Vision Research Vol. 21, pp. 205 to 213
Pergamon Press Ltd 1981. Printed in Great Britain

0042-6989/81/0201-0205$02.00/0

DISPLACEMENT DETECTION IN HUMAN VISION

GORDON E. LEGGE*
Department of Psychology, University of Minnesota, Minneapolis, MN 55455, U.S.A.
and
F. W. CAMPBELL
The Physiological Laboratory, Cambridge University, Cambridge CB2 3EG, England

(*Received* 26 *March* 1980)

Abstract—The *displacement threshold* is defined to be the smallest instantaneous target displacement that can be detected. Properties of the displacement threshold for a small, luminous spot were measured *psychophysically*. In a structureless field, the displacement threshold was near 1.5′, subject to individual variation. The effects of *pattern* were studied by measuring displacement thresholds at the centers of a set of annuli ranging from 2.85′–728′ dia. Displacement thresholds were reduced by the presence of the annuli and were as low as 0.3′. This threshold reduction could not be fully attributed to processes of *relative spatial localization* because displacement thresholds were lower than spatial localization (bull's-eye) thresholds for annulus diameters greater than 20′. The displacement threshold is virtually independent of orientation and pupil size. It increased about 75% with a three log unit decrease in photopic target *luminance*. Displacement detection appears to depend upon the motion sense rather than the position sense. It may be limited by fixation accuracy.

INTRODUCTION

In the 1870's Dvorak, Vierordt and Exner introduced the idea that seen movement is a primary sensation (Boring, 1942; Chap. 15). As such, movement is sensed directly, and is not inferred secondarily from changes in position. The modern version of this view holds that there are specialized visual mechanisms for the analysis of stimulus motion. The prevailing opinion holds that motion may be apprehended directly through the mediation of motion detecting mechanisms, and that it may also be inferred indirectly from change in position (cf. Campbell and Maffei, 1979). Kaufman (1974; Chap. 10) surveys results arguing for the separability of the motion sense and the position sense.

A great deal of physiological and psychophysical research has uncovered evidence for visual motion detecting mechanisms. Good reviews are provided by Sekuler (1975), and Sekuler *et al.* (1978). Various aspects of motion perception have been examined. There exists psychophysical evidence for the existence of direction-selective motion mechanisms (Sekuler and Ganz, 1963; Richards, 1971), velocity-selective mechanisms (Pantle and Sekuler, 1968), and mechanisms specialized for the detection of the direction of motion in depth (Regan and Beverley, 1978). Undoubtedly some properties of apparent or stroboscopic motion perception are mediated by motion detecting mechanisms as well (Anstis, 1978).

On the other hand, a phenomenon of motion perception that may be related more to the position sense than the motion sense is the velocity threshold. The velocity threshold is the minimum velocity that can be detected. Johnson and Leibowitz (1976) have shown that, for targets presented for 0.1–1.0 sec, motion can be detected only when the target's velocity is such that it moves at least 1.5′ of visual angle. This angular distance is comparable to the limits of spatial resolution in vision. Johnson and Leibowitz have suggested that the velocity threshold may be determined by the same mechanisms that underlie visual acuity. This idea is supported by experiments demonstrating that the velocity threshold changes with angle of eccentric viewing (Leibowitz *et al.*, 1972) in the same way as visual acuity (Millodot *et al.*, 1975). A similar view was adopted by Gordon (1947) for scotopic vision, based upon measurements of the velocity threshold and visual acuity in the visual periphery. For very long stimulus exposures, and very slow target velocities, such as the movement of the hour hand of one's watch, it seems almost certain that motion detection is an inferential process dependent upon the position sense.

An aspect of motion perception that has received little recent attention is the *displacement threshold.* What is the smallest movement (displacement) that can be detected? The results of Johnson and Leibowitz (1976) might suggest that the displacement threshold would be about 1.5′ and might be limited by mechanisms of *spatial resolution*. However, early measurements (Stratton, 1902; Basler, 1906) indicate that under some conditions, the displacement threshold can be substantially less than 0.5 min arc. As Basler

---

* Send reprint requests to Gordon E. Legge.

(1906) pointed out, this means that observers can detect displacements between two points whose separation cannot be spatially resolved. A similar situation exists in peripheral vision (cf. Biederman-Thorson *et al.*, 1971). The ability to detect such small displacements places the displacement threshold among the "hyperacuities" (Westheimer, 1975; Westheimer, 1976). The hyperacuities comprise a set of visual discriminative capacities, such as vernier acuity and stereoacuity, whose keenness of sensitivity means that they are not fundamentally limited by the spatial resolving power of the eye. Basler (1906) and Graham (1968) have found that the displacement threshold depends on the speed of displacement from initial point to final point, tending to be smaller for greater speeds. Tyler and Torres (1972) measured the displacement threshold for a small, vertical line undergoing horizontal, sinusoidal displacement. In the presence of a nearby reference line, maximum displacement sensitivity occurred for sinusoidal frequencies in the range of one to ten Hz. Westheimer (1978) has demonstrated that displacement thresholds for line and sinewave grating targets are as low as 10 sec arc.

The purpose of the current research was to measure several properties of the displacement threshold. What do these properties tell us about mechanisms underlying displacement detection?

