SENIOR PROJECT: OPT. 699

THE EFFECTS OF VERGENCE DEMAND AND FIXATION DISPARITY ON STEREOPSIS

by

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Abstract:

Although forced vergence is known to effect fixation disparity, studies on the effects of vergence demand on stereopsis and the relationship between fixation disparity and depth perception have been mostly inconclusive. This study was designed to investigate the hypothesis that stereopsis breaks down as vergence demand causes fixation disparity to exceed Panum's fusional area. A novel computer software application which generates anaglyph targets to separately measure fixation disparity and stereopsis under forced vergence conditions is used with a Z-100 Zenith microcomputer. Thirty-nine subjects with normal binocularity were tested. The highly variable results show a definite reduction of depth perception at the extremes of the fusional range. A correlation between stereopsis and fixation disparity is not clearly demonstrated. Only minor decreases in stereopic performance are observed in some subjects despite relatively large fixation disparity values for the same vergence demand, suggesting that stereopsis is a more deeply ingrained binocular function. A critique of the methods used in this investigation is included, with areas of possible improvement pointed out and refinements suggested.

KEY WORDS: stereopsis, fixation disparity, forced vergence, binocular fusion lock, double-ogive curve, central area of non-appreciable depth (CANAD).

Introduction:

Stereopsis and fixation disparity are both binocular phenomena which involve the highest order of cortical processing within the human visual system. Stereopsis (depth perception) involves matching corresponding points of the images in the retinas of the two eyes, measuring their disparity, and from this information deriving a perception of the three-dimensional structure and relative depth of objects in visual space[1]. Fixation disparity, as defined by Panum[2], is a small misalignment of the two eyes under the conditions of binocular fusion. The visual axes miss exact intersection at the point of fixation but sensory fusion is still perceived because corresponding retinal points within Panum's fusional area are stimulated. As first concluded by Ogle[3], the magnitude of fixation disparity often varies with the amount of stress placed on binocular fusion. Graphic representations of the change in the fixation disparity as a function of varying amounts of forced vergence are known as Ogle curves, and four types of response patterns are known.

Extensive research has been conducted on these two phenomena and the idea has arisen that fixation disparity and stereopsis might be interrelated; that perhaps stereopsis might breakdown with increasing vergence demand in some correlation with fixation disparity amounts.

Fry and Kent[4], in their research conducted in the late 1930's, were among the first to address this question. They concluded that base-in and base-out prisms affected stereoacuity in some cases, but had no effect in others. They attributed the effects observed with base-out demand to the accommodation which is known to be induced by convergence; the resulting blur reducing stereoacuity. This reasoning does not hold for base-in demand, however, and they could not explain the breakdown of stereopsis they observed with forced divergence. Also, they observed greater fatigue effects when BO prisms were presented before BI prisms.

Similar effects involving increased disparity, and thus depth, detection with BO vergence demand relative to BI vergence demand have been observed by more recent researchers. Although not directly addressing fatigue effects, their ideas are worth noting here. Fischer and Poggio[5] proposed that crossed and uncrossed disparity may be processed by different pools of disparity detectors and that since there are a larger number of cells processing crossed disparity[6] ,properties will differ. Manning, et. al.[7] found evidence to support this claim and further added that a longer duration time is maintained for neurons which detect uncrossed disparity, thus enhancing performance for BO vergence demand.

Although Fry and Kent speculated about the role of fixation disparity in depth perception, Cole and Boisvert[8] were the first to investigate this hypothesis. In the report of their research conducted in 1974, they explain a retinal area within Panum's which they call the central area of non-appreciable depth (CANAD). The following is an excerpt from their paper:

> "For a subject to appreciate stereopsis, a mimimum disparity between fused retinal images must exist. This minimum disparity is referred to as stereo-threshold and is expressed as distal threshold or proximal threshold. The total range of points between the distal stimulus and the proximal stimulus will be seen as if they were at the same depth. Because of this, a point which represents zero depth difference between the proximal and distal threshold cannot be determined. Thus, any change in threshold must be measured as a change in the total range between the two thresholds. this range is referred to as the central area of non-appreciable depth (CANAD)."

The diagram in Figure 1 represents this situation. They also contend that the CANAD, or threshold difference, increases as fixation disparity increases. Since the greater the fixation disparity, the farther away from the fovea the disparate image falls within Panum's area, the size of the CANAD thus also increases the more peripherally it occurs within the same area (Figure 2). Therefore, they conclude that an overall increase of central stereoacuity occurs as fixation disparity approaches zero. They also hypothesized that different changes in stereothreshold would be observed on either the base-in or base-out side, or both, depending on the type (I,II,III,IV) of fixation disparity curve manifested. Noting that one type of curve might be measured at distance and a totally different type plotted at near fixation, they proposed that stereothreshold would necessarily vary according to fixation distance.

One important aspect of the research cited up to this point is that fixation disparity was induced with prisms in subjects with normal binocularity. In 1976, Robert Ruthstein decided to investigate the influence of fixation disparity on the stereoacuity of persons demonstrating naturally-occurring fixation disparity[9]. In his research conducted at the University of Houston College of Optometry, each subject's fixation disparity was prismatically corrected. Then he measured their stereoacuity over a six week period.

