom operation precedes the site of binocular rivalry, then smaller retinal images processed by the zoom in a divergent (DIV) state will be equivalent to larger retinal images transformed by the zoom in the convergent (CON) state.

The strongest prediction which could be made from Fig. 7 is that the changes in the angular width needed to observe rivalry should be proportional to the changes in apparent size. This prediction can be tested directly by measuring the changes in apparent size when convergence is altered from 200 to 20 cm, and comparing these changes with the results of Figs. 2, 3 and 4.

Method

Changes in apparent size induced by accommodation and convergence were measured using the noise pattern shown in Fig. 8. This pattern was projected as before onto the polarized screen and viewed with goggles. When fused, it yielded a series of four identical vertical rectangles, each subtending $5° \times 20°$, and each set back in space from its neighbor. Thus, the stereo effect was a staircase on its side. With the nearest rectangle as a reference, the task of the subject was to match, one at a time, the width of each of the other three rectangles to the standard. Once again, as in the measurements for rivalry, the occluder near the plane of the slide was advanced in order to reduce the effective width of each

rectangle. All measurements were made with the screen at 100 cm, but each set of judgments was made with one of four different degrees of convergence and accommodation: 1. prisms at $-4\,\Delta$, lenses at $+1$ D; 2. prisms at $0\,\Delta$, lenses at 0 D; 3. prisms at $7.5\,\Delta$, lenses at -2 D; and 4. prisms at $15\,\Delta$, lenses at -4 D. These prisms and lens settings placed the screen at four different equivalent fixation distances: infinity, 100 cm, 33 cm, and 20 cm. The true fixation distance, however, varied within each condition according to which rectangle was being fixated. The relative disparities of these rectangles were equal and were arranged so that the extreme depths overlapped with one of the equivalent distances used in the neighboring condition. For example, if the left-most standard rectangle appeared optically at an equivalent distance of 60 cm in the 0 diopter condition, then the most right-hand rectangle would have an equivalent fixation distance of 60 cm when the $7.5\,\Delta$ prism and the -2 D lens condition was introduced[5]. By stepping from one condition to another in this manner, the stimulus sizes and intensities were kept approximately invariant, and yet the changes in apparent size induced by convergence would be measured over a wide range of equivalent fixation distances[6].

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5 With the steps on the projected stereo display separated by a 2 cm disparity at 100 cm, then each step corresponds to a change in the angle of convergence of $\alpha = \tan^{-1} 0.02 = 1.1$ degrees. This angle is equivalent to 0.31 meter angles for a 6.5 cm interpupil distance. With the screen at 100 cm (the convergence angle of 3.8 degrees is equivalent to 1.0 meter angles), two such steps of 0.31 meter angles each brings the nearest rectangle to an equivalent fixation distance of 1.62 meter angles, or $1/1.62 = 62$ cm. For the $7.5\,\Delta$ and $15\,\Delta$ prism conditions, the disparity steps were about 4 cm, or equivalent to 0.63 meter angles. Thus, if the prisms placed the screen optically at 33 cm, then two such steps backward would reduce the 3 meter angle distance of the screen to 1.74 meter angles, or about 60 cm as before. The error introduced by the discrepancies between the two overlapping distances is less than the error introduced by the scatter of the apparent size estimates shown in Figs. 9 to 11.

