
Stereomovement suppression for transient disparity changes

C W Tyler¶, J M Foley

Department of Psychology, University of California, Santa Barbara, California 93106

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Abstract. In a comparison between stereo and vernier thresholds in displacement and misalignment paradigms, the stereo displacement threshold was found to be about three times higher than the other thresholds. This result is consistent with the disparity inhibition hypothesis. In a second experiment thresholds in a movement/no movement discrimination task were about half those in the direction discrimination task, with the stereo threshold remaining about three times higher than the vernier threshold. This suggests that motion discrimination has a different basis from direction discrimination.

1 Introduction

In a previous study (Tyler, 1971) it was shown that human sensitivity for detection of sinusoidal movement of a bright line in depth was much lower than for the monocular components of this stimulus. Thus, though a subject with one eye closed might detect lateral movement of one of the half-images at a given frequency and amplitude of movement, yet with both eyes open he might fail to detect the movement in depth of the fused half-images. Four different hypotheses to account for the reduction in sensitivity deserve consideration:

- a. Inhibition between adjacent disparity detectors reduces stereoscopic sensitivity (and also monocular sensitivity during stereoscopic stimulation).
- b. Reduced stereoscopic sensitivity occurs for brief stimulation of a given disparity, together with inhibition of monocular information.
- c. Rapid adaptation occurs with repetitive stereoscopic stimulation.
- d. Differential eye-tracking of monocular and stereoscopic stimuli (or differential sensitivity to versional and vergent eye movements with perfect tracking) produces the observed reduction in stereoscopic sensitivity.

In the present study rapid adaptation and eye movement artifacts (hypotheses c and d) were controlled by using brief, single presentations of the test stimuli as described in section 2.2. The results show that stereomovement suppression is still obtained, indicating that neither rapid adaptation nor eye movements account for the suppression.

This leaves hypotheses a and b, which need spelling out in greater detail. As previously suggested (Tyler, 1971, 1975), inhibition between cortical cells responding to adjacent disparities could account for the suppression of stereomovement information. Over much of the frequency range, threshold extent of movement was found to be inversely proportional to frequency. Thus, at high frequencies of oscillation in depth, movements of small amplitude could be detected, but at low frequencies only movements of large amplitude could be detected. This implies that for threshold response a given disparity detector within the range of the stimulus is stimulated for a fixed length of time regardless of frequency of the stimulus. To this extent disparity inhibition with a fixed time course can provide an adequate explanation for the observed reduction in sensitivity. On this inhibition hypothesis, no reduction in sensitivity should occur for brief stimulation at a single disparity since no other

¶ Present address: Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey, 07974.

disparity is present to produce inhibition. A further experimental result that must be considered is that no movement of any kind is visible below stereoscopic threshold. This requires deactivation of monocular movement detectors in some way. Such deactivation might occur if detectors for lateral movement summed movement signals in corresponding retinal regions of the two eyes. With antiphase signals in the two eyes these detectors should show an output of zero, while disparity detectors should be maximally stimulated.

The second hypothesis, that of a reduced stereoscopic sensitivity, must equally involve deactivation of the monocular movement information in some way. It differs from the first hypothesis in suggesting that stereomovement suppression results from a general reduction in stereoscopic sensitivity for brief stimulation of a given disparity. Stimulus change would then be detected by the disparity system with a sensitivity determined independently from the movement detection system. At first sight this hypothesis appears to conflict with the observation of Tyler (1971) of inverse proportionality between frequency and movement sensitivity. This problem can be avoided because the inverse proportionality is limited to stimulus frequencies of less than 2 Hz, whereas the range of durations of interest for the sensitivity reduction is below 200 ms, corresponding to frequencies beyond the range of inverse proportionality.

Data concerning the detection of briefly presented disparities are given by Ogle and Weil (1958). They found that stereoacuity measured by the constant stimulus method was degraded for shortened exposure times, in a stimulus consisting of three parallel vertical lines in each half-image. The change in threshold (Δt) was well described by the relationship

$$\Delta t = t_1 E^{-a}$$

where t_1 is the threshold at 1 s, E is the exposure time in s, and a is a constant for each subject.