The result was that no improvement of stereoacuity was measured as a result of correcting fixation disparity, which is not what he expected to find. As an explaination, he contends that since fixation disparity shifts the nonius horopter relative to the point of fixation, the region of stereoscopic vision also shifts. Thus he concludes that the effect of fixation disparity on depth perception is negligible under normal seeing conditions, and that viewing time and fixation must be restricted for any such effect to be made apparent.

This historical overview provides the background for this investigation. While it has been shown that fixation disparity and stereopsis are both effected by forced vergence, and convergence effects differ from divergence effects, the correlation between the two seems to elude researchers. Part of the objective of this project is to offer new insights into this question. However, a brand new computer program is used and this project also serves as a trial demonstration to test the program in actual use in order to reveal where future improvements might need to be made. Designed by Dr. Glenn Hammack and Dr. J. James Saladin of the Ferris State University College of Optometry, this novel micro-computer application uses red/green anaglyph targets to separately measure fixation disparity and stereopsis, incorporating increasing vergence stress as the lateral separation of the dissociated targets is varied within a given fusional range.

Although the apparatus is unproven, the logic behind the hypothesis is sound: As the vergence stress on the system approaches the limits of an individual's fusional range, fixation disparity will eventually exceed Panum's area. Sensory fusion thus breaks and diplopia results. This leads to the development of a central suppression zone to eliminate this diplopia. Fusion is still maintained peripherally because the size of Panum's area increases according to the angle of retinal eccentricity, so total suppression is not occurring.

With the system no longer functioning binocularly within the central suppression zone which is present in one eye or the other, stereopsis is impossible and it is expected that the subject's ability to perceive depth should accordingly diminish. As the disparity of the images increases, Panum's area will be exceeded more and more peripherally, the suppression zone progressively enlarges, and eventually a complete breakdown of stereopic depth discrimination should occur. A double ogive-shaped curve (see Fig. 3) should be obtained in plotting stereopsis vs. prism demand. It is also expected that an increase in the slope of the fixation disparity curve will occur before observed stereopsis deficits. This is because the suppression which occurs as fixation disparity just exceeds Panum's area is an adaptation which requires a certain short amount of time to develop. And the diplopia which is present initially just before suppression sets in does not necessarily effect stereopsis or stereoacuity in and of itself.

Methods:

Between April 1987 and February 1988, 39 trials were conducted on subjects indiscriminately chosen from the student population at Ferris State University. All but four were students in the College of Optometry. Since the objective here does not involve a comparison of this procedure to conventional methods, the participants were not prescreened for fixation disparity, stereoacuity, or vergence ranges. Visual acuity correctable to 20/20 with no known binocular dysfunctions was required of the subjects.

The computer module used was a Zenith Z-100 with a ZVN-B Zenith RGB monitor. The subject was seated in a chair directly in front of and one meter away from the screen. In this way, each one centimeter of target separation equalled one prism diopter of vergence demand. After basic instruction about the experiment and an explanation of which keys to use to enter responses, the subject was given a pair of red-green glasses to wear with the red filter over the right eye and the green filter over the left eye. The glasses were selected from among several pairs available to provide optimum contrast and brightness equality between the two eyes. Room illumination was also controlled by means of a rheostat switch which maintained a constant ambient light intensity on the screen.

The program for fixation disparity was run first on all subjects. Although my colleague in this project, classmate Edward Redwood, concentrated on this aspect and describes the procedure in his report, I will reiterate here for the sake of completeness in this discussion. His diagram of the target parameters is presented in Figure 4.

This target consisted of larger and bolder circles, 1.5 degrees in diameter, separated by a lateral distance corresponding to a definite fusional demand. Within each circle a vertical nonius line of a single pixel width and the same color as the corresponding circle was included. The subject's task was to first voluntarily fuse the two large circles and then move the nonius lines by means of arrow keys until alignment was perceived. Once accomplished, the data was entered and a new target with a greater fusional demand was presented.
The first target presented zero demand. Subsequent targets were presented in jump-vergence fashion, alternating between convergence and divergence in the following sequence:
zero, 3 BO, 2 BI, 6BO, 4 BI, 9 BO, 6 BI, 12 BO, 8 BI, and 15 BO.
If the subject could not attain fusion within a 20 second time period, it was duly recorded as a null value and the next target presented.

When all of the fixation disparity targets were completed or at least attempted, the program immediately continued with the stereopsis screens. As shown in Figure 5, two 3.43° diameter annuli, one green and one red, served as the peripheral fusion stimuli, with small crosses above and below used to stabilize fusion. Within each of the larger circles were three smaller .41° diameter circles of the same respective color. Arranged with their centers forming the apices of an equilateral triangle, the top circle was labelled "one", the lower left,"two", and the lower right,"three". The computer randomly selected which of the three pairs would be offset by a given amount to simulate a certain disparity corresponding to a definite stereoacuity, calculated to be one minute of arc for all targets in all trials. The other two pairs were not offset relative to the first and when fused provided no objective stimulus to depth perception.