6 Because binocular parallax was used to produce the staircase effect, the accommodation within a given staircase must have been partially uncoupled with the changes in convergence. However, the results of Heinemann *et al.* (1959) show a) "that changes in convergence are a sufficient condition for the occurrence of the changes in apparent size, and b) that changes in accommodation are not necessary conditions for the occurrence of the changes in apparent size". The extent to which changes in accommodation alone can change apparent size is unsettled. In order to measure the error in estimating the apparent size changes using the staircase method, two of the observers (MS was unavailable) were rerun at a much later date using a newer technique. This new method involves the successive matching in the dark of the vertical separation between two pairs of two pin-points of light. Only one pair of lights can be seen at a time. One pair of pin-points is seen at 200 cm, whereas the second pair is placed optically at varying fixation distances by prisms and lenses before the observer's eyes. The lenses are adjusted to provide optimum focus (and were slightly less strong than the values used above). The observer then adjusts the vertical separation of one pair of lights until the separation appears the same as that of the second pair seen through the prisms and lenses. The measured changes in apparent size with convergence were $1.33\times$ for HF and $1.67\times$ for WR, or within 5% of the values given in the Table. The similarity of the results, in spite of the probable accommodative differences between the two methods, suggests that it is not accommodation, but rather convergence which is the most relevant variable for zooming.
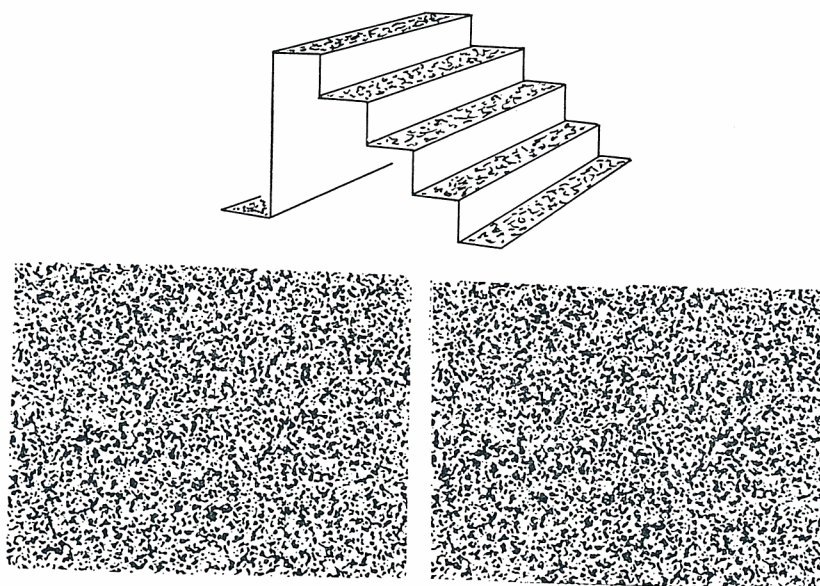
Fig. 8. Patterns used to generate a "stereo-staircase". The inset shows the staircase
in perspective

This procedure yielded relative apparent widths for each of the four "steps"
of the stereostaircase, for each of the four prism conditions. For example, when
the screen was placed at the simulated viewing distance of 100 cm, the ratios of the
widths of the stairs might be 1.0; 0.9; 0.8; 0.7. Now if the preceding condition,
with the screen placed at infinity, yielded the ratios 1.1; 1.05; 1.0; and 0.9, then the
100 cm values would be reduced by 0.9 to 0.9; 0.81; 0.72; 0.63, thus making them
relative to the adjacent condition with the screen at infinity. A similar procedure
was followed for pinning the remaining two conditions. The final ratios were then
normalized to 1.0 at the simulated fixation distance of infinity.

Results

The individual measurements of apparent size versus equivalent
fixation distance are shown in the upper left-hand portion of Figs. 9,
10 and 11. Each figure contains the data for a different observer, with
the apparent-size measurements normalized to 1.0 at infinity. The curves
showing the changes in apparent size with equivalent fixation distance
are similar for all observers, with customary individual variations in the
magnitude of the effect (Heinemann *et al.*, 1959).

Also included on the figures are vertical dashed lines which indicate
the two equivalent distances of particular interest: 200 and 20 cm. At
each of these two fixation distances the relative apparent sizes of the
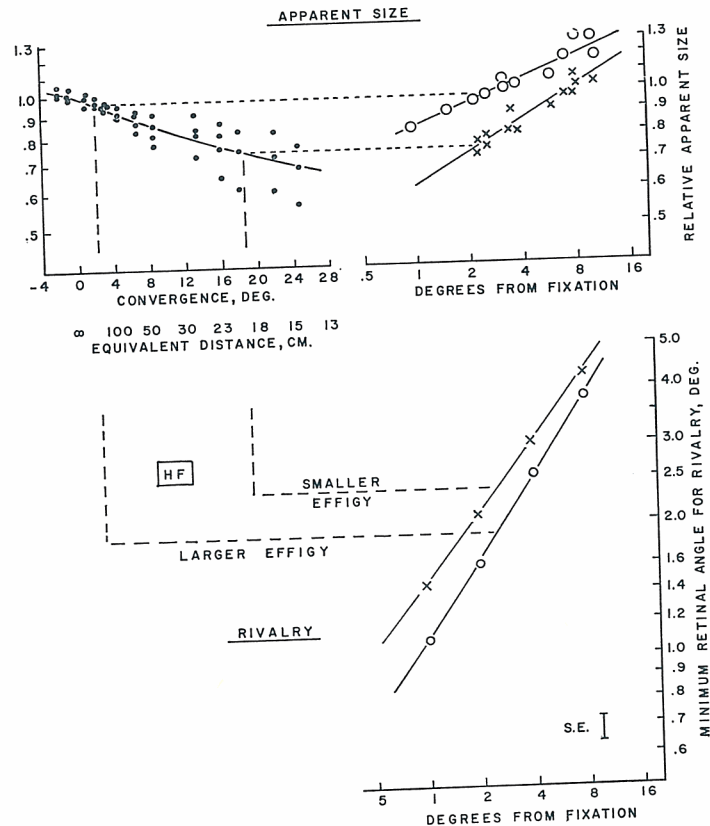invariant retinal images may be determined for each observer, and