In the experiments, the target was a small spot of light on a CRT screen. The spot's motion consisted of instantaneous displacements from one point to another. Displacement thresholds were measured as a function of the meridian of displacement (orientation), the luminance of the spot, and the diameter of surrounding annuli. A "bull's-eye" detection experiment was performed as well to assess how accurately observers can locate the center of a circle. The purpose of the "bull's eye" measurements was to determine whether displacement thresholds could be accounted for by the locating ability of the eye.

METHOD

Apparatus

The stimulus whose displacement was to be detected was an illuminated white spot of light on the face of an HP 1300A X-Y CRT display. The 1.0 mm dia spot was circular, and subtended 0.45 min arc at the viewing distance of 760 cm. The spot's horizontal and vertical screen positions were controlled by a DEC PDP-8 computer via D/A converters and dB attenuators whose voltage outputs were applied to the X and Y inputs of the display. A spot displacement was effectively instantaneous.

In several of the experiments, annular surrounds were present. These were circular apertures of various diameters cut out of black cardboard. High contrast white rings, width 1.5 mm, were painted around the circumference of the apertures on the black cardboard. The visual field interior to the rings appeared uniform to the observers. The apertures were built to fit snugly against the display screen. When in use, the centers of the apertures formed the starting point for the spot's displacements.

Procedure

Except where specified below, observers viewed the display from a distance of 760 cm. Viewing was monocular with natural pupils, except for one control experiment in which a 3 mm artificial pupil was used.

For experiments conducted with unstructured fields, no annular surrounds were present, and all room lights were extinguished. The spot's luminance was 1.0 cd/m^2. Prior to an experiment, the observer was given 10 min of dark adaptation. During the experiments, he perceived a luminous spot in an otherwise uniform, unstructured, dark field. Under these conditions, some observers perceived apparent drifts in position of the spot, not associated with its physical displacement (autokinetic effect).

When annular surrounds were used, experiments were conducted in a normally illuminated room so that observers could see the white annular rings. Spot luminance was increased to 100 cd/m^2 so that it was readily visible. The luminances of the circular fields, annuli, and black surrounds were 60 cd/m^2, 160 cd/m^2, and 14 cd/m^2, respectively. Under these conditions, the spot appeared to lie within a uniform circular field circumscribed by the white annuli on the black surround.

Displacement thresholds were measured by a version of the two-alternative forced-choice staircase procedure (Wetherill and Levitt, 1965). With the luminous spot at rest in view, the observer initiated a trial by striking a key. One sec and 2.5 sec later, bells sounded. Concurrent with one of the bells, the spot was displaced to its new position where it remained at rest for the remainder of the trial. The assignment of displacements to bells was random, with equal probability. Following the second bell, the observer depressed one of two keys, indicating whether he believed the displacement had occurred on the first or second bell. All responses were followed by the disappearance of the spot, and its subsequent reappearance at the center of the display in readiness for the next trial. Correct choices were followed by a bell.

A displacement threshold estimate was obtained from a block of forced-choice trials. The series of trials began with displacements that pilot studies indicated were about twice the threshold value. Three consecutive correct decisions for a given value of displacement were followed by a decrement in displacement (10% of the starting value), and one incorrect decision was followed by an increment of the same size. The mean of the first 6 displacement minima and maxima in the resulting sequence was taken as an estimate of the 79% correct level for spot displacement. The arithmetic mean of several such estimates was taken as the measure of displacement threshold under the specified conditions. The error bars in the figures represent ±1 SEM. Typically, a block consisted of about 35 trials. Sixteen to 24 blocks of trials could be run in a 2 hr session. Although there were considerable variations between individuals, variability for a given individual across days was irregular and small. Accordingly, data for an individual were often pooled across days.

Except in Experiment 1 in which displacement thresholds were measured as a function of orientation, displacements were always horizontal, from right to left.

In Experiment 3, an observer's ability to localize a spot at the center of a circle was examined. A forced-choice trial consisted of a single exposure in which the luminous spot appeared for one sec at a specified position along the horizontal diameter of the circle defined by one of the annuli. The observer's task was to indicate whether the spot had appeared to the left or the right of center. For a given trial, the offset was randomly determined to lie to the right or left with equal probability, and the observer was informed when he made a correct decision. Prior to a block of forced-choice trials, the spot was presented at rest at the center of the circle. The staircase procedure, analogous to the one just described for displacement detection, was used to obtain an estimate for the offset that could be identified as lying to the right or left of center on 79% of trials. Means of four such threshold estimates are plotted as the data in Fig. 3. They are termed "bull's-eye" thresholds.

Observers

Six observers participated in the experiments. The observers' normal distance corrections were used. Table 1 lists the observers, the eye used, its distance correction, and some results to be discussed below.

RESULTS AND DISCUSSION

Experiment 1: displacement detection as a function of orientation

We began our examination of displacement thresholds by measuring the influence of displacement orientation. Twelve orientations, ranging from 15° to 180° in 15° steps, were chosen. Displacement orientation of 0° refers to horizontal motion from left to right, and displacement orientation of 90° refers to vertical displacement upward.

