Exp. Brain Res. 10, 380-388 (1970)

Stereopsis and Stereoblindness

WHITMAN RICHARDS

Department of Psychology, Massachusetts Institute of Technology, Cambridge (USA)

Received December 20, 1969

Summary. Psychophysical tests reveal three classes of wide-field disparity detectors in man, responding respectively to crossed (near), uncrossed (far), and zero disparities. The probability of lacking one of these classes of detectors is about 30% which means that 2.7% of the population possess no wide-field stereopsis in one hemisphere. This small percentage corresponds to the probability of squint among adults, suggesting that fusional mechanisms might be disrupted when stereopsis is absent in one hemisphere.

Key Words: Stereopsis -- Squint -- Depth perception -- Visual perception

Stereopsis was discovered in 1838, when Wheatstone invented the stereoscope. By presenting separate images to each eye, a three dimensional impression could be obtained from two pictures that differed only in the relative horizontal disparities of the components of the picture. Because the impression of depth from the two combined disparate images is unique and clearly not present when viewing each picture alone, the disparity cue to distance is presumably processed and interpreted by the visual system (Ogle, 1962). This conjecture by the psychophysicists has received recent support from microelectrode recordings, which show that a sizeable portion of the binocular units in the visual cortex of the cat are sensitive to horizontal disparities (Barlow *et al.*, 1967; Pettigrew *et al.*, 1968a). Thus, as expected, there in fact appears to be a physiological basis for stereopsis that involves the analysis of spatially disparate retinal signals from each eye. Without such an analysing mechanism, man would be unable to detect horizontal binocular disparities and would be "stereoblind".

With the advent of computer technology, it is now practical to design efficient and elegant tests for stereopsis and stereoblindness. Julesz's ingenious method (1964) is to present a random pattern of small black and white squares to each eye. A certain portion of each pattern, however, is identical except for a horizontal displacement. Those viewers who possess stereopsis are able to process this disparity information and see the correlated portions of each pattern as a figure in depth. Because there are no other cues which serve to identify the hidden figure, individuals who cannot process the disparity information will be unable to see the hidden figure. A survey among 150 members of the M.I.T. community shows that about 4% of the students are unable to use the cue offered by disparity, and another 10% have great difficulty and incorrectly report the depth of a Julesz figure relative to the background. This difficulty in deciding whether the hidden Julesz; figure is in front or behind the background suggests that some individuals may have disparity detectors which signal whether or not a figure is on or off the plane of fixation, but who lack disparity detectors that signal the direction of the disparity. If this interpretation is correct, then there must be at least two or more classes of disparity detectors and stereoblindness would result only when all such classes were absent. This report offers evidence for at least three independent classes of disparity detectors in man.

Methods

The subject views a screen of sand-blasted plexiglass at 200 cm, onto which are projected polarized images that are observed with polarized glasses. All the images consist merely of two adjacent vertical lines, 1/4° wide by 2° high. Each line is generally polarized at 90° to the other, and then only one line will be seen by each eye. When the right eye sees the left line, and the left eye sees the right line, the disparity will be crossed and the two lines may be fused as a single line appearing in front of the projection screen. Similarly, the two lines will appear as one line located behind the screen when the disparities are uncrossed: the left line seen only by the left eye and the right line seen by the right eye. A third condition whereby both lines went to the same eye was also included. In this case, the stimulus had no disparity and appeared located on the plane of the screen being fixated.*

The stimuli were prepared as polarized 2" x 2" slides, and were loaded into a Kodak carousel projector in a random order. As this projector is remotely controlled, the subject could go through all the stimuli at his own rate. When he was ready and was fixating properly, he would advance the carousel projector himself, and a slide would be flashed for 80 msec approximately one second later. The short flashes were used to preclude the possibility of detecting the direction of disparity by using eye movements.

Three fixation conditions were used: one with the test lines presented 4° to the left of the fixation spot; a second with the test lines appearing 4° to the right of the fixation spot; and the third where the lines straddled the fixation cross. This latter condition was possible because the geometrical disparity between the pairs of lines was either 1/2°, 1°, or 2°. Even though pilot studies included separations up to 8°, these three spacings were found to be the most suitable for the data of interest.

The subject's task was to report the disparity of each pair of lines flashed on the screen. His responses were limited to "in front", "behind", or "on it" (the screen). Because of the large disparities used in this experiment, these judgements almost always involved the judgement of depth of double images, i.e., the pair of lines were rarely seen as fused into a single line. Even so, most individuals were capable of correctly reporting disparities up to 2°, and a few subjects could correctly identify the stimuli even when the two lines were separated by as much as 7 or 8 degrees, even if each line went to a separate hemisphere (Richards, 1969). Such wide-field stereopsis would be of great value for fusional mechanisms.