For their subjects t_1 averaged about 10 seconds of arc and $-a$ was about -0.3 . Similar results were found by Shortess and Krauskopf (1961) who used both free-viewing and retinally-stabilized stimuli. The slopes for their three subjects varied between approximately -0.5 and -0.3 (measured from their figures) and did not seem to differ consistently between normal and stabilized conditions. A comparison may be made with vernier acuity, measured by Keesey (1960) under similar conditions on one of the same subjects. Again stabilization had no appreciable effect on the thresholds, indicating that eye movements play no role in either vernier or stereoscopic acuity for these stimuli. Direct comparison of the free-viewing vernier and stereoscopic thresholds for G.K.S. shows that they do not differ for stimulus presentations longer than 500 ms but diverge by a factor of two or three for shorter durations. Comparison of the other subject in vernier acuity with the subject showing the least change in stereoscopic acuity shows a similar divergence. This comparison suggests that for short stimulus presentations stereoacuity is degraded by a factor of two or more relative to vernier acuity.

2 Experiment I

2.1 Introduction

The first experiment was therefore designed to test whether stereoacuity is degraded to the same extent by brief presentation of a disparity (hypothesis b) as by disparities succeeding one another in time (hypothesis a). Two conditions were compared. A briefly presented line stimulus at a variable disparity from a fixation line provided a test of stereoacuity in the absence of disparity inhibition (stereoalignment condition). If disparity inhibition occurs, a stimulus present at zero disparity in the retinal location of the test line should inhibit the detection of the test disparity. Such an

inhibitory stimulus was produced by presenting a stimulus line continuously at zero disparity and displacing it to the test disparity during the experimental trial, after which it returned to the fixation disparity (stereomovement condition). This arrangement has the advantage that removal of the inhibitory stimulus line during the test trial minimises the ambiguity inherent in the simultaneous presence of several similar stimuli of different disparities. In order to ensure that any effects measured were restricted to stereoscopic processing, control conditions measuring binocular sensitivity to lateral movement and lateral misalignment of the two types of stimuli were included. These vernier stimuli were produced simply by altering the stereoscopic stimuli so that movement or misalignment occurred in the same, rather than opposite, directions in the two eyes.

Stimulus duration was set at 100 ms so as to avoid the possibility of stimulus-related eye movements, which do not occur with a latency less than about 200 ms (Westheimer, 1954; Rashbass and Westheimer, 1961).

It is also possible that learning effects noted by other authors (Westheimer and Tanzman, 1956) may have contributed to the suppression effect. If stereoscopic thresholds require extensive testing before they reach an asymptotic level, early data could produce a spurious impression of stereoscopic suppression. Unpublished data of Westheimer (personal communication) suggest that in the discrimination of large disparities one session of training with error feedback can produce approximately 50% improvement, but further training for up to 10 sessions does not produce significant extra improvement. For threshold determinations Shortess and Krauskopf (1961) show some evidence of practice effects over the first one or two sessions, but they do not report using feedback. The present experiment therefore included an initial practice trial with feedback. The results showed no consistent tendency to improve after the practice trial.

Finally, consideration should be given to the relationship between vernier and stereoscopic thresholds in the absence of a suppression effect. If sensitivity were determined by retinal factors, the initial expectation for detection of a stereoscopic stimulus would require the presence of the just detectable vernier stimulus in each eye, and hence threshold disparity should be twice threshold vernier displacement.

The literature relating to this prediction is confused. Berry (1948) found that lateral vernier thresholds with binocular viewing were between 1.5 and 3 times greater than thresholds for stereoscopic depth, except at vertical stimulus separations of less than 2 minutes, when vernier thresholds decreased to as little as half the stereothreshold. Stigmar (1970) found that above 4 minutes vertical separation stereoacuity and binocular vernier acuity were similar and at smaller separations stereoacuity was degraded by a factor of three. The latter finding can be described as spatial inhibition of stereoacuity. Tyler (1973) found that under optimal conditions stereoacuity was equal to monocular vernier acuity. Since Stigmar showed that binocular vernier acuity was equal to monocular acuity of the best eye, the two results are probably equivalent. The configuration used in the present paper is most similar to Stigmar's, which suggests that stereoacuity will be measured as equal to vernier acuity if suppression effects are absent, e.g., at long exposure durations.