With the red and green targets fused, the subject was instructed to choose which of the three circles he/she perceived stereoscopically, by selecting the corresponding number key on the keyboard. Five separate trials were conducted for each prism demand. The procedure of increasing fusion demand was exactly the same as that previously described for fixation disparity measurements. If the subject could not make a definite selection within 20 seconds, they were instructed to make their best guess. The computer automatically recorded each response and tabulated data in the form of the percentage of correct choices out of five trials for each prism demand. If the target could not be fused, the top circle was chosen five times - equivalent to guessing on all five trials - and the next target presented. It is important to include here that neither the subject nor I knew in advance which circle was the correct choice.

A Silver-Reed EXP-555 automatic printer was connected to the computer module and, at the conclusion of the program, automatically typed all data for fixation disparity and stereopsis.

Results:

As previously mentioned, Edward Redwood analyzed the fixation disparity data. I will only summarize his conclusions here. He reports variability in the Ogle curves derived, with eso disparity absent in almost all cases. He attributes this to the absence of proper peripheral fusion locks, thus allowing accommodative fluctuation which tends to disrupt fusion. He also observed steep slopes for most of the curves, an indication, he states, of poor adaptation to prism-induced stress, especially for base-in demand. He cites the work of Saladin and Carr[10], reporting their conclusion that the slope also has a tendency to increase as fusional ability weakens with increased size of the fusional contour.

Analysis of data obtained for stereopsis reveals some interesting tendencies. Table 1 represents the data for the entire sample, with the modes for each prism demand circled. If one only considers the circled data, it seems that a double-ogive curve is present with performance on the stereopsis targets falling off at each end of the fusional range. However, closer scrutiny of all data reveals inconsistencies which must be accounted for before any generalized conclusion is put forth.

To begin with, greater variability of the results is seen near the middle of the fusional range. For small amounts of base-out prism, almost as many subjects performed poorly as responded flawlessly. This is a curious finding which may be related to observations made by Blakemore[11]. He found depth discrimination to be more acute at 5 degrees in the periphery than with central vision and speculates that this is related to limits in the amount of bilateral representation in the human cortex. In this case, it could also be due to a disproportionate number of subjects having poor convergence ability or it might simply be a coincidental occurrence. Indeed, the performance of any given subject for any given vergence demand has shown to be highly unpredictable and the data may have concentrated at certain points by chance. While some subjects performed at or near 100% for all targets, others performed poorly for most targets or performed well on one end of the range but not the other. A significant number exhibited inconsistent performance, having a high percentage of correct responses for one demand, a low percentage for the next, and then a high percentage again on another. So the data of Table 1 is a conglomeration of widely varying individual response curves. Table 2 shows the raw scores converted to percentages of the total sample.

The graphs of Figure 6 illustrate the variability for each given vergence demand. No definite peak is present for 2 BI, zero, and 3 BO, and it seems that one might just as easily assume poor performance as good performance. However, at the extremes of the vergence range a much more definite tendency toward lower percentages of performance is apparent for the sample.

Comparing stereopsis results to those for fixation disparity showed many subjects to perform better on the stereopsis targets, despite exhibiting a large fixation disparity or even inability to attain fusion of the fixation disparity target of the same vergence demand. Although dissimilarities between the testing stimuli may be responsible, this suggests the possibility that depth perception is a more persistent function of the human visual system. A correlation between higher fixation disparity values and decreased stereopsis was not established. Results for individuals were widely variable, with no consistent pattern of increased slope of the FD curves observed to be coincident with the onset of decreased depth discrimination. However, in almost all subjects, fixation disparity increased or diplopia occurred before any definite decay of stereopsis.

Discussion:

Tendencies observed in the experimental data seem to support the hypothesis that stereopsis does break down under extreme vergence demand and that a lag indeed may exist between the progression of fixation disparity beyond Panum's area and the onset of the central suppression which prevents normal binocular depth perception. And it appears that results for stereopsis performance are normally distributed across the fusional range, with marked decreases occurring at the extremes as predicted.

These conclusions are severely limited, however, by individual subject variability and flaws which exist in the computer program itself. In hindsight, it might have been advisable to pre-screen subjects and only those with sufficient amplitudes of divergence and convergence allowed to participate. This would eliminate inconsistencies introduced by subjects who have inadequate fusional capabilities.

Measuring fixation disparity and stereoacuity with conventional methods prior to testing would reveal unknown pre-existing binocular problems.

As in any task dependent on subjective responses, variability of attention and effort among individuals effect the results. To what extent this applies here is difficult to determine, but some subjects were more distractable or more easily fatigued than others. Any number of imaginable psychological factors such as stress, emotional state, time of day, etc. are also possible sources of error.

But subjective error cannot entirely explain the prevalence of variability observed in the results. Few, if any, of the subjects who performed poorly can be expected to actually have poor binocularity or such narrow fusional ranges. Criticism must ultimately be directed at the nature of the stimuli used and the procedure of the experiment.

