DIFFERENTIAL MOTION HYPERACUITY UNDER CONDITIONS OF COMMON IMAGE MOTION*

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Abstract—Sensitivity to horizontal shearing motion in random dots was measured as a function of common image motion amplitude. Without common image motion, thresholds for differential motion are comparable or better than vernier acuity. Above about 2 arc min of common image motion there is a proportionate increase in motion parallax thresholds such that for 20 arc min of common image motion, differential motion thresholds have risen by an order of magnitude. This differs from a comparable lack of threshold elevation for vernier acuity targets under similar conditions of movement (Westheimer and McKee, 1975). By varying movement duration, it can be shown that common image motion amplitude rather than common image velocity is the primary determinant of the effect. Furthermore this degradation of performance is not affected by changes in random dot size. Under favorable circumstances the phenomenon can also be seen with differentially moving vernier lines. The effect shows directional selectivity such that common motion directions closest to the horizontal leads to the greatest interference. The results add weight to the view that differential motion hyperacuity is mediated by a separate mechanism than differential position hyperacuity.

INTRODUCTION

In 1975, Westheimer and McKee reported that retinal image motion had a surprisingly small effect in degrading the discrimination of visual acuity and hyperacuity targets. Landolt C resolution as well as vernier acuity remained essentially unimpaired for image velocities up to 3°/sec. Special mention was made with regard to vernier targets, "...the task can be accomplished to a precision of the order of a fifth of a receptor diameter while the configuration is moving across the retina at rates up to 300 receptors per sec." Such results show that the visual system is remarkably sensitive to very small differences in relative retinal position regardless of large changes in absolute retinal position.

Vernier acuity, however, is only one type of hyperacuity among many, including stereoacuity. Another distinct type of hyperacuity involves the detection of relative motion rather than relative position (Nakayama and Tyler, 1981). Because of the simultaneous and very sensitive ability to detect very small differences in relative position, however, the isolation of motion hyperacuity has been extremely difficult. Graham *et al.* (1948), for example, measured the threshold for differentially moving vernier lines but they could not determine whether the actual detection of the moving stimulus was based on relative motion *or* whether the detection was inferential, based on the

comparison of a series of successive vernier acuity judgements.

Recently Nakayama and Tyler (1981) have demonstrated a technique to remove this ambiguity between relative position and relative motion hyperacuity. Two types of visual pattern were subjected to a differential horizontal shearing motion, equivalent to a transverse standing wave. When stationary, the two patterns consisted either of a straight vertical line or a dense field of random dots (Julesz, 1971). Despite the fact that the actual parameters of motion were the same in both cases (in terms of the spatial and temporal frequency of the movement), a large and an important difference emerged.

The detection of horizontal shearing motion in the straight vertical line was essentially independent of movement temporal frequency. This occurred because the observer could see the change in shape of the line as various sections of it moved differentially. For the random dot pattern, however, the threshold amplitude required for detection rose dramatically as temporal frequency was reduced. In other words for very low temporal frequencies, corresponding to the lowest velocities of motion, the observer was unable to detect the presence of very large differential displacements (over 10 times the vernier acuity threshold). This remarkable lack of positional sensitivity when using the random dot stimulus confirms earlier statistical arguments which have deduced that the brain must be severely limited in its information processing capacity (Attneave, 1954; Barlow, 1961). When overloaded as in the case of a random dot pattern, it is forced to disregard details, such as the
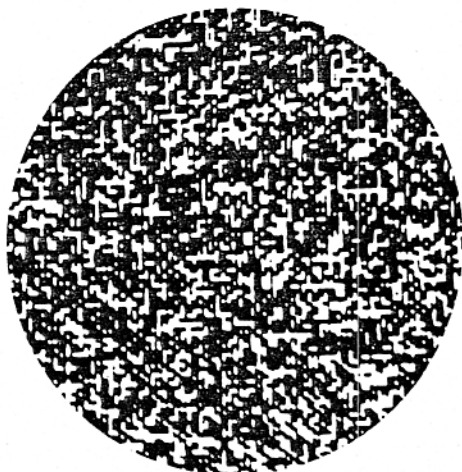
Fig. 1. Random dot array as it appears in its static form. When moved differentially (see text), its pattern of motion can be described in terms of the sum of two velocity vector fields (see Fig. 2).

exact positional relation of the individual random dots, coding only the general features, movement, texture, etc.