The experimental hypothesis to be tested is whether inhibition occurs between disparity detectors, producing elevation of the stereomovement threshold relative to the vernier movement threshold and to both alignment conditions (figure 1a). If the stereomovement threshold elevation is due to a lower stereoscopic sensitivity combined with suppression of vernier movement information, an equivalent elevation should be found in the stereo-alignment threshold, with both vernier thresholds matching classical values (figure 1b). Finally, if the suppression is a general effect of either lateral or depth positions succeeding one another rapidly in time, both vernier and

stereoscopic movement conditions should show higher thresholds than the corresponding alignment condition. Previous results (Tyler, 1971) suggest that in this case the vernier thresholds will also be reduced relative to the corresponding stereoscopic sensitivities (figure 1c).

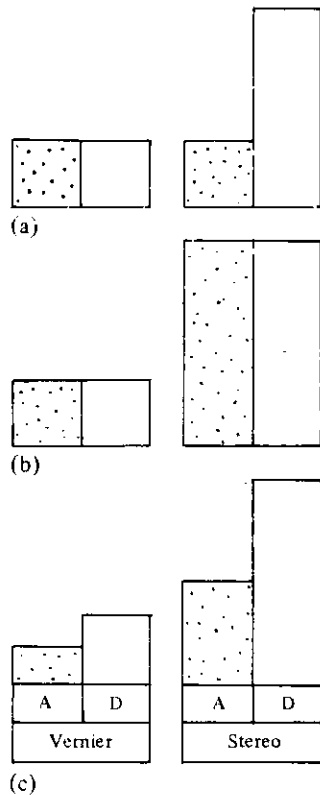


Figure 1. Pattern of threshold values expected under three experimental hypotheses: (a) disparity inhibition, (b) poor stereoscopic sensitivity, (c) poor movement sensitivity. A alignment condition, D displacement condition. Ordinate represents hypothesized amount of stimulus displacement at threshold visibility.

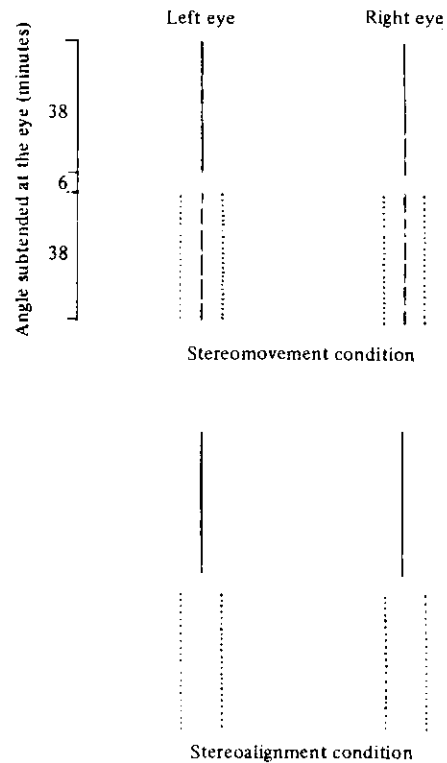


Figure 2. Stimulus configuration for the two experimental conditions. Stereomovement condition: full line, continuous presentation; dashed line, continuous except during 100 ms trial; dotted line, present only during 100 ms trial. Stereoalignment condition: similar to stereomovement condition except that lower line is present only during 100 ms trial. Left and right eye views each show two alternative positions of the test line (dotted), making any of four possible combinations on a given trial.

2.2 Method

The line stimuli were generated on the face of a fast phosphor dual-trace Telequipment oscilloscope laid on its side and viewed in the dark. The oscilloscope time-base, triggered from a 1 KHz rectangular wave, provided the vertical extension of the lines. Each trace was selected to project to one eye by means of conventional crossed-polarizing filters. The stimulus configuration (figure 2) consisted of an upper vertical reference line subtending 38 minutes in length and 1 minute in width at the eye, a 6 minute gap masked by black tape and two possible conditions for the lower (stimulus) line. [The 6 minute gap between the test and reference line was used to avoid the spatial suppression of stereoacuity found by Stigmar (1970) with smaller gaps. Beyond 6 minutes gap size had a negligible effect.] For the movement task