Fig. 9. The upper left-hand graph shows the changes in apparent size of a fixed retinal image as convergence is increased. These data were obtained using Fig. 8, as described in the text. The upper right-hand graph shows how apparent size changes with increasing retinal eccentricity. The circles represent measurements made at 200 cm viewing distance; the crosses are similar measurements made at an equivalent fixation distance of 20 cm. The lower right-hand graph shows the previously measured minimal retinal angles needed to see rivalry for observer HF. The horizontal dotted lines indicate how the upper two graphs are related. The dashed lines merely indicate corresponding positions on the upper-left and lower right-hand graphs; the positions of the data points are independent of this construction. The vertical displacement between the two curves for both right-hand graphs may be compared directly, because the ordinates have the same log scale. Equal vertical displacements for each retinal eccentricity (degrees from fixation) indicate that the change in the retinal angle needed to detect rivalry is inversely proportional to the change in apparent size

then compared with the changes in the minimum angle for binocular rivalry. The relative apparent-size values at the two fixation distances have been tabulated be low in the left-hand portion of the table,

together with their ratio. For comparison, the right-hand side of the Table also shows the minimum angular widths needed to see rivalry. These data are the same as that given in Figs. 2, 3 and 4 at 2° eccentricity from the fovea. The right-most column is the inverse of the ratio of the minimum widths for the 200 cm and 20 cm conditions listed in the neighboring two columns. The comparisons of most interest, therefore, are the values in the two ratio columns for each observer. These two ratios may also be compared directly on Figs. 9, 10 and 11, as all ordinates have the same logarithmic scale.

Table

Observer	Apparent size Relative to 1.0 at ∞			Minimum width for Rivalry, deg.		
	200 cm	20 cm	ratio	200 cm	20 cm	ratio^{-1}
HF	0.97	0.74	1.31	1.80	2.30	1.28
WR	0.89	0.55	1.61	0.40	0.63	1.57
MS	0.88	0.50	1.75	1.60	2.60	1.62

For all observers, the proportionate changes in apparent size are approximately identical to the proportionate changes in the minimum angle needed to see binocular rivalry. Ideally, if it were the apparent size of the image which solely determined the minimum tolerance for rivalry, then the relative increases in the minimum widths for rivalry should exactly equal the fractional change in apparent size. The close agreement between the two ratio columns — within 4% — supports this possibility, and suggests that the same zoom mechanism underlies both the changes in apparent size and the changes in binocular rivalry.

As a further test for the direct proportion between apparent size and changes in angular widths needed to see rivalry, measurements of apparent size were made at different retinal eccentricities at the two equivalent distances used before: 200 and 20 cm. Of particular interest is whether or not the effect of fixation distance upon apparent size decreases with eccentricity in the same way that the differences in the tolerances for rivalry are altered.