Equipped with a stimulus which can isolate movement from position sensitivity, Nakayama and Tyler made several additional observations. First were the threshold values. They required only a minimum of 5 arc sec of differential displacement if the velocity threshold was also reached (approx. 25 arcsec/sec). Most remarkable was the very large spatial range over which this tiny differential displacement was detectable. Performance was optimal when the spatial separation of the area between maximum moving points were over 2.5 deg apart. The above result sug-

gested a very large difference between motion and positional hyperacuity, indicating that motion hyperacuity is not based on measured forms of positional sensitivity. As such it is of particular interest to see whether it is also very different in its ability to withstand the presence of small amounts of retinal image motion.

METHODS

Stimulus

The primary stimulus in its static form was a 3 deg circular field of random picture elements (pixels), such that each pixel subtended 2.0 arc min at the normal viewing distance of 160 cm.

To obtain this pattern, a repeating two-level pseudo-random video signal was generated using a 14 bit shift register clocked at a very fast rate (6 MHz). Synchronization of this video signal and a 400 Hz raster produced a static field of random dots appearing on the CRT screen as seen in Fig. 1. Further details of the stimulus generating apparatus are described elsewhere (Nakayama and Tyler, 1981).

Movement of the random dots consisted of two separate vector components. First, there was a differential component in which the top and bottom half of the screen moved with equal amplitude but in opposite horizontal directions. Second, there was a common component which could be moved in any direction and over a wide range of velocities. These two components add vectorially producing a composite motion. Figure 2 shows two examples of component fields adding to produce composite velocity fields. The observers psychophysical task was to detect the differential component from the composite velocity field.
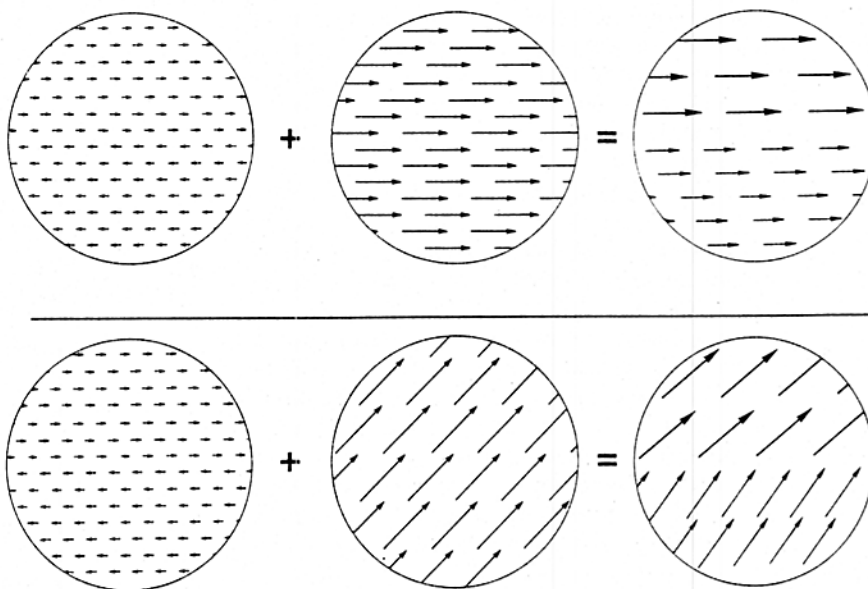