The three upper sets of data in Fig. 1 represent displacement thresholds in minutes of arc as a function of displacement orientation in degrees of arc for

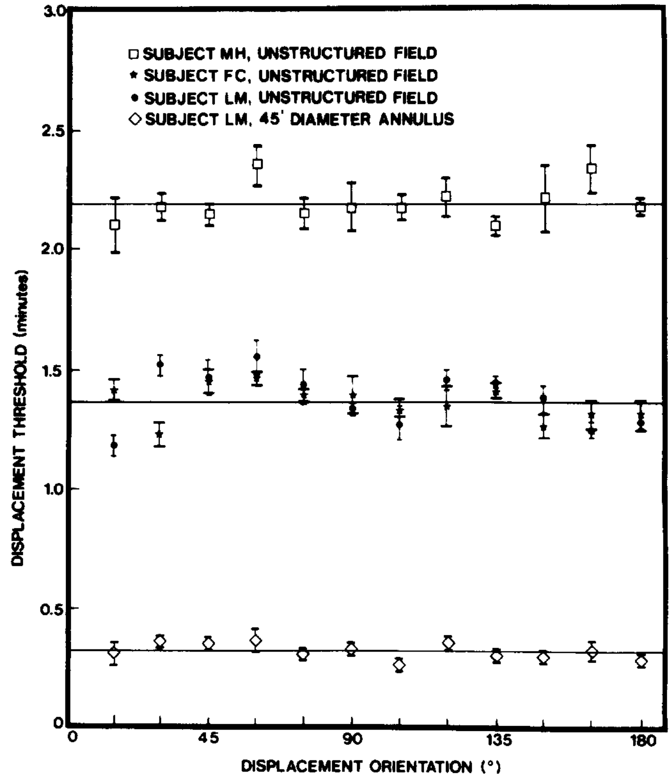


Fig. 1. Displacement threshold as a function of orientation. Displacement thresholds for a small luminous spot are plotted as a function of the direction (orientation) of displacement within the fronto-parallel plane—0° represents displacement from left to right and 90° displacement upward. Symbols are means of six threshold estimates, each obtained from a forced-choice staircase. Error bars represent ±1 SE. The three upper sets of data—(□) MH, (*) FC, (●) LM—were obtained with 1.0 cd/m² spots in uniform, unstructured fields. The lower set of data—(◇) LM—was obtained with a 100 cd/m² spot displaced from the center of a 45′ diameter circular field surrounded by a white annulus. Horizontal solid lines have been drawn through the sets of data at 2.19′, 1.37′, and 0.33′.

three observers. These three sets of data were collected in a dark, structureless field in which only the spot of luminance 1.0 cd/m^2 was visible to the observer. The mean displacement threshold, computed across all orientations, was 1.38′ for observer LM and 1.36′ for observer FC. A horizontal solid line has been drawn through these two sets of data at 1.37′. The mean displacement threshold across all orientations for observer MH was 2.19′, and a solid line has been drawn through her data at this level.

These displacement thresholds are in excess of 1 min arc and might, in principle, be limited by spatial resolution. They are consistent with the displacements associated with the velocity thresholds (for exposure durations of 0.1–1.0 sec) found by Johnson & Leibowitz (1976). However, these displacement thresholds are much higher than the 20″ vertical displacement thresholds found by Basler (1906), and the 10″ horizontal displacement thresholds found by Stratton (1902) and Westheimer (1978). A possible source for the discrepancy is the nature of the surround conditions. In those studies in which thresholds well below 1′ have been found, patterned structures of various types have been present in the visual field.

In order to check for the effects of pattern, displacement thresholds were measured for target spots whose starting position was located at the center of a 45′ dia annulus. These measurements were conducted with a 100 cd m^2 spot with normal room illumination so that the observer could easily see both the spot and the white annulus on the black cardboard aperture. The bottom set of data for observer LM in Fig. 1 demonstrates the effects of the presence of pattern on the displacement threshold. A horizontal line has been drawn through the data at the overall mean level of 0.33′ (20″). Compared with her performance in the structureless field, LM's displacement thresholds in the presence of the surrounding annulus have been reduced by a factor of about 4. These lower displacement thresholds are of the same magnitude as those measured by Stratton (1902), Basler (1906) and Westheimer (1978). Displacement thresholds near 20″ must be classed among the "hyperacuities."

Table 1 presents mean horizontal displacement thresholds for several observers with and without the 45′ annulus. Each mean is based on at least 4 blocks of forced-choice trials. In every case, thresholds obtained in the presence of the annulus are well below 1.0′ and those obtained in the structureless field exceed 1.0′.

The individual differences, apparent in Table 1, are consistent with individual differences found by Gordon (1947) for velocity threshold measurements, and by McKee and Westheimer (1978) for vernier thresholds. In the case of the displacement threshold, individual differences may be related to fixation accuracy. During a trial, observers fixated the spot whose displacement was to be detected. Small fixational eye movements cause the spot's image to move about on the fovea, adding "noise" to the displacement "signal." Eye movement studies indicate that the image of a small fixation point is confined to a small foveal region over periods of prolonged fixation by small, corrective eye movements. The size of this region shows individual variation over a factor of at least 3, from diameters of about 1.5′–5.0′ (Steinman, 1965; Rattle, 1969). If fixational eye movements add noise in the displacement threshold task, then individual differences in fixation accuracy might manifest themselves as individual differences in displacement thresholds. This hypothesis raises the possibility that fixation accuracy may impose fundamental limitations upon the keenness of displacement sensitivity.