First of all, anaglyph methods are far removed from normal viewing conditions and fusional ranges may inherently be reduced for these targets as compared to others more similar to normal. Also, the pre-dominately featureless, black background provides very few peripheral cues to fusion. Accommodative stabilizers were incorporated into the screen patterns, but these are insufficient without a better fusional stimulus. The large circles used to achieve and maintain fusion in the present program design may be too simple, perhaps a more angular or linear shape with more detail would work better.

Secondly, the momentary disappearance of the screen each time the subject presses the arrow key during fixation disparity testing is a most annoying flaw. Fusion is frequently disrupted and subjects often complained that they were unable to make the circles single again on a target previously fused. Unnecessary fatigue is also introduced. Future refinements of the program should enable testing to be conducted with a constant screen.

The introduction of vergence facility by alternating base-in demand with base-out demand is another possible hindrance. The fatigue induced as the total vergence jump progressively increases may be partly responsible for the difficulty subjects had with the extremes of the range. It might be better to alter the demand in smaller, equal steps from zero to the base-in limit and then from zero to the base-out limit.

Also observed during the stereopsis trials was that a greater number of errors occurred when the top circle was the correct choice than when one of the other two circles was the proper selection. This curious effect can be explained by referring to the diagram of Figure 4a. It is patterned after the flashlight diastereo test used by previous investigators[12]. One can see that the lateral distance between the edge of the top circle and the larger fusion circle is greater than the same distance for each of the bottom two circles. It is more difficult to detect a difference in depth for stimuli that are more widely separated from the nearest fusion contour[13] and it is this principle which accounts for the more prevalent error for the top circle. The bottom two circles are closer to the large circle and relative depth is easier to perceive. Ideally, four smaller circles instead of three should be used and arranged in a square so that distances between circles are equal as well as between each small circle and the encompassing fusion stimulus.

Lastly, comparisons and correlations between fixation disparity and stereopsis might be more conclusively ascertained if identical targets are used for each aspect rather than the grossly dissimilar screens employed in this program. Even better would be a computer program capable of generating a target which could test both simultaneously. Incorporating the four-circle configuration described previously with nonius lines included to measure fixation disparity, it might resemble the diagram shown in Figure 6. The large circles would serve as the fusion stimuli, with four smaller circles to test stereopsis in much the same manner as was done in this project. The central circle contains the nonius lines for fixation disparity measurement.

While improvements are necessary, one must not hold the impression that this method is worthless. The fact that reliable data was obtained on some subjects indicates that this program has significant promise for academic and clinical applications. Refinements will eliminate sources of error and enable more consistent testing. The design used here is simply the initial step in a progression of further improved designs. The challenge is thus presented to develop improved computer applications to be used in future studies of fixation disparity and stereopsis.