Fig. 2. Differential and common motion components as they add to form a composite motion field. Upper panel shows addition of horizontal differential motion to a horizontal common motion. Lower panel shows addition of horizontal differential to an oblique common image motion. The observer's task is to identify the direction of the differential motion.
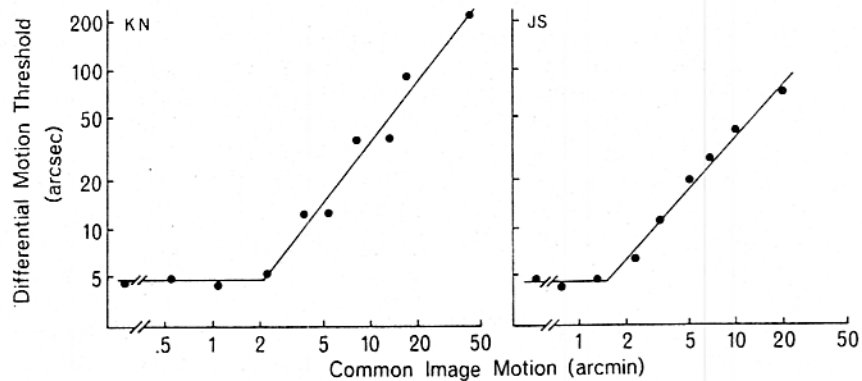
Fig. 3. Effect of common image motion amplitude on displacement thresholds for differential motion in a random dot pattern (two observers). Differential motion consists of a split screen as seen in Fig. 2 and common motion is horizontal (as seen in the upper panel of Fig. 2). Duration of motion is 100 msec. Pixel size is 2 arc min.

To generate the differential motion stimulus, a computer-generated voltage ramp was fed into the AM input of an AM/FM function generator set in the square wave mode. Unless noted, this function generator was set at a carrier frequency close to the screen refresh rate, so that when synchronized to the CRT raster and fed into the CRT x axis, the screen moved differentially with the upper half moving in the opposite horizontal direction with respect to the lower. To generate the common image motion in any direction, additional digital ramps with amplitudes proportional to $A\cos\theta$ and $A\sin\theta$ were fed into the x and y axis respectively (θ denotes the angle of the common motion with respect to a horizontal direction, and A represents the total displacement). The digital "movement" ramps were produced by a machine language subroutine such that the time between each individual ramp step was kept small, as low as 600 μsec and never exceeding 5 msec. This timing, coupled with the high refresh rate of the raster (400 Hz), ensured that there was never any perceived discontinuity of motion. The motion was always seen as smooth, with no hint of any stroboscopic appearance.

In addition to this "split-screen" random dot-stimulus, two other configurations of movement were employed. First, we used the same random pattern but with nine equally spaced horizontal panels of differentially moving areas, such that each panel moved as a rigid unit in a direction opposite to its neighboring panels (see inset of Fig. 7). Second, we utilized a vernier type line undergoing a differential motion (see inset in upper right of Fig. 8).

Procedure

To eliminate the contaminating effects of eye movements, the differential and the common motion were confined to a time period less than the reaction time for a pursuit eye movement. Thus, all movements in this study (with one exception) were 100 msec or less, well below the latency generally attributed to pursuit. To prevent a systematic improvement in performance as a result of anticipatory

pursuit eye movements (Kowler and Steinman, 1979), the direction of the common motion was randomized from trial to trial. For example, common motion at 30° counter-clockwise to the horizontal was randomly alternated between an 8 o'clock and a 2 o'clock direction.

Staircase forced choice psychophysical techniques were used for all experiments. Depending on the particular task, either a two interval or a one interval paradigm was adopted. For the two interval case, the observer had to designate in which interval the differential movement occurred, whereas for the one interval case, the observer had to specify the direction of the differential movement.

In each case (whether it be a one or two interval paradigm) an interval began by the appearance of the random dot stimulus replacing the blank featureless screen. After 0.5 sec, the constant velocity movement began and this was accompanied with a tone. Two hundred and fifty milliseconds later, after the movement had stopped, the dot display was removed and again replaced by the featureless screen. Mean luminance of the display was 70 cd/m^2, contrast held at 55%. The room was moderately illuminated and between trials the oscilloscope face had a luminance of 20 cd/m^2.