the lower line, which was of identical proportions to the upper line, was continuously visible. During the experimental trial it moved to a new position for 100 ms and then returned, the movement occurring either in the same direction or in opposite directions in the two eyes, for the vernier or stereoscopic movement conditions respectively. This was achieved by gating the triggering rectangular wave into the Y axis (now horizontal) of the oscilloscope so that the positive phase constituted the lower line which was therefore displaced correspondingly. The zero-voltage phase coincided with the upper line, which therefore remained stationary. For the alignment task the lower line was presented at the same or opposite interocular misalignments in an equivalent manner to the movement conditions, but the lower line was absent at all other times. The alignment configuration was achieved by using the same arrangement as for the movement task during the 100 ms presentation. A large-amplitude rectangular wave was added to the stimulus at all times except during the 100 ms presentation. This had the effect of moving the lower line off the screen so as to make it invisible except during the trial. The stimulus lines had a luminance of approximately 2 cd m^{-2} , which is in the photopic range, so dark adaptation was not necessary. The subject's head was held steady with a bite-board. He or she was instructed to fixate the lower end of the upper (reference) line during each trial. The trial was marked auditorily by a click at the onset and offset of the displacement, and extraneous sounds from the apparatus were masked by white noise.

Thresholds were measured by a two-alternative forced-choice staircase technique (Rose *et al.*, 1970). The subject's task was to indicate the lateral or depth direction of displacement of the test line in the vernier or stereoscopic conditions respectively. For each session the initial displacement was set at twice the threshold displacement of the preceding session (or the practice session in the case of the first test session). Direction of displacement was alternated randomly throughout the session. Amplitude was increased by one step for each error in direction response, and decreased by one step whenever the response was correct twice in a row. This ratio should give a threshold close to 70% correct judgement (Rose *et al.*, 1970). Thirty-six trials were run in each condition. Disparities generally stabilized within the first twelve trials, so the last twenty-four were used in computing threshold. A session consisted of one thirty-six trial set for each of the four conditions (vernier movement, vernier alignment, stereomovement, stereoalignment). Four sessions were run in a counter-balanced Latin square so that each condition appeared in each position both during the session and relative to other conditions, to control for practice, fatigue, adaptation and interaction effects. The three subjects tested all had 20/20 vision with normal refractive correction, and stereoacuity of 5 seconds on the Keystone Orthorater test.

2.3 Results

Thresholds for each condition in each session are listed in table 1. It may be noted that there is no consistent tendency for thresholds to improve over sessions in either vernier or stereoscopic conditions, with one possible exception. Stereomovement thresholds for subject L.F. start approximately a factor of ten higher than for the other two subjects, and are consistently reduced over sessions. Accordingly L.F. was tested on seven extra sessions for that condition, with each run starting in the region of the other subjects' thresholds rather than 6 dB above his previous threshold, in an attempt to ensure that he could not discriminate in that region. The extra data, although averaging lower thresholds than the average of the initial sessions, do not show any further practice effects, but manifest a high variability, so the last eight values were averaged for the results presented. The summary histogram (figure 3) shows the data for the three subjects under four conditions. Since psychophysical variability is usually proportional to mean settings, geometric means were used.

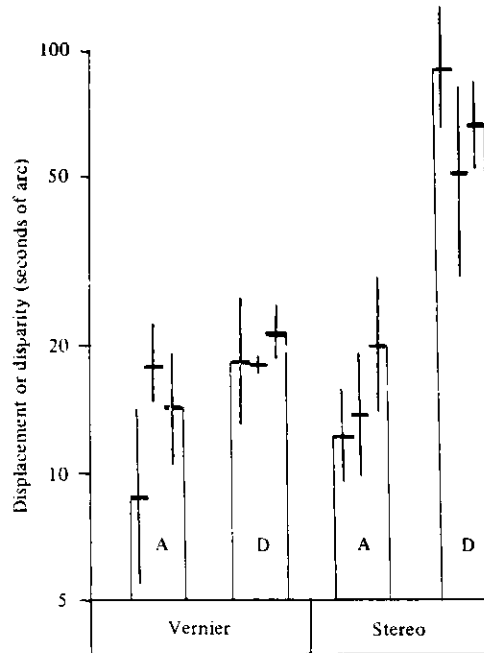


Figure 3. Threshold displacement (vernier) or disparity (stereo) for alignment (A) and displacement (D) conditions. Mean logarithmic thresholds for three subjects are shown as three horizontal bars in each column. Vertical line shows one standard deviation on either side of threshold. Note that stereo-displacement threshold is about three times higher than for the other three conditions.