Subjects

Approximately 75 subjects have been tested; their ages ran from 5-70 years. The majority, however, were M.I.T. students. Appropriate ocular corrections were used in all cases. In addition, a pair of Risley prisms was used to adjust for phoria, as measured by a misalignment of two nonius lines, one seen by each eye.

Scoring

The classical method for evaluating a subject's ability to perceive disparity would be to measure his percent correct as the disparity between the two lines increases. If the subject is unable to process uncrossed (behind) disparities, then presumably his percent correct would hover near 50% for all the uncrossed stimuli. Let us suppose for a moment, however, that there are only two disparity conditions: crossed and uncrossed, and that the subject is able to perceive the crossed disparities correctly. Then clearly, by inference, he can deduce those stimuli which must be uncrossed, even though he cannot perceive uncrossed disparities. Percentagewise, the subject will therefore do as well on uncrossed disparities, which he cannot perceive, as he will on crossed disparities.

Exactly the same argument may also be applied to a d' measure of discriminability, whereby large d's may be obtained even when stimuli are not detected physiologically by an appropriate feature detector. Furthermore, even if the absence of disparity detectors lowers discriminability, extraneous differences between observers would have to be minimal if variations in d' were to be used to indicate the presence or absence of stereopsis. Ideally, if there were no extraneous inter-observer differences, then d' should be distributed with multiple modes, each mode indicating a distinct set of disparity detectors. In fact, a histogram of d's derived from the present data does suggest three modes, one centered at d' = 0, but the remaining two modes are not sufficiently distinct to permit any one individual to be classified accurately. Thus, factors other than the simple presence or absence of whole classes of disparity detectors must contribute to the observed discriminability. One very plausible factor is that the observer's criterion may change when stimuli are presented to non-existent disparity detectors. In this case, a discriminability index that is sensitive to changes in response strategies may be more appropriate. Of particular interest is the dissociation of "deduced" or inferred responses from those responses elicited directly.

An index sensitive to response strategies can be calculated in a manner analogous to d', using the same response probability matrix. This new index of response strength will be designated s'. The major difference between the d' and s' indices of discriminability is that the response probability matrix is broken up in different ways. In particular, the s' measure uses the three stimulus categories (crossed, zero, uncrossed) as a rating scale, in contrast to the d' procedure. Thus, in the present case, the strength estimate, s', is made by calculating the probability, p(C/f), that the stimulus was crossed when the subject responded "front", and comparing this value with the probability that the stimulus was crossed when the subject responded "on-it" or "behind". Because the latter two responses fall into the single category "not-front", this second probability may be designated as p(C/f). Together, the two probabilities, p(C/f) and p(C/f) provide an estimate of the response strength, s_f', which can be found from a table of signal detectability values for probabilities obtained in a yes-no situation (Swets, 1964). In a similar manner, a second estimate of response strength, s_f'', can be obtained by cumulating the response categories for both the crossed and zero disparity stimuli. As long as the response judgements are monotonic with retinal disparity, the two estimates of s will be roughly equal providing the subject can, in fact, detect crossed, zero, and uncrossed disparities. On the other hand, if the subject is able to perceive only crossed disparities, and does not have feature detectors that distinguish between the zero and uncrossed stimuli, then the second estimate of s_f (called s_f ") will be lower. In particular, if the physiological signal only occurs when crossed disparities are presented, then the zero disparity stimuli win be reported correctly only by inference, which increases the response "noise". Thus, the second estimate of response strength based upon both crossed and zero disparities should suggest that the variance of the noise distribution has at least doubled, with no increase in signal strength. In terms of a strength measure of detectability, the second measure of s_f (i.e., s_f'') would then be half the first s_f'' = 1/2s_f'.

Similarly, if the subject cannot detect crossed and zero disparities, but can correctly identify the uncrossed disparity stimuli, then the "front" responses will be equally distributed in the crossed and zero conditions. The response strength index will then double when the first and second estimates of s_f are compared: s_f" = 2s_f'.

To summarize, depending upon the subject's ability to detect crossed, zero, or uncrossed disparities, at least three relations between s_f' and s_f " may be expected: 1) s_f" = s_f' indicating that the crossed disparities plus zero or uncrossed disparities are detected; 2) s_f" =1/2S_f', implying that crossed disparities are detected whereas zero and perhaps crossed disparities are not; and 3) sf" 2sf', indicating that crossed disparities are not detected.