Before conducting the staircase procedure, the observer adjusted a control to generate a differential movement amplitude slightly above the perceived threshold. This value determined the starting point of the staircase sequence. Following the observer's response, a buzzer signaled whether the response was incorrect. If the observer made 3 consecutive correct responses, the differential movement amplitude was decremented by an eighth log unit step. Only one error, however, incremented the amplitude by the same step size.

Thresholds obtained approximate a 79.4% correct level. To remove the variable effects of observer "warm up", the computer was instructed to begin the data collection only after the second reversal in the staircase. After this point, the experiment continued

until there were a total of nine staircase reversals. The stimulus values after the second reversal were averaged to provide an estimate of the observers psychophysical threshold. An average of approx. 40 presentations (or pairs of presentations for the two interval forced choice paradigm) were necessary to reach this nine reversal criterion. Each plotted point in this paper is the average of at least 4 such staircase sequences.

RESULTS

The primary experiment examined the influence of common motion amplitude on differential motion thresholds. The movement pattern is schematized by the upper panel of Fig. 2 showing that the differential and the common motion are confined to the horizontal direction. A one-interval forced choice procedure was used. The observer had to specify whether the top portion of the split screen moved to the right or left relative to the bottom portion.

At the outset, it should be noted that under some circumstances motion parallax sensitivity can be excellent (Fig. 3). For the smallest values of common image motion, only 5 arc sec of differential displacement is required, a result which is as good or better than that reported for vernier acuity.

The principal finding of this study is that for both observers (Fig. 3) there is an orderly increase in the differential movement threshold as the common image velocity is increased beyond a critical "break-point" and this is very different from the results obtained when measuring vernier acuity in the presence of retinal image motion.

Note the differential movement threshold for a common image motion of 20 arc min (over a 100 msec interval). This corresponds to a velocity of 200 arc min/sec or 3.3°/sec. Using comparable velocity and duration, Westheimer and McKee (1975) found essentially no impairment in vernier acuity (a finding also confirmed below, see later, also see Fig. 8). For differ-

ential motion sensitivity, however, there is an unmistakeable increase in the differential motion threshold, approximating 75 arc sec, a 15 fold increase over the case where there is no common motion.

Besides this principal finding, several other aspects of the data should be noted. First, is the lack of any impairment for common image motion below 15–20 arc min/sec or a total displacement of 1.5–2 arc min. Second, is that beyond this 2 arc min break point, the rise in thresholds are seen to approximate Weber's law, having a slope of $+1$ when plotted in the log–log form. Weber fractions for the two observers are approximately 5%, a figure comparable to the differential velocity sensitivity obtained by McKee (1981) when comparing successive episodes of motion.

The fact that the break point in Fig. 3 in terms of total displacement (2 arc min) is very close to the picture element size raises the issue as to whether pixel size determines this break point. To answer this question the pixel size was increased to 5.6 arc min, accomplished by reducing the viewing distance to 57 cm and appropriately masking the CRT display to preserve a field size of 3°. Figure 4 shows that the relation between motion parallax threshold and common image motion amplitude remains essentially unchanged. The break point where the threshold begins to rise does not shift up to 5.6 arc min but remains in the same position at 2 arc min. Increasing the pixel size does not displace the position of this break point. This indicates that differential motion sensitivity suffers degradation above a displacement of approx. 2 arc min. It rules out any simple explanation based on picture element size.

Displacement vs velocity

The experiments described so far have all used the same duration of 100 msec. Thus an increasing com-
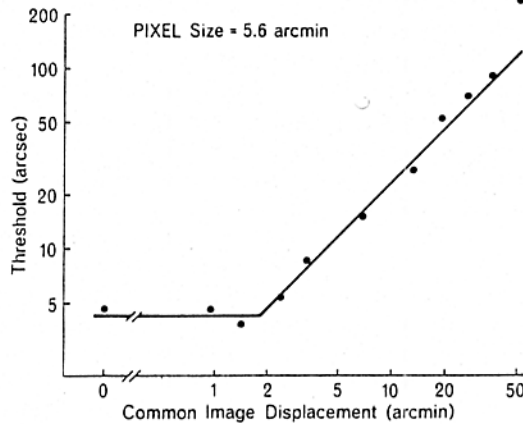