Table 1. Vernier and stereoscopic thresholds by session for alignment (A) and displacement (D) tasks, in seconds of arc, with geometric means.

Subject	Session	Vernier		Stereo	
		A	D	A	D
L.F.	2	12.70	29.35	16.82	362.48
	3	5.36	16.03	12.44	345.01
	4	5.81	11.04	9.89	222.96
	5	15.55	20.62	10.22	141.35
	mean	8.86	18.09	12.06	267.45
	6				28.47
	7				133.90
	8				69.83
	9				84.95
	10				138.14
	11				58.59
	12				330.09
	mean				89.64
L.T.	2	19.05	18.19	15.11	21.63
	3	14.96	18.64	7.79	50.63
	4	24.84	16.69	19.45	59.49
	5	14.01	17.92	15.12	94.72
	mean	17.75	17.85	13.64	49.84
W.T.	2	20.68	18.60	15.82	59.90
	3	11.49	18.15	35.64	57.60
	4	10.34	23.36	19.61	52.69
	5	16.81	25.56	13.14	95.66
	mean	14.26	21.19	19.52	64.58

The histogram makes clear that for all three subjects there is no consistent tendency for the two vernier thresholds to differ from each other or from the stereoalignment threshold. In contrast, stereomovement threshold is elevated by between three and six times the disparity of the other three thresholds. The results conform to the pattern in figure 1a, the pattern predicted by the disparity-inhibition hypothesis. Thus this experiment, done under conditions in which most likely artifacts have been eliminated, appears to substantiate both the results and the interpretation of Tyler (1971).

3 Experiment II

3.1 Introduction

Although experiment I and Tyler's (1971) experiment both show an elevation of the stereo displacement threshold relative to the vernier displacement threshold, a difference between the two tasks poses a further question. In experiment I the task was to discriminate the direction of the displacement. Tyler's subjects set the stimulus to a value at which there was no impression of movement of any kind. It is not clear whether this motion threshold corresponds to the depth discrimination threshold or not. From subjective reports there seem to be two salient criteria that Tyler's subjects might have used; movement in depth and transient diplopia, possibly accompanied by lateral movement. For the former criterion the stimulus might appear fused throughout the threshold region but appear to move in depth above threshold and remain stationary below. Alternatively, with a criterion of transient diplopia the perception of movement in depth might be absent near the threshold, which would be determined solely on the basis of image doubling due to the antiphase movement of the stimulus lines in each eye. The choice between these alternatives is of theoretical importance because under most conditions disparity sensitivity is far greater than sensitivity to diplopia (Ogle, 1952).

A second experiment was therefore designed to compare sensitivity in a movement/no movement discrimination with the sensitivity to direction of depth change measured in the stereomovement task in experiment I. Since in the stereoalignment condition no suppression was found and movement as such does not occur, the alignment tasks were omitted. Sensitivity to movement in the vernier movement stimulus was measured for comparison with stereomovement sensitivity.

There are two questions to which this experiment is addressed:

- (i) Could the visual processes underlying performance in the movement/no movement task be different from those in the stereomovement direction task of experiment I? If so, then thresholds might be expected to be lower in the movement/no movement task.
- (ii) If the answer to the first question is yes, then is discrimination based on transient diplopia responsible for this difference in whole or in part? If so, then the threshold reduction should be either confined to the depth movement condition, or at least greater in the depth movement condition than in the lateral movement condition.