A similar analysis also applies to the detection of uncrossed disparities, except that the response categories "behind" and "not-behind" are used to calculate s_b' and s_b". Once again, the relations between S_b' and s_b" are used to indicate which disparities are detected.

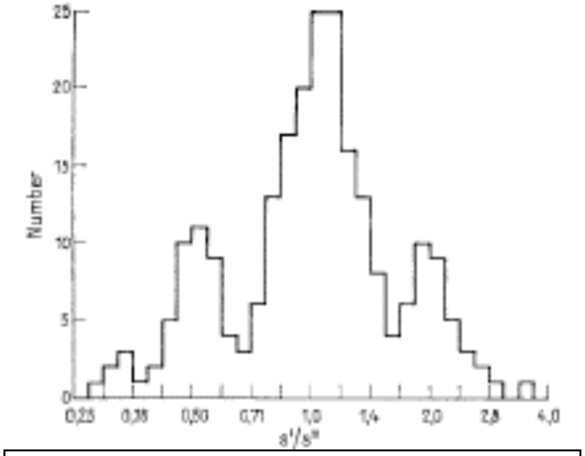

Figure 1. Histogram showing the number of occurrences of a given s'/s" ratio among 50 members of the M.I.T. community

Distribution of s'/s''

The histogram of Fig. I provides a test of the prediction that the first and second estimates of response strengths, s' and a", may differ by a factor of two if the subject cannot detect certain disparity conditions. In this figure, the ratio s'/s" is plotted on a log scale, and the number of occurrences of a given ratio is indicated on the ordinate. Ratios obtained for both s_f'/s_f" and s_b'/s_b" have been included, for all three fixation conditions. The data were compiled from the first 50 subjects tested. Excluded from the histogram, however, were s'/s" ratios where s' < .5, because a plot of negative values of s' showed that s's less than .5 may be considered as zero within experimental error.

The histogram clearly shows three modes, the major one peaking at about 1.10, and two lesser modes near .50 and 2.0. The major mode near s' = s " suggests that in most cases, the variance of the response strength is almost entirely associated with guessing, and that disparities may be ordered along a continuum in order to create a rating scale. On the other hand, the minor modes near .5 and 2.0 indicate that in some cases the response strength has doubled (or halved). In these cases, we infer that the subject deduced, rather than actually perceived one or two of the stimulus conditions.

By calculating s' and s" from the response distributions for each stimulus condition, it is thus possible to decide from Fig. I whether one or more categories of disparity detectors are present. The use of a ratio of s's has the further advantage that individual differences in absolute discriminability are irrelevant. The essence of the scoring procedure is roughly as follows:

i) calculate s' and s" for both the "front" and "behind" response categories.
ii) if s'/s" > 1.5, then subject perceives this condition.
iii) if s'/s" < .7, then the stimulus condition is not perceived.
iv) if 1.5 ≥ s'/s" ≥ .7, then the subject perceives this stimulus condition plus one other.
v) if the "on" responses yield a s' that is not less than a factor of .7 of the largest s' for the "front" and "back" responses, then zero disparities are detected.
vi) (Corollary) if all three responses yield s's which are within a factor of .7 of each other, then the subject perceives all stimulus conditions: crossed, uncrossed, and zero disparities.

Results

The initial question of interest is whether the difference between individual abilities to detect disparity is merely one of degree or position along a Gaussian distribution, or whether disparity detection is clearly absent in a sub-group of the population. The histogram in Fig. 1 answers this question: some disparities are not seen in some cases, leading to two smaller separate modes near s'/s''=.5 or 2.0. This dichotomy between the presence or absence of disparity detection becomes particularly obvious in certain individual cases. For example, all crossed disparities presented to one hemisphere (or visual field) may be seen easily (s' = 1.50), whereas the remaining two conditions may yield s's much closer to zero. The probability of detecting only one of the three disparity conditions can be estimated from Fig. 1. This figure indicates that about 20% of the population is unable to detect two of the three disparity conditions.

The probability of being able to detect a given disparity is summarized in Table 1. The table is divided to show that there is a slight difference in the perception of disparity in the right versus the left hemisphere (to the left or right of the fixation point). The average s' for the left hemispheric conditions was 1.58, slightly higher than the average of 1.33 obtained for presentations to the right cerebral hemisphere. The difference is largely due to the reduced chance of finding disparity detectors in the right hemisphere,

The average probabilities of perceiving disparities under the three conditions are given in the next-to-last column of Table 1. It is of interest to compare these percentages with those obtained for the "straddle" fixation condition, where the stimulus straddled the mid-line in order that both lines go to separate hemispheres.