Fig. 4. Same experiment as in Fig. 3 except with a larger pixel size, equal to 5.6 arc min. Observer is K.N. Note that the break point in the function remains essentially the same as for a smaller pixel size (compare to K.N.'s results in Fig. 3).
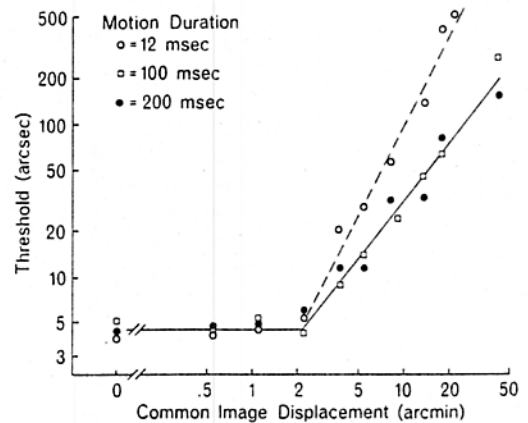

Fig. 5. Rise in differential movement threshold plotted as a function of common image displacement amplitude for three different durations of motion. Open circles represent a 12 msec duration, open squares represent a 100 msec duration and filled circles represents a 200 msec duration movements. Note that the break points of the curves superimpose most satisfactorily when plotted in these terms rather than in terms of common image velocity (as seen in Fig. 6).
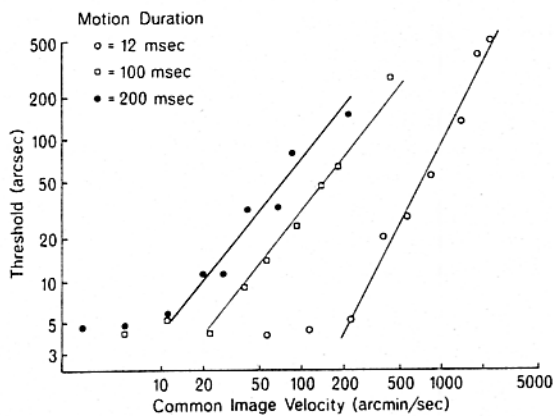
Fig. 6. Same as in Fig. 5 except the thresholds are plotted in terms of common image *velocity* rather than common image *displacement*.

mon motion amplitude has always been confounded by an increase in common image velocity. What happens if this relation between velocity and displacement is altered? Is the impairment determined mainly by the velocity of the common motion or is it determined by the displacement? To answer this question, the same type of experiment was repeated but with two additional movement durations, 12 msec and 200 msec.

The results indicate that common image displacement rather than common image velocity is the dominant factor, especially in determining the break point of the basic function. Figure 5 shows differential thresholds plotted against image *displacement* for three durations (12, 100 and 200 msec). In each case, the point where the threshold rise begins, corresponds to the same 2 arc min displacement mentioned earlier. On the other hand plotting the same thresholds as a function of image *velocity* (see Fig. 6) shows no superimposition, especially in terms of the break point. Image displacement rather than image velocity is the important factor.

A secondary aspect to be noted is the much steeper slope seen for the 12 msec duration of movement. The differential threshold rises much more rapidly than predicted by Weber's law, although it appears to be a straight line on the log–log coordinate representation (open circles in Figs 5 and 6). The disproportionately large amount of differential velocity required to overcome common image motion for this short duration of movement indicates that a minimal time is required for the the coding of sequence direction. This particular phenomenon will be the subject of a subsequent paper.

Influence of common motion direction

Psychophysical and electrophysiological evidence indicates that there is directional selectivity in motion sensitive mechanisms. Psychophysical masking experiments indicate that the directional channels have a full angular tuning width of around 60° (Ball and

Sekuler, 1979). Electrophysiological studies show various degrees of directional selectivity ranging from a very broad angular tuning (Barlow and Hill, 1963) to more narrow angular tuning (Frost *et al.*, 1978).