Pattern vision exhibits an "oblique effect" under many conditions and paradigms of measurement (Appelle, 1972) in which sensitivity along oblique meridians in the visual field is less than along horizontal and vertical meridians. The oblique effect appears to be cortical in origin (Campbell and Maffei, 1970) and may be due to anisotropy in the distribution of optimal meridians for orientation selective neurons (Mansfield, 1974; Mansfield and Ronner, 1978). However, the sets of displacement thresholds in Fig. 1 exhibit very little sensitivity to displacement orientation. Analyses of variance indicate that both sets of LM's displacement thresholds do deviate significantly from the mean levels of 0.33′ and 1.38′ ($P < 0.01$), but the data of MH and FC do not deviate significantly (at the 0.05 level) from their means. These results indicate that, unlike pattern sensitivity, displacement sensitivity exhibits little or no "oblique effect."

Richards (1971) has found that sensitivity of the motion after effect is greater along the horizontal and vertical than along obliques. Moreover, oblique

Table 1. Individual data

	LM	FC	MH	SH	FWC	WWL
Optical correction						
Eye	left	left	left	right	right	right
Sph (D)	0.25	0	1.0	−3.0	−1.0	−2.0
Cyl (D)	−0.5	0	0.5	−2.0	−0.5	−1.25
Axis (°)	90		120	0	90	135
Mean horizontal displacement threshold (min)						
Unstructured field	1.28	1.30	2.17	1.30		1.05
45′ annulus	0.31	0.28	0.61	0.54	0.52	0.30

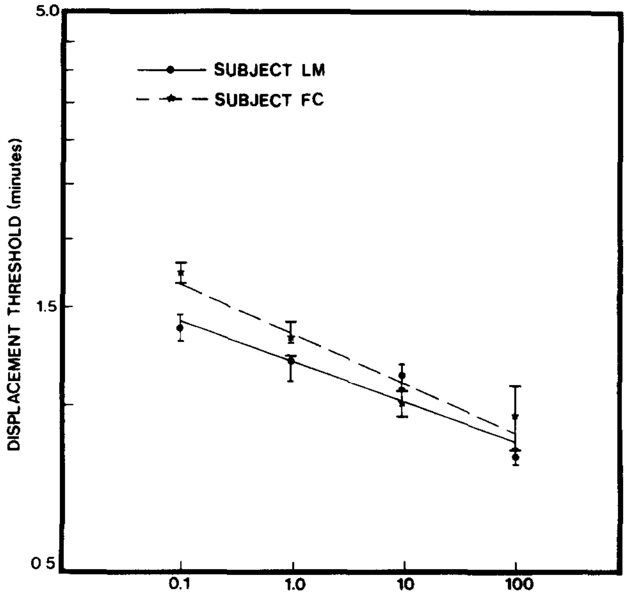


Fig. 2. Displacement threshold as a function of luminance. Displacement thresholds for a small spot are plotted as a function of spot luminance. The spot appeared in a uniform, dark field. Displacement was horizontal. Symbols are means of 4 threshold estimates, each obtained from a forced-choice staircase. Error bars represent ± 1 SE. Best fitting straight lines (least squares criterion) have been drawn through the sets of data for LM (●) and FC (*) in the log–log coordinates, with slopes of -0.073 and -0.089 respectively.

effects have been noted for various forms of hyperacuity (Leibowitz, Myers and Grant, 1955; Andrews *et al.*, 1974; McKee and Westheimer, 1978). McKee and Westheimer (1978), however, have noted that the oblique effect for vernier acuity is subject to considerable individual variability and may be reduced or entirely abolished with prolonged practice.

Experiment 2: displacement detection as a function of annulus diameter

In Fig. 1, LM's displacement thresholds in the presence of the 45′ diameter annulus were about a factor of four lower than those in the unstructured field. This result suggests that the presence of pattern in the visual field leads to a substantial reduction in the displacement threshold for a spot target. The purpose of Experiment 2 was to examine the dependence of the displacement threshold on the proximity of pattern to the target.

It is possible that two factors, besides the surround conditions, may account for the fourfold difference between the two sets of LM's data in Fig. 1. The use of the 45′ annulus was accompanied by an increase in spot luminance from 1.0–100 cd/m^2. The room lights were turned on so that the annulus could be seen, resulting in pupilary contraction. In two control experiments, the effects of spot luminance and pupil size were examined.

Spot luminance. Figure 2 presents displacement thresholds in min arc as a function of spot luminance in the range 0.1–100 cd/m^2. Besides the spot, no other pattern was present in the visual field. Data points represent means derived from 5 or 6 blocks of forced-choice trials. Best fitting straight lines (least squares criterion) through the two sets of data in the log–log coordinates have slopes of -0.073 and -0.089 for observers LM and FC respectively. Over a 3 log unit range of spot luminances, displacement thresholds varied by a factor of only about 1.75. Clearly, the change in spot luminance from 1.0 to 100 cd/m^2 that accompanied measurements with and without the surrounding annuli in Fig. 1 and Table 1 does not fully account for the large change in corresponding displacement thresholds.

Basler (1906) also noted a dependence of the displacement threshold upon luminance, but did not quantify it. The changes in displacement thresholds with spot luminance depicted in Fig. 2 are less than changes in spatial resolution acuity over a similar range of luminances (cf. Le Grand, 1967; Chap. 5). (Note, however, that most measures of visual acuity have used dark targets on light adapting fields. Wilcox (1932) measured visual acuity for light targets on dark fields. In this case, acuity first increased with luminance, then decreased.) By comparison, the influence of photopic luminance on other hyperacuities also appears to be rather small (Baker, 1949; Westheimer and McKee, 1977a). The velocity threshold also demonstrates a very weak dependence on photopic target luminance (Leibowitz, 1955).