Method

The apparent size measurements were made by projecting the capital letter "I" of fixed size (1° high by 0.14° wide) to the fovea and of variable size to the periphery. The foveal "I" was present continuously and provided both a fixation point and the standard size. The variable "I's" were projected irregularly with 40 msec flashes, and appeared at varying eccentricities from the standard fixation "I". The steady-state luminance of both "I's" was 100 ft-L, presented on top of the 20 ft-L background luminance of the screen. For each flash, the task of the
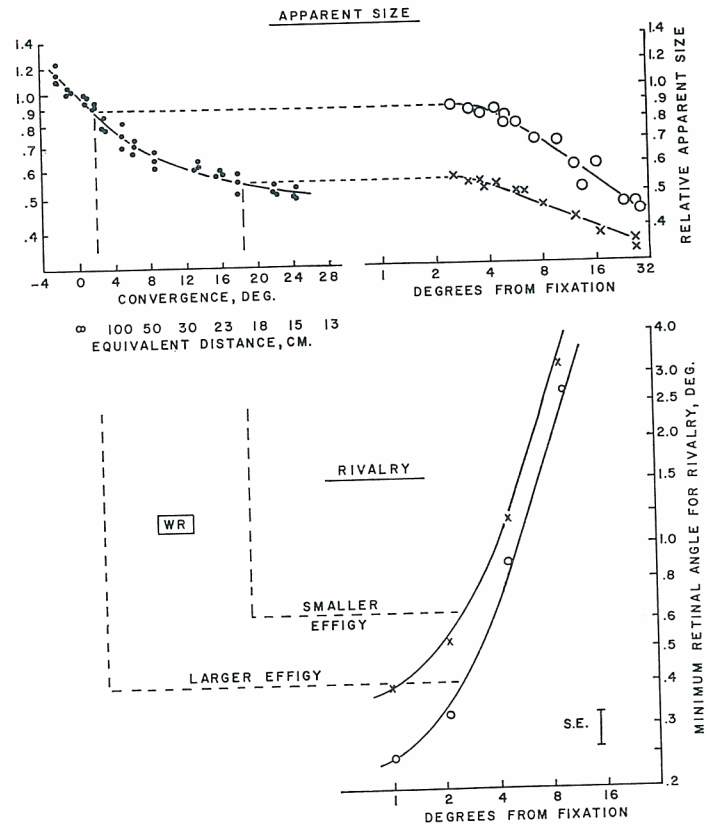
Fig. 10. Same as Fig. 9; Subject: WR

subject was to report whether the peripheral "I" appeared larger than or smaller than the foveal standard. If the variable "I" appeared too large, then the eccentricity of the "I" was generally increased, or vice versa if the "I" appeared too small. (The procedure had to be reversed for HF, who reported an increase in apparent size when an object of a fixed size was moved away from the fovea.) In this manner, the retinal eccentricity which yielded an equal number of "greater-than" vs "less-than" responses was determined for ten "I's", each of different size. Two such sets of data were collected, one at a 200 cm viewing distance and the second at the viewing distance equivalent to 20 cm. The ratio of the sizes of the foveal and peripherally presented "I's" could then be used to calculate how apparent size changed as retinal eccentricity increased for both the 200 and 20 cm viewing distances. The data for each viewing condition were also normalized in order to account for the fact that the apparent size of the 1° foveal standard seen under the 20 cm viewing condition appeared smaller than the same 1° standard seen at an equivalent viewing distance of 200 cm. This normalization was made by using the data obtained previously from the stereo staircase, which showed how the apparent size of a foveal stimulus changed with fixation distance.
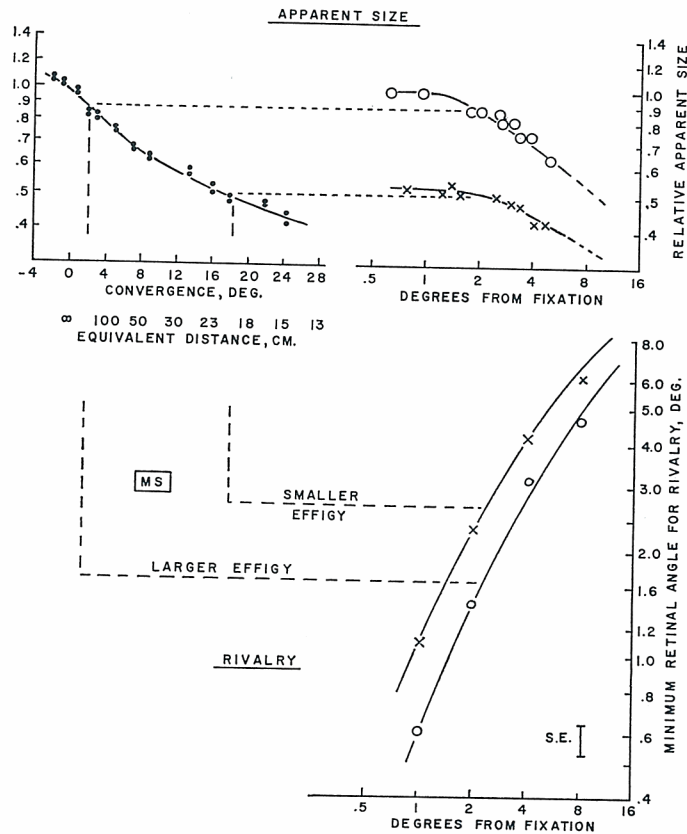
Fig. 11. Same as Fig. 10; Subject: MS