In order to examine the correlates of these hypothetical channels in the present study, differential horizontal motion thresholds were measured in the presence of different directions of common image motion. If the detection of the horizontal shearing motion were based on velocity mechanisms sensitive to direction of motion, one might expect that as the angle of the motion became greater with respect to the horizontal, the interfering effects of the common motion should diminish.

By introducing a vertical component in addition to the horizontal component when presenting common motion in different directions the border location between the upper and lower panel could become uncertain. To make sure that this uncertainty alone could not contribute to any result obtained by variation of common image motion direction, the differential movement configuration was altered. Instead of a single split screen of differential motion, the horizontal shear consisted of multiple panels of motion each subtending a vertical angle of 20 arc sec (see inset of Fig. 7) with each panel moving in the opposite direction with respect to its adjacent neighbor. The introduction of these differentially moving panels provided the observer with no incentive to fixate a particular set of dots on the screen.

In this experiment the two alternative forced choice paradigm was used because the observer was unable to distinguish one direction of differential motion from the opposing direction. Figure 7 shows the
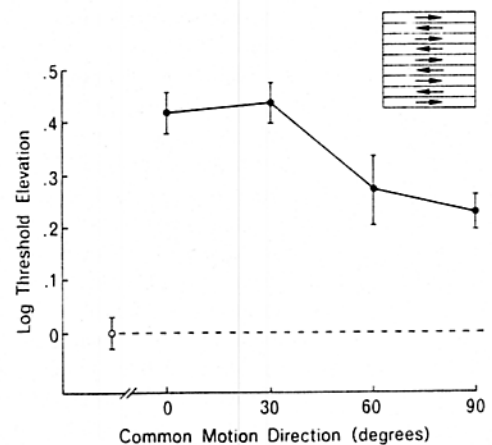

Fig. 7. Effect of angular orientation of the common motion on the elevation of displacement thresholds for differential horizontal motion. Threshold displacement for detecting differential motion in the absence of any common image motion is depicted as the open circle and dashed horizontal line and is 17 arc sec. The differential motion stimulus is a series of horizontal panels each subtending 20′ in the vertical direction and moving in opposite directions (see Insert). Filled circles show threshold elevation for differing angles of common image motion with respect to the horizontal. Each point represents the data obtained from 240 of stimulus presentations.

thresholds obtained without any common motion (open circle) and for 4 different directions of common image motion (filled circles).

First it should be noted that the threshold without any common motion is considerably higher than that obtained in the earlier experiments. It is 17 arc sec as opposed to around 5 arc sec (see Figs 3–6), confirming the fact that differential motion sensitivity is poorer at higher movement spatial frequencies (Nakayama and Tyler, 1981).*

Of primary interest is the fact that the interfering effects of common image motion show a noticeable degree of directional selectivity. Motion confined to within 30° of the horizontal raises thresholds considerably more than motion which has a direction which is further away from the horizontal, although there is a clear interference even for common motion which is orthogonal.

This finding suggests that we are dealing with a process which has directional selectivity and it reduces support for the view that the interference attributed to common image motion is a non-specific masking effect, perhaps of the type that has been suggested to account for saccadic suppression (MacKay, 1970).

Vernier-type line stimuli

The random dot experiments demonstrate a large susceptibility of differential motion sensitivity to the degrading effect of common image motion if the common image motion exceeds a displacement of approximately 2 arc min. To show that the phenomena is not a quirk confined to moving random dots, but applies to other moving stimuli as well, an additional experiment was conducted using differentially moving lines.

The target consisted of a pair of lines in a vernier type configuration. It differed from the classical vernier stimulus, however, by a very large horizontal average offset, over 15 arc min (900 arc sec) and an even larger vertical separation (20 arc min).