Our method of measuring movement sensitivity involved insertion of 50% trials in which no movement occurs. The remaining trials were equally divided between the two directions of movement. The subject's task was simply to indicate the presence or absence of movement (movement sensitivity). This contrasts with experiment I in which the subject had to indicate the direction of movement (direction sensitivity). In experiment I sensitivity was taken, as is conventional, to be one-half the disparity or vernier separation between the discriminated stimuli at threshold. In experiment II we defined sensitivity in the same way, that is as one-half the difference between the two discriminated stimuli at threshold. This means one-half the difference between the zero disparity (no movement) stimulus and the non-zero disparity.

ignoring the variation in the sign of the non-zero disparity. If disparity is a continuum along which discriminability increases with the difference between the stimuli and, if both kinds of sensitivities are determined by the same central events, then we would expect sensitivities in the two tasks to be approximately equal. A large difference between sensitivities would suggest that the two discriminations have different bases.

3.2 Method

Stimulus presentation and observation conditions were similar to those in experiment I, except that in one-half of the trials, randomly selected, displacement amplitude was zero. The other half were randomly crossed or uncrossed disparities in the

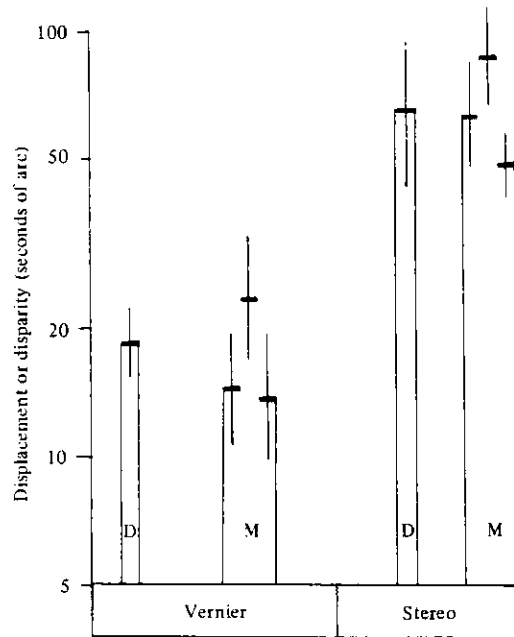


Figure 4. Threshold displacement (vernier) or disparity (stereo) for displacement condition. Depth criterion (D) averaged from figure 3. Movement condition (M) shown for three subjects as in figure 3.

Table 2. Threshold movement for vernier and stereo displacement, in seconds of arc, with geometric mean.

Subject	Session	Vernier	Stereo
L.K.	6	21.79	66.08
	7	10.30	66.46
	8	11.47	40.42
	9	17.12	86.52
	mean	14.49	62.60
W.T.	6	11.31	59.90
	7	20.37	51.05
	8	17.84	47.01
	9	9.08	38.81
	mean	13.90	48.60
L.F.	6	36.87	131.51
	7	20.50	88.91
	8	26.90	68.64
	9	16.01	71.52
	mean	23.89	87.04

stereoscopic task or randomly left or right displacements in the lateral-movement task. The subject indicated after each trial whether or not movement of any kind had occurred. The same ratio of two correct or one incorrect response was used to determine 2 dB increases and decreases in amplitude of movement disparity. Four threshold determinations were made for each of the three subjects used in experiment I in random order.

3.3 Results

A histogram (figure 4) of movement thresholds compared with the stereoscopic depth thresholds from experiment I and the two corresponding vernier thresholds is plotted from the mean thresholds given in table 2. It is clear that all three subjects show marked elevation of stereomovement thresholds relative to vernier-movement thresholds. Note that despite the appearance of a declining trend in the tabulated data of two subjects over sessions, all movement thresholds are similar to the respective direction thresholds, which corresponds to a reduction in sensitivity by one-half (see section 3.1);

4 Discussion

The results of experiment I establish that stereomovement suppression of a factor of about three occurs for transient displacements of disparity. Stereomovement suppression is therefore probably a general property of detection of time-limited disparity changes, and not restricted to sinusoidal depth movement. The presence of a brief *change* in disparity must be the important factor, since sensitivity to briefly presented disparities in the alignment condition was unimpaired relative to detection of lateral changes. A comparison of the low threshold for the stereoalignment condition with the high threshold for the stereomovement condition is evidence in support of disparity inhibition (hypothesis a) rather than a generally low stereoscopic sensitivity for brief stimulation (hypothesis b), as described in figure 1.