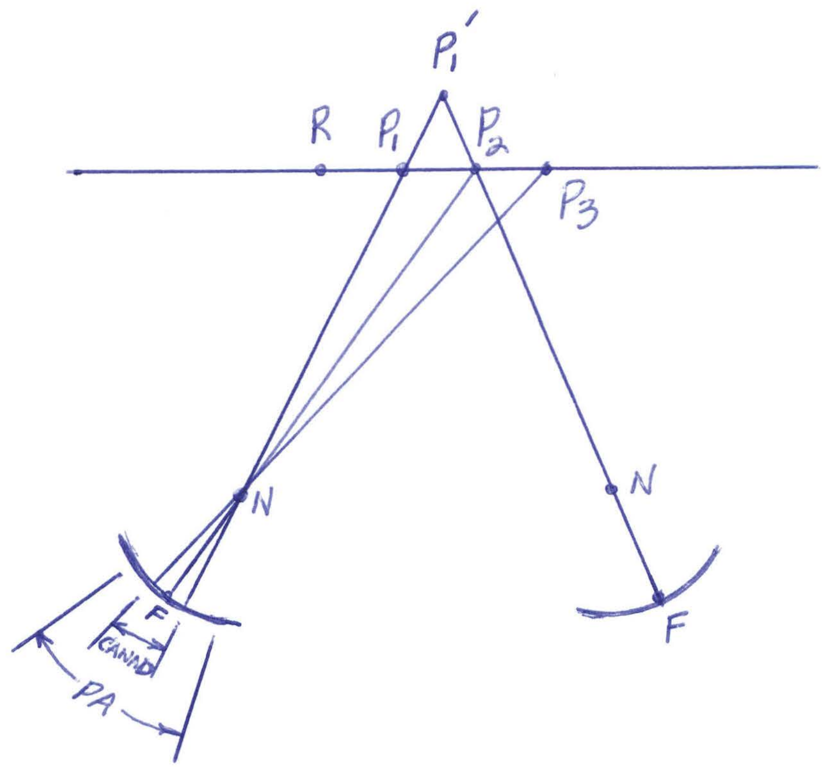

FIGURE 1. STEREOSCOPIC VISION AS REPRESENTED BY COLE AND BOISVERT

R = REFERENCE POINT IN PLANE OF FIXATION

P_1, P_2, P_3 = THREE POSITIONS OF MOVEABLE TARGET

P_1', P_3' = APPARENT POSITIONS OF FUSED TARGETS

CANAD = CENTRAL AREA OF NON-APPRECIABLE DEPTH

PA = PANUM'S AREA

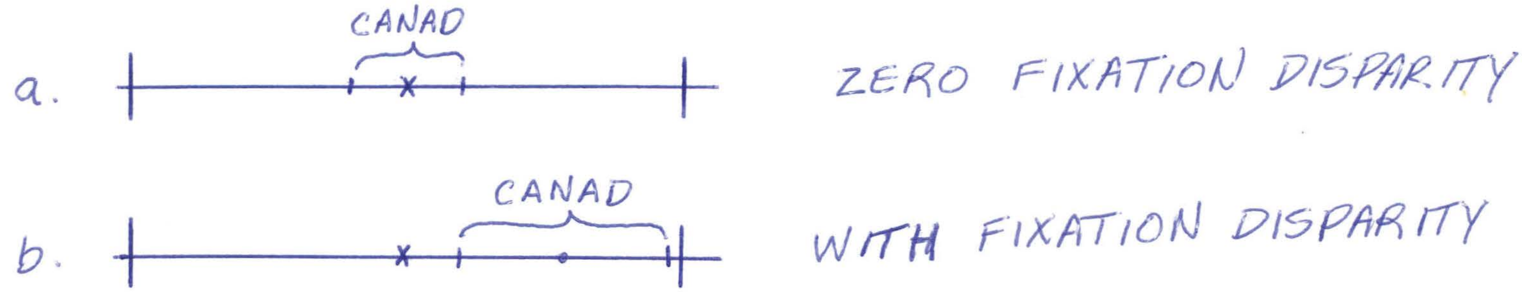

FIGURE 2. DIAGRAM FROM COLE AND BOISVERT SHOWING LARGER CANAD WITH LARGER FD.

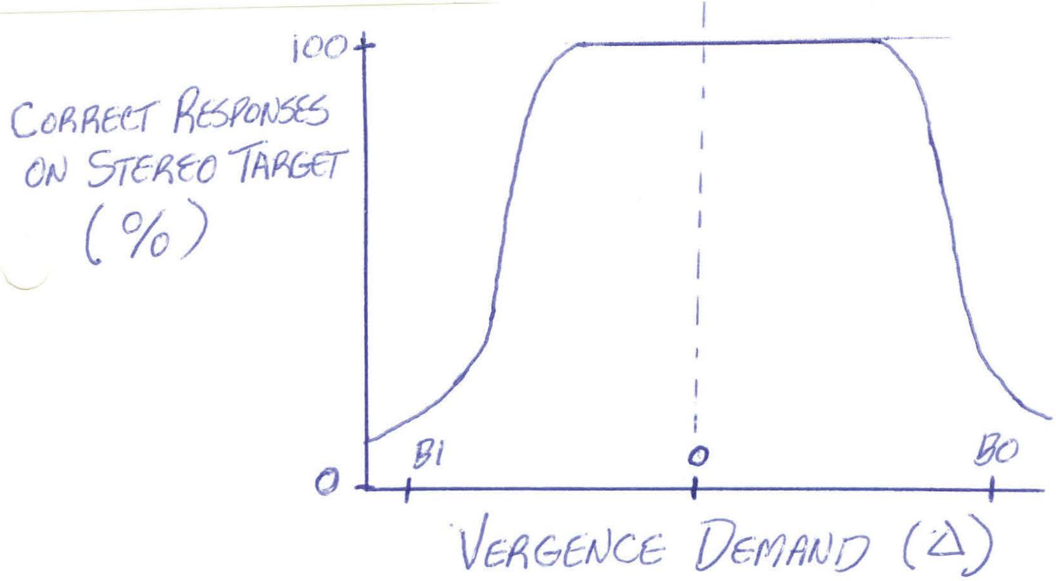

FIGURE 3. REPRESENTATION OF DOUBLE-OGIVE DISTRIBUTION OF STEREOPSIS RESULTS.