This large separation between the two vernier lines was adopted to minimize the observers ability to perform the task on the basis of differential *position* rather than differential *motion*. Westheimer (1979), for example, has shown that observers are surprisingly accomplished at judging and memorizing the distances between lines, showing an accuracy comparable to vernier acuity if the lines are separated by distances as great as 5 arc min. Only when distances between line stimuli are sufficiently great does motion sensitivity dominate over position sensitivity in the determination of psychophysical thresholds. With this modified vernier configuration, the observer had difficulty in noticing whether the offset is larger or smaller

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* It should be emphasized that spatial frequency refers to the spatial frequency of the differential movement rather than the more usual meaning which refers to the spatial frequency of the luminance distribution.
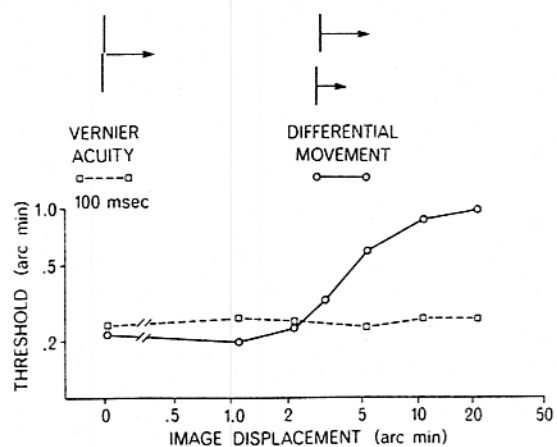

Fig. 8. Influence of common image motion on differential movement and differential position (vernier acuity) sensitivity. Open circles show the effect of common motion on differential movement thresholds using vernier lines. Line width is 2.0 arc min. Inset labeled *differential movement* shows an example of such lines moving at different velocities. Open dots represent vernier acuity thresholds (see inset upper left) as they were obtained for the same range of velocities. Duration in each case is 100 msec.

at the beginning and end of the movement. Thus, at least over some range (see below), motion sensitive rather than position sensitive mechanisms were required (Nakayama and Tyler, 1981).

In its procedure, the experiment was identical to the ones using random dots. The offset pair of lines were presented to the observer. They underwent the composite motion consisting of the common and differential horizontal components, and the observer was required to identify the direction of the differential motion.

The function depicted by the open circles and solid line in Fig. 8 shows the relation between differential movement threshold and image velocity for this vernier type stimulus. Note that beyond an image displacement of approx. 2 arc min, the threshold also begins to rise, as it did with the motion task using the random dots.

Because the elevation of threshold for the intermediate displacements are the same for the vernier line stimulus and the random dot stimulus, it is reasonable to conclude that the interfering effects of image motion are due to the common motion of the target rather than to some non-specific masking effect emphasized particularly by the displacement of a whole field of random dots. Thus, the elevation of differential motion thresholds by common image motion indicates that the primary finding of this paper is not a peculiarity confined to moving random dot stimuli.

It should be obvious, however, that as common image motion is further increased, beyond 10 arc min using the line stimulus, it shows a correspondingly smaller rise in differential movement thresholds and deviates from Weber's law (Fig. 8). This differs signifi-

cantly from the results obtained using the random dots, where the threshold rises proportionately over a much greater range. The falloff in the threshold rise is best understood by considering the contaminating effects of positional information (Nakayama and Tyler, 1981). At threshold, detection is made solely on the basis of velocity sensitive mechanisms because at the offset distance of the vernier lines, differential position thresholds are higher than differential motion thresholds. As the common image velocity increases above a certain value (approx. 2 arc min) the motion threshold rises in proportion to Weber's law. Beyond a certain point. however, it rises so high that it is finally higher than the threshold to detect differences in differential position. Under these conditions differential position, not differential motion, determines the threshold.

The interpretation is obvious to the psychophysical observer. Above a certain amount of differential movement, he notices that the horizontal distance between the lines has changed before and after the movement, and he can often use this positional information when making the forced choice judgment.