Scobey and Horowitz (1976) have suggested that under some conditions of peripheral viewing, displacement thresholds and luminance discrimination may be based on the same neural mechanisms. Their suggestion was motivated by studies of the response properties of phasic retinal ganglion cells in monkeys. However, the very weak dependence of displacement thresholds on luminance in Fig. 2 makes it very difficult to imagine a single neural mechanism underlying both displacement detection and luminance discrimination in human foveal vision. Westheimer and McKee (1977b) have demonstrated that another hyperacuity, spatial interval discrimination, cannot be accounted for by simple luminance discrimination.

Campbell and Gubisch (1966) have demonstrated that the line spread function of the physiological optics may be represented by a Gaussian core, due to diffraction, and exponential "skirts" due to optical aberrations and light scatter. For large pupils, the line spread function is dominated by the exponential "skirts". If the effective width of the line spread function is determined by some criterion luminance level on the "skirt", then effective width of the line spread function will grow logarithmically with luminance. In the case of a spot target, it is possible that logarithmic growth in effective diameter with luminance might lead to a corresponding slow decrease in displacement threshold. A possible mechanism might be related to fixation accuracy. Steinman (1965) has demonstrated that fixation accuracy is slightly decreased by one log unit decrease in photopic target luminance. Presumably, this decrease occurs because larger excursions of the lower luminance, and slightly smaller target, are required before error signals are generated leading to corrective eye movements.

Pupil size. Displacement thresholds in unstructured fields were measured with a spot target in an otherwise dark field. Under these conditions, the pupil is dilated, reducing spatial resolution (Campbell and Gubisch, 1966). If displacement sensitivity were to depend on spatial resolution, pupil dilation should lead to increased displacement thresholds. However, a 3 mm artificial pupil should restore displacement sensitivity to nearly optimal values, since spatial resolution is nearly optimal for pupils of this size (Campbell and Gubisch, 1966). In a control experiment, displacement thresholds were measured in the dark *with* and *without* a 3 mm artificial pupil. Over 6 blocks of forced-choice trials, the displacement thresholds for one observer were 6% higher with the 3 mm pupil, and for a second observer 9% higher. These small changes, opposite in direction to changes that would be predicted on the basis of spatial resolution, show that pupil size has only a very slight effect upon the displacement threshold. Apparently, displacement thresholds are not critically dependent upon spatial resolution.

These two control experiments demonstrate that neither target luminance nor pupil size can account for the large reduction in the displacement threshold, evident in Fig. 1 and Table 1, resulting from the addition of an annular surround.

Displacement thresholds were measured for 100 cd/m^2 spots whose initial positions were at the center of a white annulus. The six annuli had inner diameters of 0.25, 0.5, 1.0, 2.0, 4.0 and 8.0 in. At the standard viewing distance of 760 cm, the corresponding angles, subtended at the eye, ranged from 2.85′–91.2′. Because larger annuli would extend beyond the CRT screen, it was not convenient to construct annuli with diameters greater than 8 in. In order to extend the range of angles subtended by the annuli, viewing distances of 380 cm, 190 cm, and 95 cm were used with the 8 in. annulus. The range of annulus subtense was accordingly extended to 728′.

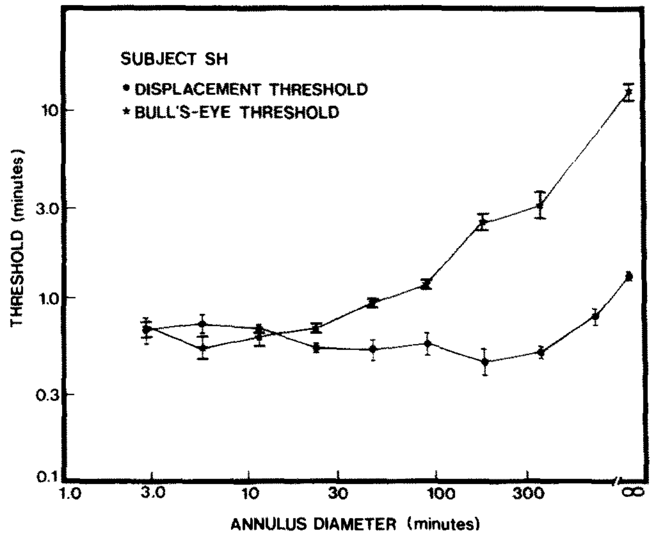
In Fig. 3 (a) and (b), displacement thresholds (filled circles) for observers SH and MH are plotted as a function of annulus diameter. (Displacement thresholds were not collected for SH at 728′.) Displacement thresholds obtained in the absence of an annulus (unstructured field) have been designated by an abscissa value of infinity. Each symbol is the mean of four threshold estimates, each derived from a block of forced-choice trials. The symbols have been joined by straight line segments. The "bull's-eye" thresholds (*) will be discussed in connection with Experiment 3.

Figure 3 demonstrates that displacement thresholds depend only weakly upon annulus diameter in the range 2.85′–364′. Over this range, the displacement thresholds for SH and MH remain near 0.55′ and 0.65′ respectively. For larger annuli, the thresholds rise to values of 1.3′ and 1.7′ respectively. Less extensive data of the same sort for LM and FC also demonstrate that the displacement thresholds are largely independent of annulus diameter over a wide range. These results indicate that the presence of pattern in the visual field exerts a nonspecific influence on the displacement threshold. Annuli with diameters ranging from 2.85′ to about 6° reduce displacement thresholds by factors ranging from two to four (see Table 1) compared with displacement thresholds obtained in the absence of pattern.