Table 1. *Probability of Perceiving Disparities*

The probabilities are broken down according to the disparity of the stimulus (column 1) and according to the cerebral hemisphere to which the stimulus was presented. The values in column 4 are averages for the preceding two columns, and indicate the average probability of possessing a disparity detector in one hemisphere. The final column (straddle) shows the probabilities for possessing disparity detectors that span the midline and correlate disparity information between the two cerebral hemispheres.

Stimulus	Probability			
	Left Hemisphere	Right Hemisphere	Average	Straddle
crossed (front)	.82	.68	.75	.63
zero (on the fixation plane)	.70	.60	.65	.35
uncrossed (behind)	.70	.63	.67	.54
mean	.74	.64	.69	.51

The percentages for the straddle condition are clearly lower than the average probabilities for each hemisphere Instead, the straddle probabilities are closer to the product of the probabilities obtained for the left and right hemispheres, suggesting that disparity detection across the midline first requires disparity processing in each hemisphere.

The probabilities given in Table 1 are not those for a completely random sample, being collected largely from young males with good eye-sight. Even though those individuals requiring ocular corrections generally have lower s's, it is too early to tell whether or not the occupancy probabilities for disparity detection are lower in these cases. There is also no obvious difference between the sexes. Except for a decrease in s' with age, age also does not appear to be a significant variable that alters the occupancy probabilities in Table 1.

Table 2. *Contingency Probabilities*

The table shows the observed probabilities of detecting the stimuli listed in column 1, given that the subject already detects one other stimulus condition. If the classes of disparity detectors are independent, then the average values given in the last column of this table should agree with the average probabilities listed in column 4 of Table 1.

Stimulus	Probability			
	Crossed detected	Zero detected	Uncrossed detected	Average
crossed (front)	-	.70	.84	.77
zero (on the fixation plane)	.61	-	.56	.59
uncrossed (behind)	.78	.58	-	.68
mean				.68

Table 2 shows the probability of detecting a stimulus given that the subject already detects another one of the disparity conditions. If the detection of crossed, or zero disparities are independent of each other, then the probabilities given in Table 1 should be unaffected by whether or not an individual perceives one of the conditions. A comparison of the average probabilities in Table 1 and Table 2 implies that each kind of disparity is perceived independently (excluding the "straddle" condition). These considerations, together with the clear inability of some individuals to process certain disparities even after repeated retests, suggests that the perception of crossed, uncrossed, or zero disparities are independent, and probably inherited traits.

In order to decide whether such a trait, if inherited, would appear as dominant or recessive, a small sample of children and their parents were tested. The results are summarized in Table 3. In this table, the four parental combinations are shown in the left-hand column. The next two column are the calculated probabilities that the offspring will perceive the same disparity condition seen (or not seen) by the parent. These estimates were made assuming that the probability of detecting a given disparity condition was .7 -- the average value reported in Table 1. The error introduced by this approximation should not exceed the experimental errors. Each disparity condition, crossed, zero, or uncrossed, has been treated separately and the results pooled for presentation in the table. As there were no obvious differences between sons and daughters, this breakdown was omitted. The final column lists the occurrence probabilities actually observed in the offspring. These values agree within experimental error with the theoretical values in the adjacent column. Thus, if stereopsis is an inherited trait, it must be autosomal dominant.

Table ***3.*** *Dominant and Recessive Trait predictions for inheriting disparity detectors*

Filled symbols correspond to the presence of a class of wide-field disparity detectors, open symbols indicate their absence. Data are omitted for the last pairs, whose scarcity would require an impractically large sample before a significant comparison could be made.

Parents				Hypothetical		Observed
Father		Mother	N	Recessive	Dominant	
■	X	●	37	100%	92%	89%
■	X	○	26	47%	60%	69%
□	X	●	15	47%	60%	67%
□	X	○	3	13%	0%	*

Discussion

As early as 1910, Worth considered the possibility that stereopsis may be an inherited ability (Chevasse, 1939). However electrophysiological. evidence of Hubel and Wiesel (1965) suggest that certain environmental conditions can lead to abnormal binocular interactions in the visual cortex. In particular, there is a great reduction in the number of units that respond to both eyes when squint is artificially induced. Thus, it is very likely that in the absence of proper alignment of both eyes, stereoscopic mechanisms will degenerate (Pettigrew *et al.*, 1968b).