Before considering further comparisons of the two hypotheses of stereoscopic processing it is necessary to discuss the precise relationships of vernier and stereoscopic acuity. It was hypothesized on the basis of previous work that, in the absence of suppression effects, vernier acuity would equal stereoscopic acuity. This hypothesis was borne out in the alignment condition within experimental error. This confirmation is of some interest because the acuities are specified on the basis of equal total displacement rather than equal retinal displacement, so that the retinal displacement in each eye at stereoscopic threshold is half the detectable vernier displacement, even when the latter is present in both eyes. It is therefore highly probable that vernier acuity is determined at a cortical level, since human stereoscopic processing is almost certainly cortical (Tyler, 1973, note 1). The limiting neural organization may be represented by the form and dimensions of higher-order receptive fields such as described for monkey by Hubel and Wiesel (1968). Cortical determination of vernier acuity had been indirectly suggested by the fact that it is about a factor of ten less than the diameter of a foveal cone (Polyak, 1941) and therefore requires binocular integration of receptor information in a manner which is unlikely to occur in the retina.

The results of experiment II show that sensitivity to movement alone is greater by a factor of about two than sensitivity to the direction of movement, but the ratio of vernier to stereo sensitivity remains about three, the same factor as found in experiment I. These results suggest that the movement/no movement task is mediated by central processes which differ in some respect from those that mediate discrimination of stereomovement direction. The fact that stereo and vernier thresholds both

decrease by the same proportion suggests that transient diplopia is not responsible for the improvement, since this cue is available only in the stereo condition.

We conclude that two eyes are less sensitive than one in the detection of transient as well as sinusoidal antiphase displacements, but not for the discrimination of misalignment. Neither eye movements nor adaptation are responsible for stereomovement suppression, which is probably an inherent limitation imposed by the complexity of disparity processing. Further, sensitivities in a movement/no movement discrimination task are lower by about half than those in a direction-discrimination task. Stereoscopic thresholds exceed vernier ones by about three to one in both tasks. These results suggest that motion discrimination has a different basis from direction discrimination.

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References

- Berry, R. N., 1948, "Quantitative relations among vernier, real depth and stereoscopic depth acuities", *Journal of Experimental Psychology*, **38**, 708-821.
- Hubel, D. H., Wiesel, T. N., 1968, "Receptive fields and functional architecture of the monkey striate cortex", *Journal of Physiology*, **195**, 215-243.
- Keesey, U. T., 1960, "The effects of involuntary eye movements on visual acuity", *Journal of the Optical Society of America*, **50**, 769-774.
- Ogle, K. N., 1952, "On the limits of stereoscopic vision", *Journal of Experimental Psychology*, **44**, 253-259.
- Ogle, K. N., Weil, M. P., 1958, "Stereoscopic vision and the duration of the stimulus", *Archiv für Ophthalmologie*, **56**, 4-17.
- Polyak, S. L., 1941, *The Retina* (University of Chicago Press, Chicago).
- Rashbass, C., Westheimer, G. H., 1961, "Disjunctive eye movements", *Journal of Physiology*, **159**, 149-170.
- Rose, R. M., Teller, D. Y., Rendleman, P., 1970, "Statistical properties of staircase estimates", *Perception and Psychophysics*, **8**, 199-204.
- Shortess, G. K., Krauskopf, J., 1961, "Role of involuntary eye movements in stereoscopic acuity", *Journal of the Optical Society of America*, **51**, 555-559.
- Stigmar, G., 1970, "Observations on vernier and stereo acuity with special reference to their relationship", *Acta Ophthalmologica*, **48**, 979-998.
- Tyler, C. W., 1971, "Stereoscopic depth movement: Two eyes less sensitive than one", *Science*, **174**, 958-961.
- Tyler, C. W., 1973, "Stereoscopic vision: cortical limitations and disparity scaling effect", *Science*, **181**, 276-278.
- Tyler, C. W., 1975, "Characteristics of stereomovement suppression", *Perception and Psychophysics* (in press).
- Westheimer, G. H., 1954, "Mechanism of saccadic eye movements", *Archiv für Ophthalmologie*, **52**, 710-724.
- Westheimer, G. H., Tansman, I. J., 1956, "Qualitative depth localization with diplopic images", *Journal of the Optical Society of America*, **46**, 116-117.