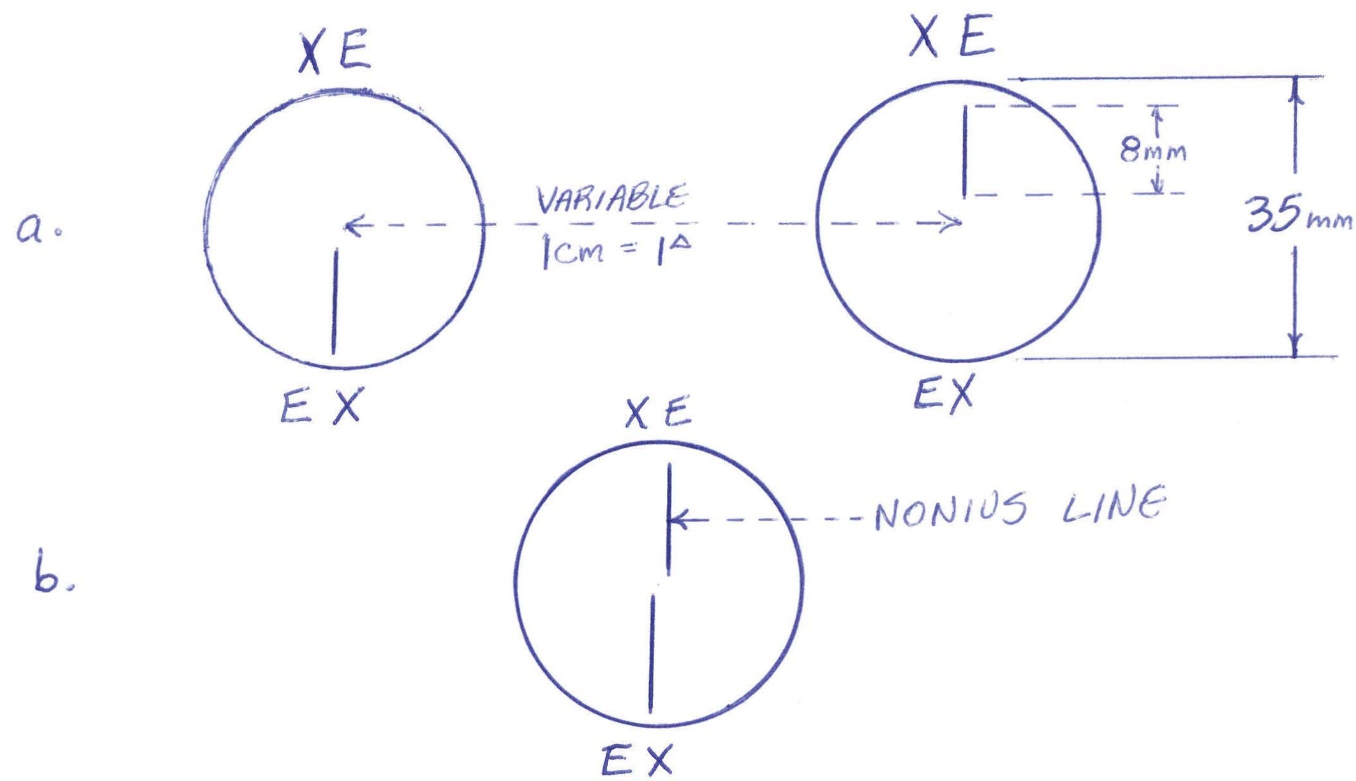

FIGURE 4. FIXATION DISPARITY TARGET WITH DIMENSIONS (NOT TO SCALE)

a. SCREEN DISPLAY (ONE SIDE RED, OTHER GREEN)

b. FUSED PERCEPTION. ANGULAR SEPARATION OF NONIUS LINES EQUALS FD.