In agreement with these results, Tyler and Torres (1972) mention a pilot experiment in which the presence of a reference line in the visual field at distances ranging from 10′ to 30′ from a target line had roughly similar effects in reducing the displacement threshold.

There exists a good deal of evidence for more specific influences of spatial configuration upon hyperacuity thresholds. For example, Ludvigh (1953) measured the ability of an observer to align a target dot with two reference dots. Alignment thresholds decreased with increases in reference dot separation from 2.5′ to 20′ and then increased for wider separations. Westheimer and Hauske (1975) have shown that vernier acuity improves as the separation of flanking horizontal or vertical bars increases from about 2.5′ to near 7′. Interestingly, vernier acuity also improves for flank separations less than 2.5′. Westheimer and Hauske (1975) demonstrated that these spatial interactions are not strictly retinal in origin because they occurred when flanks and vernier stimuli were presented separately to the two eyes.

The effects of spatial configuration upon various aspects of motion perception are well known (cf.



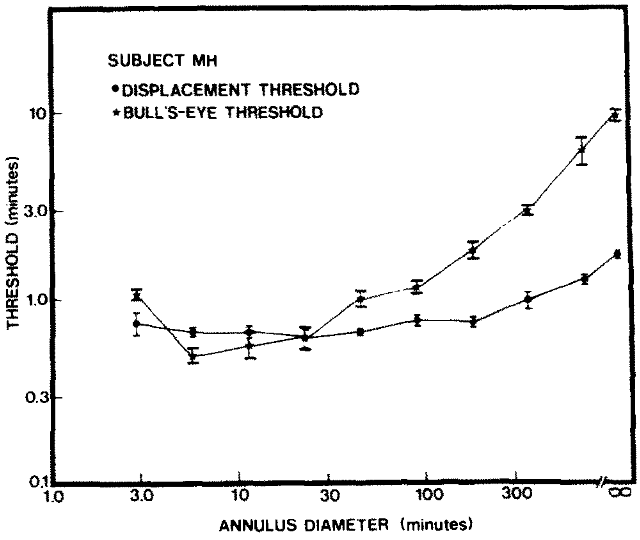


Fig. 3. Displacement threshold and bull's-eye threshold as a function of annulus diameter. (a) observer SH. (b) observer MH. All symbols are means of 4 threshold estimates, each derived from a forced-choice staircase. Error bars represent ± 1 SE. Straight line segments connect data within a set. Angular diameters of annuli ranged from 2.85′–728′. The absence of an annulus is represented by an abscissa value of ∞. Displacement thresholds (●): displacement thresholds for a small, luminous spot with starting position at the center of the annulus were measured. Bull's-eye threshold (*): observers were required to indicate whether a small, luminous spot, appearing for one sec along the horizontal diameter of the annulus, was positioned to the left or right of center.

Kaufman, 1974; Chap. 10). Aubert (1886) discovered that the velocity threshold increased by a factor of 10 when reference patterns were removed from the visual field. Duncker (1929) showed that motion of a rectangular surround can "induce" apparent motion of a stationary interior spot, the basis of the "waterfall illusion."

In a patternless field, the eyes cannot maintain steady fixation, but "wander" away from the original line of sight (cf. Matin, 1972). However, for targets ranging in diameter from 1.9′ to 240′, steady fixation accuracy is good and depends only very weakly on target diameter (Steinman, 1965; Rattle, 1969). This nonspecific dependence of fixation accuracy on target diameter is analogous to the dependence of displacement threshold on annulus diameter. It suggests the possibility that the presence of the annulus reduces "noise" in the displacement task by contributing to improved fixation accuracy.

The results of Experiment 2 demonstrate that the presence of pattern in the visual field influences the displacement threshold. In this respect, displacement detection is similar to other hyperacuities. The question arises, can the "hypersensitivity" of displacement detection in the presence of annuli be explained by a property of the position sense? When displacement thresholds were measured in the presence of annuli, observers were required to detect the displacement of a spot away from the center of an annulus. Perhaps their decisions were not based upon the detection of motion per se, but upon detection of the decentering of the spot within the annulus. Experiment 3 was conducted to measure observers' abilities to detect the decentering of spots within annuli, and to compare this capacity with the ability to detect displacements.

Experiment 3: bull's-eye detection as a function of annulus diameter

The purpose of Experiment 3 was to determine whether the effects of annular surrounds on displacement detection can be explained by the capacity to localize the center of a uniform circular field. The acuity associated with this capacity will be termed "bull's-eye acuity."

In a forced-choice trial, the target spot appeared once for one sec at some position along the horizontal diameter of a uniform circular region circumscribed by an annulus of specified diameter. The observer was required to indicate whether the spot appeared to the left or to the right of center. A staircase procedure (see Method) was used to find the center-to-spot offset that yielded 79% correct decisions in this task. The set of annuli used in Experiment 2 was used again in Experiment 3. Each block of trials was preceded by the presentation of the spot at the center of the annulus for about 10 sec.

In Fig. 3 (a) and (b), bull's-eye thresholds (*) for observers SH and MH are plotted as a function of annulus diameter. The right most points, with abscissa values of infinity, were obtained in unstructured fields (annulus diameter = infinity). Each symbol is the mean of 4 threshold estimates, each derived from a block of forced-choice trials. Symbols have been joined by straight line segments. The bull's-eye thresholds and the displacement thresholds in Fig. 3 can be compared because both sets of data were collected under comparable stimulus conditions with the same observers.