To make a direct comparison of the present results with those reported for vernier acuity, we also confirmed the key finding of the Westheimer and McKee (1975) study. In this instance, the observer's task was a simple vernier acuity task, again using the one-interval forced choice procedure. The observer had to designate the top portion of the vernier target in relation to the bottom portion using a staircase procedure where target velocity was varied. The vernier stimulus appeared coincident with the beginning of the motion and disappeared at the termination of motion and the direction of the image motion was randomized from trial to trial. Thus the vernier target was always moving when visible and was visible only for 100 msec. A peripheral square of fixation LEDs (sides equaling 2 deg) provided a figure within which the subject could centrally fixate.

The function represented by the open squares and the dashed lines in Fig. 3 shows that there is essentially no effect of retinal image motion on this vernier acuity task. Vernier acuity remains at its optimal value above 3°/sec (displacement of 20 arc min).

Thus the two experiments using vernier line stimuli show very different effects. Differential motion hyperacuity is severely degraded by retinal image motion, whereas vernier acuity is not.

DISCUSSION

Superficially, human sensitivity to motion parallax appears comparable to vernier acuity; both can detect shifts on the order of 5 arc sec. Despite this apparent similarity in absolute sensitivity, however, there are three important differences. First, is the fact that although vernier acuity and differential motion hyperacuity require a minimum positional offset, differential motion sensitivity also requires a minimum vel-

ocity (Nakayama and Tyler, 1981). Second, is the different spatial range over which the detection of differential motion is most sensitive. In contrast to position sensitivity (as exemplified by vernier acuity), differential motion sensitivity is optimal when the separately moving areas are large. This indicates that the hypothetical receptive fields mediating the threshold perception of motion are also very large, exceeding 2°, even in the foveal region. The present study reveals a third difference between the two forms of sensitivity, namely the lack of tolerance of differential motion sensitivity to common image motion. These three differences indicate that motion and position sensitivity are subserved by very different neuronal subsystems, with different spatial properties, and different computational logic.

The exact nature of the relation between parallax detection and common image motion deserves additional comment. Of interest is the existence of a tolerance zone. Image motion of less than 2 arc min appears to have essentially no effect on differential motion thresholds and this holds whether the target is a set of random dots, or a line, or whether the pixel elements are differing in size. In all cases the tolerance zone is the same.

The fact that this tolerence zone is descriptive only in terms of image displacement and not in terms of image velocity may be significant. It suggests that although we are dealing with a system specialized for the detection of motion, thus having space-time properties, its *spatial* properties may be particularly revealed by these psychophysical findings. A similar view also seems to emerge with regard to an upper spatial limit of motion processing, where investigators have found that there is a short range movement processing limit which fails above 15 arc min, and this limit holds under a wide variety of temporal conditions (Banks and Kane, 1976; Braddick, 1974).

Implications for space perception and oculomotor function

Motion parallax sensitivity has often been considered as a potential carrier of depth information (Helmholtz, 1962; Gibson, 1950) and it has been suggested that velocity sensitive neurons having center-surround organization could play a major role in the delineation of surface edges in three dimensional space (Nakayama and Loomis, 1974; Prazdny, 1980). Furthermore recent psychophysical evidence also supports a significant role for motion as a cue to depth (Rogers and Graham, 1979), effectively removing doubts raised by earlier studies.

The present experiments show a fundamental limitation of the visual system's capacity to extract differences in velocity between adjacent regions in the face of common image motion. Could this limitation prevent the registration of depth information obtained from motion parallax?

At the outset, it should be recognized that within a particular region of visual field, common image

motion due to observer translation, can be nulled by appropriate rotations of the eye (see mathematical appendix of Nakayama and Loomis, 1974). Thus the oculomotor system could play a major role in overcoming limitations of differential motion processing as observed in this paper. In fact, its potential role in the extraction of differential velocity information appears far greater than its role in stabilizing the eye to obtain good visual acuity. Large errors of eye stabilization have little consequence in degrading visual acuity (Westheimer and McKee, 1975) or stereoacuity (Westheimer and McKee, 1979), but would have large consequences in degrading the perception of differential velocity. As such, it is possible that the main selective pressure on the evolution of eye fixation and stabilization reflexes is not to ensure good visual acuity (Walls, 1961) but rather to ensure the optimal pickup of motion parallax information.

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