Results

The results showing how apparent-size varies with retinal eccentricity appear on the upper right-hand portion of Figs. 9, 10 and 11. The data points represent a combination of right and left-field measurements, and reveal no significant differences in apparent size in the left and right hemi-fields over this range of eccentricities. The crosses are the measurements taken at a 20 cm equivalent fixation distance; the circles are the corresponding points obtained at 200 cm. The vertical positions of both sets of points have been adjusted to match their respective counterparts at 200 cm and at 20 cm on the apparent-size curve shown in the upper left-hand graph of each figure.

The final comparison of interest is the ratio between the apparent sizes of an invariant retinal image at 200 and 20 cm (upper right-hand graph) and the minimum retinal angle for rivalry, replotted in the lower

right-hand graph. As the logarithmic scale of each ordinate is the same, equal vertical separations will correspond to equal ratios. Thus, the ratio comparisons between the two right-hand graphs may be made directly. In spite of the fact that the curves are grossly different for each observer, the proportionate changes in apparent size agree closely with the changes in the angular tolerance for binocular rivalry. The proportions are nearly the same at each retinal eccentricity; only the ratios are inverted for apparent size as compared with angular width needed to see rivalry. This inversion is in complete accord with Fig. 7, and provides strong evidence that the zoom operation which affects apparent size is also the same mechanism which altered the angular tolerances for binocular rivalry.

Discussion

If the site of binocular rivalry is taken to be area 17 in the visual cortex, as is suggested by electrophysiological data, then the results of the previous experiments show that the site of zooming must be at or precede this stage in the visual pathway. The zooming appears to have affected the monocular inputs before they have reached the level of binocular interaction. The most crucial assumption behind this statement is the one which regards the cortical tolerance for rivalry as fixed, independent of oculomotor adjustments. If the cortical tolerance (see Fig. 7) is altered, for example by a shift in the observer's criterion for threshold, then the site of zooming cannot be determined without first locating the site where the criterion shifted. The strongest argument against such a criterion shift is the data themselves: why would a criterion be altered in proportion to the changes in apparent size? The simplest explanation is to assume instead that the criterion remains reasonably constant and that it is the apparent-size shift which caused the proportional changes in the angular limits for just-detecting rivalry.

The assumption that the cortical tolerance remains invariant is tantamount to requiring that the dendritic fields of the cortical neurons receiving binocular inputs do not change size. These dendritic fields should supposedly be physically invariant over the limited time span of the experiments. The invariance of dendritic fields, however, does not require that the receptive fields of the neurons, as measured on a tangent screen, should also be invariant. Because the receptive fields are not defined in terms of millimeters at the cortex, but rather in terms of objective visual angles, the size of the receptive field will depend upon the particular state of the zoom system, which lies between the cortex and the tangent screen. Restated: the neuroanatomical data should be invariant, but the electrophysiological maps should be affected by oculomotor adjustments.

Possible structures corresponding to a zoom system proceding the site of binocular rivalry are the retina, the lateral geniculate nucleus, and the fourth layer of the visual cortex, where the dendrites of the axons from the geniculate cells terminate. Of these three sites for the zoom, the lateral geniculate is the most reasonable for two important reasons: 1. it receives efferent activity correlated with oculomotor adjustments (Bizzi, 1966; Feldman and Cohen, 1968) and 2. its many layers provide several spatial maps of the visual field (Polyak, 1957). If the flow of information through the lateral geniculate nucleus can be altered by the oculomotor centers, then such switching from one geniculate layer to the next could result in different retinal projections onto the cortex (Richards, 1968). These changes in the mapping of each retina onto the cortex would be seen as changes in apparent size even though the retinal images themselves might have been invariant.

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