The bull's-eye thresholds show a strong dependence upon annulus diameter, reminiscent of other hyperacuities. As the diameter increases from 2.85′, there is an initial brief drop in threshold, followed by a steady increase. For annulus diameters in the range 23′–730′, the slopes of the best fitting straight lines (least squares criterion) through the data in the log–log coordinates have values of 0.58 and 0.63 for SH and MH respectively. Accordingly, for a range of annulus diameters, the bull's-eye thresholds rise as power functions of annulus diameter with exponents near 0.6. Bull's-eye acuity does not conform to Weber's law, but instead, its relative sensitivity increases with increasing annulus diameter. If the bull's-eye thresholds are plotted as a function of the area within the annulus, the deviation from Weber's law is even greater, since the area exponent will be about 0.3. Volkmann (1863) (cited in Le Grand, 1967; Chap. 7) had observers adjust one of three vertical threads to lie midway between the other two. His results conformed with Weber's law, except for very small separations of the fixed threads. Volkmann found a constant fraction of about 1%. Data of the current bull's-eye experiment indicate that a Weber fraction of about 1% is achieved for an annulus diameter of about 300′ (5°).

The United States Army Official 50 ft Small Bore Rifle Target consists of a basic set of seven concentric rings with the largest subtending a visual angle of about 8′ and the smallest about 0.8′. In Fig. 3, bull's-eye thresholds for the two observers (neither known for their expert marksmanship) for annuli of 11′ were of the order 0.5′. Hence, although expert marksmen may not be able to resolve the innermost ring of the target, they will be able to visually localize the center of the target with requisite accuracy.

The features of the bull's-eye threshold curves in Fig. 3 differ from those of the displacement threshold curves. The rising portion of the bull's-eye curve begins much earlier and is much steeper than the rising portion of the displacement threshold curve. For both observers, the two curves diverge for annulus diameters larger than about 20′. For annulus diameters less than 20′, the curves crisscross, but appear to follow different courses. For annuli exceeding 20′, it seems certain that the mechanism underlying displacement detection is different from the mechanism underlying bull's-eye detection.

Concluding remarks

According to Table 1, observers with keen displacement sensitivity can detect sudden movements of a spot across angular distances of 0.3′ (18″). However, this capacity requires the presence in the visual field of pattern (e.g. , annular surrounds) because the displacement thresholds are elevated substantially in structureless fields. Reduction in displacement thresholds in the presence of annular surrounds cannot be ascribed to spatial localization sensitivity because Experiments 2 and 3 (Fig. 3) indicate that displacement thresholds are substantially lower than bull's-eye thresholds for annulus diameters exceeding about 20′. Displacement thresholds exhibit a weak dependence on photopic target luminance, and are virtually independent of orientation and pupil size down to 3 mm.

The keenness of displacement sensitivity under some conditions suggests that it should be classed among the hyperacuities. As such, an explanation of its underlying mechanisms is likely to go beyond issues of spatial resolution. It is probable that displacement sensitivity is a property of a visual motion detection system. In this connection, it is pertinent to note that observers reported that their decisions in the displacement detection task were based upon sensations of spot movement, not upon inferences based upon sensations of spot position.

An hypothesis, meriting further investigation, is that the displacement threshold is influenced by the accuracy of fixational eye movements. These eye movements may constitute "noise" in the displacement detection task. Factors that decrease fixation accuracy might therefore increase displacement thresholds.

Acknowledgements—These experiments were conducted while GEL was a visitor in FWC's laboratory, supported by a Postdoctoral Research Fellowship from the Medical Research Council of Canada. GEL is grateful to FWC for his hospitality and for the opportunity to collaborate in this research. We thank our observers for their care and attention.

REFERENCES

Andrews D. P., Webb J. M. and Miller D. T. (1974) Acuity for length comparison in continuous and broken lines. *Vision Res.* **14,** 757–766.

Anstis S. M. (1978) Apparent Movement. In *Handbook of Sensory Physiology. VIII: Perception* (Edited by Held R., Leibowitz H. W. and Teuber H.-L.), pp. 655–673. Springer-Verlag, Berlin.

Appelle S. (1972) Perception and discrimination as a function of stimulus orientation: the "oblique effect" in man and animals. *Psychol. Bull.* **78,** 266–278.

Aubert H. (1886) Die bewegungsempfindung. *Pflugers Arch. ges. Physiol.* **39,** 347–370.

Baker K. E. (1949) Some variables influencing vernier acuity. *J. opt. Soc. Am.* **39,** 567–576.

Basler A. (1906) Über das sehen von bewegungen. I. Die wehrnehnung kleinster bewegungen. *Pflugers Arch. ges. Physiol.* **115,** 582–601.

Biederman-Thorson M., Thorson J. and Lange G. D. (1971) Apparent movement due to closely spaced sequentially flashed dots in the human peripheral field of vision. *Vision Res.* **11,** 889–903.

Boring E. G. (1942) *Sensation and Perception in the History of Experimental Psychology.* Irvington, New York.

Campbell F. W. and Gubisch R. W. (1966) Optical quality of the human eye. *J. Physiol., Lond.* **186,** 558–578.

Campbell F. W. and Maffei L. (1970) Electrophysiological evidence for the existence of orientation and size detectors in the human visual system. *J. Physiol., Lond.* **207,** 635–652.