The argument that ocular misalignment is responsible for the present results, however, is untenable. If stereoscopic mechanisms were to degenerate following misuse, there is no obvious reason why only the crossed and not also the uncrossed perceptions of disparities would be lacking. Ocular imbalance should lead to equal deficits in the perception of all three disparity conditions together, and not merely the absence of but one condition -- the most frequent observation. The simpler hypothesis is that of Worth and Chevasse (1939): namely that stereopsis is an inherited ability (which will be lost if misused).

From the data of Table 1, the probability of lacking stereopsis in one hemisphere is about 2.9%. This figure corresponds closely to the incidence of squint among adults. Is it possible that squint arises in some cases because there is no appropriate physiological response to disparity information? Without stereoscopic mechanisms in one hemisphere, fusional mechanisms would have to be disrupted for stimuli presented to the corresponding visual field. Furthermore, fusional responses to stimuli located along the midline may also be disrupted. Such convergence responses to bilaterally presented stimuli require correlating disparity information between the cerebral hemispheres (Westheimer and Mitchell. 1969).

The data for the straddle condition in Table 1, however, suggest that such correlations are not made unless stereopsis is present in *both* hemispheres. Apparently appropriate binocular fusion and fixation represents minimal inter-hemispheric imbalance of physiologic disparity -- a condition that cannot be met with stereopsis present in only one hemisphere. Thus, all individuals lacking stereopsis in one or both hemispheres should be anomalous corresponders or squinters.

Table 4. *Predicted and Observed inheritance of squint*

The probability of inheriting squint has been calculated by assuming that the probability of possessing a given class of disparity detectors is .7 -- the average value in Table 1. The values in parenthesis are probabilities estimated by Richter (1967) for a population of Berlin children.

		Father	
		Afflicted	Normal
Mother	Normal	65.0 (68)	16.6 (15)
	Afflicted	16.6 (15)	1.8 (2.2)

If certain types of squint are the result of inherited stereoblindness, then the probabilities of a child inheriting squint may be predicted from Table 1. These predictions are given in Table 4. Thus, if both parents are stereoblind in one hemisphere, then approximately 65% of their children will also be stereoblind in one hemisphere, and will presumably be squinters. A recent study by Richter (1967) estimated that 64-72% of such children would be affflicted. The other percentages estimated from the population of Berlin children are given in parenthesis in Table 4. The empirical and predicted percentages are in reasonable agreement.

Acknowledgement: Supported by AFOSR under contract F44620-69-C-0108. Drs. John Foley and Wayne Wickelgren provided particularly helpful criticisms of preliminary versions of this report. Special acknowledgement to CWT for continuing encouragement over many years.

References

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

Chevasse, F.B.: Worth's Squint or the Binocular Reflexes, 7th ed., Blakiston, Philadelphia, 1939.

Hubel, P.H., Wiesel, T.N.: Binocular interaction in striate cortex of kittens reared with artificial squint. J. Neurophysiol. **28**, 1041-1059 (1965).

Julesz, B.: Binocular Depth Perception without Familiarity cues. Science **145**, 356-362 (1964).

Ogle, K.N.: The Optical Space Sense, part H. In: The Eye, vol. IV, pp. 211-418. Ed. by H. Davson. New York: Academic Press 1962.

Pettigrew, J. D., Nikara, T., Bishop, P.O.: Binocular interaction on single units in cat striate cortex. Exp. Brain Res. **6**, 391-410 (1968 a).

-- Neural mechanisms concerned in the development of amblyopia ex anopsia. Proc. Aus. Ass. Neurol. **5**, 221-224 (1968b).

Richards, W.: "The Influence of Oculomotor Systems on Visual Perception", Report No., AFOSR 69-1934TR, pp. 121, July 1969.

Richter, S.: Untersuchungen über die Heredität des Strabismus concomitans. Leipzig: Georg Thieme 1967.

Swets, J. A.: Signal Detection and Recognition by Human Observers. New York: Wiley 1964.

Westheimer, G., Mitchell, D.E.: The sensory stimulus for disjunctive eye movements. Vision Res. **9**, 749-755 (1969).

Wheatstone, C.: Contributions to the Physiology of Vision 1. Phil. Trans. B, pp. 371-394 (1838).

Dr. Whitman Richards
Massachusetts Institute of Technology
Department of Psychology
Cambridge, Mass. 02139 (USA)

---

* A fourth condition presented the top half of both lines with a crossed (or uncrossed) disparity, while the lower-half of the lines appeared with uncrossed (or crossed) disparity. When seen correctly, this fourth condition appeared as one line split in depth: i.e., the upperhalf might have been seen in front whereas the lower-half would be seen behind the screen. This odd display was rarely seen correctly, and was included as "noise" in some experiments in order to obtain a better measure of response biases.