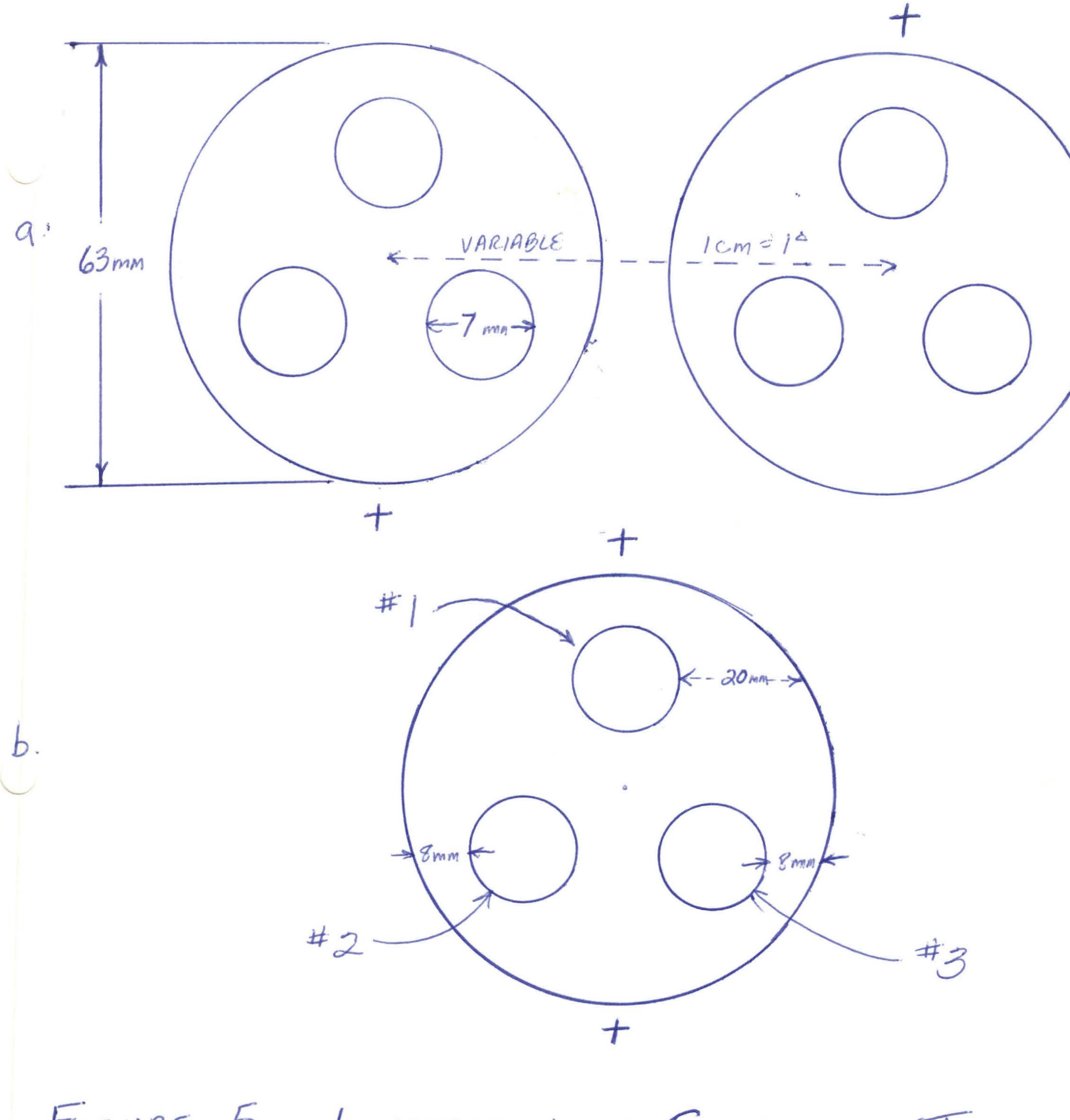

FIGURE 5. ILLUSTRATION OF STEREOPSIS TARGET WITH DIMENSIONS (NOT TO SCALE)

a = ACTUAL SCREEN DISPLAY (ONE RED, ONE GREEN)

b = FUSED PERCEPTION. SUBJECT INSTRUCTED TO MAKE SELECTION OF CIRCLE PERCEIVED STEREOSCOPICALLY. FIVE TRIALS FOR EACH PRISM DEMAND.

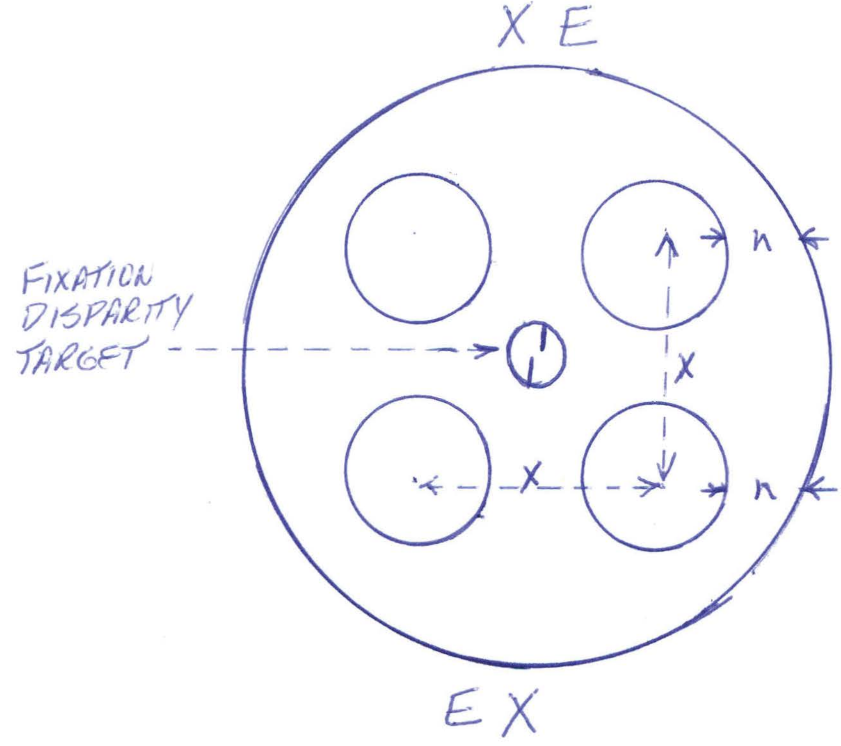

FIGURE 6. POSSIBLE TARGET DESIGN TO SIMULTANEOUSLY TEST FIXATION DISPARITY AND STEREOPSIS. FOUR CIRCLES IN SQUARE CONFIG. FOR STEREO. CENTRAL SMALL CIRCLE WITH NONIUS LINES FOR FD. EQUAL DISTANCES BETWEEN STEREO CIRCLES AND FUSION ANNULUS.

Percentage Correct	-8	-6	-4	-2	0	3	6	9	12	15
100	4	3	6	**12**	**20**	**12**	**13**	**16**	7	8
80	0	1	2	5	11	5	6	5	8	5
60	2	4	5	7	2	8	5	4	5	5
40	6	3	**23**	8	3	11	5	3	**16**	5
20	**27**	**28**	3	7	2	4	1	12	1	**15**
0	0	0	0	0	1	0	9	0	1	0

BI | BO

VERGENCE DEMAND (Δ)

TABLE 1. NUMBER OF SUBJECTS SCORING A CERTAIN PERCENTAGE OF CORRECT RESPONSES FOR A GIVEN VERGENCE DEMAND. MODE FOR EACH DEMAND IS CIRCLED. DOUBLE-OGIVE DISTRIBUTION ILLUSTRATED BY DOTTED CURVE.