Campbell F. W. and Maffei L. (1979) Stopped visual motion. *Nature* **278,** 192.

Duncker K. (1929) Über induzierte bewegung. *Psychol. Forsch.* **12,** 180–259.

Gordon D. A. (1947) The relation between the thresholds of form, motion and displacement in parafoveal and peripheral vision at a scotopic level of illumination. *Am. J. Psychol.* **60,** 202–225.

Graham C. H. (1968) Depth and movement. *Am. Psychol.* **23,** 18–26.

Johnson C. A. and Leibowitz H. W. (1976) Velocity-time reciprocity in the perception of motion: foveal and peripheral determinations. *Vision Res.* **16,** 177–180.

Kaufman L. (1974) *Sight and Mind.* Oxford University Press, London.

LeGrand Y. (1967) *Form and Space Vision.* Indiana University Press, Bloomington.

Leibowitz H. W. (1955) The relation between the rate threshold for the perception of movement and luminance for various durations of exposure. *J. exp. Psychol.* **49,** 209–214.

Leibowitz H. W., Johnson C. A. and Isabelle E. (1972) Peripheral motion detection and refractive error. *Science, N.Y.* **177,** 1207–1208.

Leibowitz H. W., Myers N. and Grant D. (1955) Radial localization of a single stimulus as a function of luminance and duration of exposure. *J. opt. Soc. Am.* **45,** 76–78.

Ludvigh E. (1953) Direction sense of the eye. *Am. J. Ophthal.* **36,** 139–142.

Mansfield R. J. W. (1974) Neural basis of orientation perception in primate vision. *Science, N.Y.* **186,** 1133–1135.

Mansfield R. J. W. and Ronner S. F. (1978) Orientation anisotropy in monkey visual cortex. *Brain Res.* **149,** 229–234.

Matin L. (1972) Eye movements and perceived visual motion. In *Handbook of Sensory Physiology VII/4: Visual Psychophysics* (Edited by Hurvich L. and Jameson D.), pp. 332–373. Springer-Verlag, Berlin.

McKee S. P. and Westheimer G. (1978) Improvement in vernier acuity with practice. *Percept. Psychophys.* **24,** 258–262.

Millodot M., Johnson C. A., Lamont A. and Leibowitz H. W. (1975) Effect of dioptrics on peripheral visual acuity. *Vision Res.* **15,** 1357–1362.

Pantle A. and Sekuler R. (1968) Velocity-sensitive elements in human vision: Initial psychophysical evidence. *Vision Res.* **8,** 445–450.

Rattle J. D. (1969) Effect of target size on monocular fixation. *Opt. Acta.* **16,** 183–192.

Regan D. and Beverly K. I. (1978) Illusory motion in depth: aftereffect of adaptation to changing size. *Vision Res.* **18,** 209–212.

Richards W. (1971) Motion detection in man and other animals. *Brain Behav. Evol.* **4,** 162–181.

Scobey R. P. and Horowitz J. M. (1976) Detection of image displacement by phasic cells in peripheral visual fields of the monkey. *Vision Res.* **16,** 15–24.

Sekuler R. (1975) Visual motion perception. In *Handbook of Perception. V: Seeing* (Edited by Carterette E. C. and Friedman M. P.). Academic Press, New York, 389–430.

Sekuler R. and Ganz L. (1963) Aftereffect of seen motion with a stabilized retinal image. *Science* **139,** 419–420.

Sekuler R., Pantle A., Levinson E. (1978) Physiological basis of motion perception. In *Handbook of Sensory Physiology. VIII: Perception* (Edited by Held R., Leibowitz H. W. and Teuber H.-L.), pp. 67–96. Springer-Verlag, Berlin.

Steinman R. M. (1965) Effect of target size, luminance and color on monocular fixation. *J. opt. Soc. Am.* **55,** 1158–1165.

Stratton G. M. (1902) Visible motion and the space threshold. *Psychol Rev.* **9,** 433–443.

Tyler C. W. and Torres J. (1972) Frequency response characteristics for sinusoidal movement in the fovea and periphery. *Percept. Psychophys.* **12,** 232–236.

Volkmann A. W. (1863) *Physiologische Untersuchungen im Gebiete der Optik.* Breitkopf und Härtel, Leipzig.

Westheimer G. (1975) Visual acuity and hyperacuity. *Invest. Ophthal. visual Sci.* **14,** 570–572.

Westheimer G. (1976) Diffraction theory and visual hyperacuity. *Am. J. Optom. Physiol. Opt.* **53,** 362–364.

Westheimer G. (1978) Spatial phase sensitivity for sinusoidal grating targets. *Vision Res.* **18,** 1073–1074.

Westheimer G. and Hauske G. (1975) Temporal and spatial interference with vernier acuity. *Vision Res.* **15,** 1137–1141.

Westheimer G. and McKee S. P. (1977a) Integration regions for visual hyperacuity. *Vision Res.* **17,** 89–93.

Westheimer G. and McKee S. P. (1977b) Spatial configurations for visual hyperacuity. *Vision Res.* **17,** 941–947.

Wetherill G. B. and Levitt H. (1965) Sequential estimation of points on a psychometric function. *Br. J. Math. Stat. Psychol.* **18,** 1–10.

Wilcox W. W. (1932) The basis of the dependence of visual acuity on illumination. *Proc. natn. Acad. Sci.* **18,** 47–56.