

PSYCHOPHYSICAL ISOLATION OF MOVEMENT SENSITIVITY BY REMOVAL OF FAMILIAR POSITION CUES*

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Abstract—To isolate differential motion sensitivity from the contaminating effects of position sensitivity, we used a field of random dots undergoing a differential shearing motion. Movement threshold amplitude vs temporal frequency showed a slope of -1 on double-logarithmic coordinates, confirming that the detection was based on motion rather than on positional information. A comparison of motion and position sensitivity showed both to be very high, each requiring a differential displacement of only 5 sec arc. In comparison to position sensitivity, motion sensitivity showed a 10-fold superiority at the lowest spatial frequencies tested and a poorer sensitivity at higher spatial frequencies.

We conclude that the random-dot stimulus can isolate motion- from position-sensitive mechanisms and that motion comprises a distinct form of sensitivity, not derivable from the measured forms of position sensitivity.

INTRODUCTION

A proven psychophysical strategy useful in the analysis of parallel visual mechanisms is to dissociate systems by appropriate and selective variation of stimulus conditions. To isolate the separate contribution of rods and cones, for example, appropriate selection of wavelength, adapting background and flicker rate is needed. Otherwise, attempts to measure one system can be contaminated by the responses of the other.

An even more serious form of contamination appears in human motion sensitivity. In particular, the problem is caused by the fact that movement of a visual target *always* involves a change of shape or position. Consider a familiar example—the barely perceptible movement of the minute hand of a clock. After looking at it for some time, we know that it has moved. But did we really see it move or did we infer that it moved because of its change in position?

This mixture of motion and position information has confounded previous attempts to measure the minimum motion threshold (Aubert, 1886; Graham *et al.*, 1948). Only in a few particular and relatively limited cases has it been possible to deduce that the psychophysical response is mediated by a motion rather than by a position system (Leibowitz, 1954; Tyler and Torres, 1972).

To provide a general method to overcome this contamination of position information and thereby to develop a widely applicable approach to the study of movement sensitivity, we have used a random-dot

pattern where adjacent sections move differentially. Our initial supposition was that because there are no familiar position cues in a random-dot pattern, the observer would be unable to detect changes in the local shapes of the display as it moves.

METHOD

Random-dot moving grating

In its static form, the stimulus consists of a $5^\circ \times 6^\circ$ rectangular field of random picture elements (pixels) on the face of a CRT (Hewlett-Packard 1332A). Each picture element (pixel) subtended 2.8 arc min and had a 50% probability of being light or dark. Mean luminance of the display was maintained at 10 cd/m² as measured by a Pritchard photometer and the contrast was set to 80%. A high contrast photograph of a portion of the display is shown in Fig. 1B.

The electronic circuitry required to generate this TV raster and noise is schematized in Fig. 1A. In brief, the highly dense field of random-dots was generated using a pseudorandom noise source based on 14 bit shift register circuitry, clocked at a very high rate (6 MHz). The repeating noise sequence was reset on each frame. As a consequence, the same pattern of visual noise was refreshed 400 times/sec. To generate a differential displacement in the horizontal direction, an amplitude modulated function generator (FG-2 in Fig. 1A), synchronized to the vertical sweep, was connected to the horizontal oscilloscope axis. This deformed the whole raster, such that the relative horizontal position of each row was a sinusoidal function of its vertical position. It should be clear that the spatial frequency of this deformation is determined by the carrier frequency of FG-2. To generate differential horizontal movement in the display, the AM gener-

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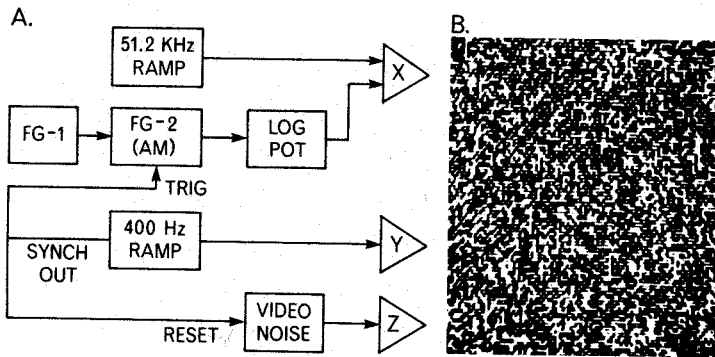