Percentage Correct	-8	-6	-4	-2	0	3	6	9	12	15
100	10.2	7.7	15.4	**30.8**	**51.2**	**30.8**	**33.3**	**41.0**	17.9	20.5
80	0	2.6	5.1	12.8	28.9	12.8	15.8	12.8	20.5	12.8
60	5.1	10.2	12.8	17.9	5.1	20.5	12.8	10.2	12.8	12.8
40	15.4	7.7	**59.0**	20.5	7.7	28.2	12.8	7.7	**41.0**	12.8
20	**69.2**	**71.8**	7.7	17.9	5.1	10.2	2.6	30.8	2.6	**38.5**
0	0	0	0	0	2.6	0	23.0	0	2.6	0

VERGENCE DEMAND (Δ)

TABLE 2. RAW SCORES FROM TABLE 1 CONVERTED TO %.

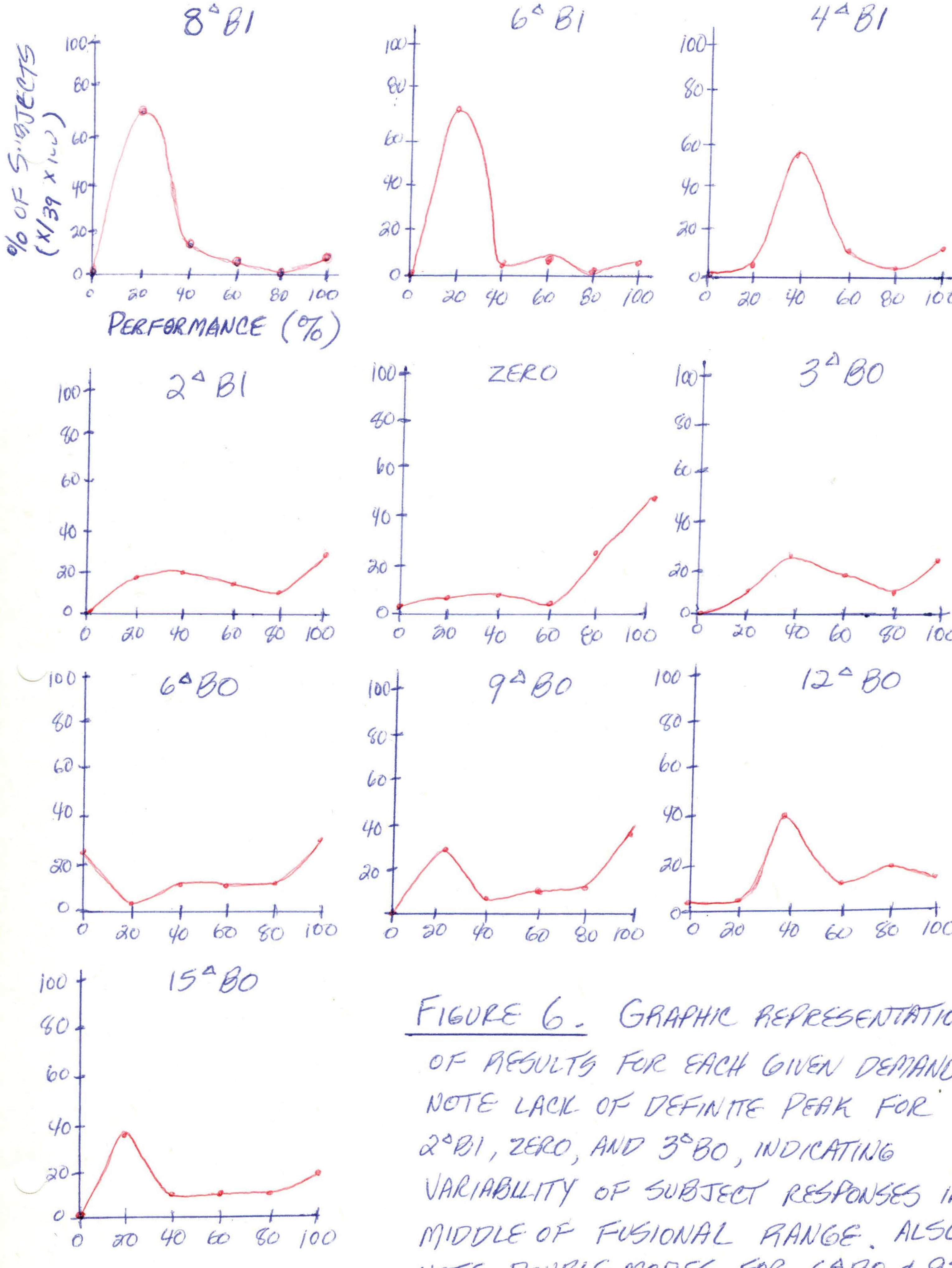

FIGURE 6. GRAPHIC REPRESENTATIONS OF RESULTS FOR EACH GIVEN DEMAND. NOTE LACK OF DEFINITE PEAK FOR 2△BI, ZERO, AND 3△BO, INDICATING VARIABILITY OF SUBJECT RESPONSES IN MIDDLE OF FUSIONAL RANGE. ALSO, NOTE DOUBLE MODES FOR 6△BO & 9△BO

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