Fig. 1A. Block diagram of apparatus used to generate sinusoidal movement gratings in a random-dot pattern. A raster was formed by suitably triggering two electrically generated ramps at 51.2 KHz and 400 Hz and feeding them into the X and Y axes respectively. Video noise was produced by a triggered shift-register circuit. To generate differential motion according to equation (1) a triggered AM-modulated carrier signal (from FG-2) was fed into the X axis which, in turn, was modulated by a low frequency sinusoid (from FG-1). B. A portion of the random-dot display as it appears in its static form on the CRT screen.

ator was amplitude modulated by another function generator (FG-1 in Fig. 1A).

It should be apparent that the movement of the whole screen of random dots is identical to a standing wave, with characteristic nodes and antinodes. The instantaneous horizontal velocity can be described by the expression

$$\dot{X} = A \sin(2\pi f_t t) \sin(2\pi f_s Y) \quad (1)$$

where the temporal frequency of oscillation (f_t), the spatial frequency (f_s), and the amplitude (A) are under electronic control. Time is represented by t and the vertical position of each pixel is represented by Y . Because it is a transverse standing wave, with points in any horizontal row moving at the same horizontal velocity, there is no expansion or contraction in any given region. Dot density always remains constant.

A vector representation of the instantaneous velocity field for two different spatial frequencies of motion is depicted in Fig. 2. Note the sinusoidal change in velocity as a function of the vertical position of each row and the fact that the spatial frequency of this velocity profile can be varied (cf. A vs B). It should be noted that a similar type of differential movement and its relation to depth perception has been described by Rogers and Graham (1979).

AM modulated sinusoidal line

To provide a comparison with the results obtained from a stimulus which contains no familiar position cues, we also made measurements with a stimulus which would be least expected to isolate motion processing. This consisted of a single vertical line which was sinusoidally deformed in exactly the same man-

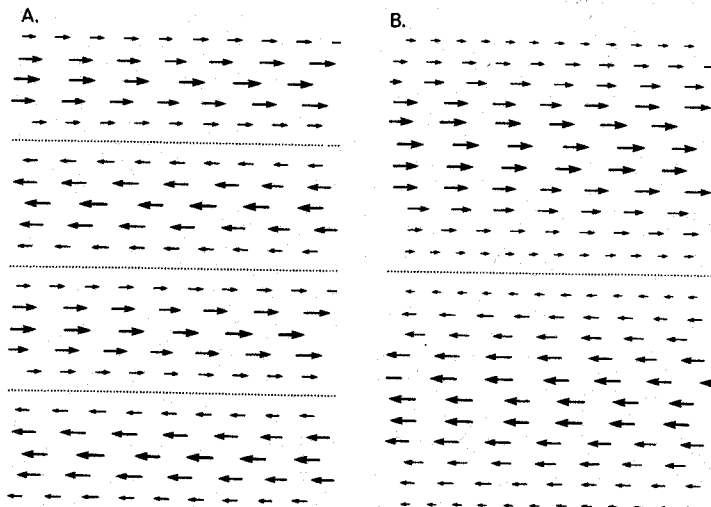


Fig. 2. Vector field representation of the instantaneous velocity field of the movement of random dots for two different spatial frequencies. Movement spatial frequency in A is twice that of B. Length of each arrow is proportional to velocity. It should be stressed that spatial frequency refers to the spatial distribution of the differential movement rather than to the luminance distribution.

ner as the screen full of random dots. It was generated by disconnecting the noise source from the Z input and the horizontal 51.2 Hz sawtooth ramp from the X input. Although its changing appearance was radically different from that of the random-dot stimulus (see inset of Fig. 4), its motion remains a standing wave conforming to equation (1).

Periodic vernier acuity target

As a final point of comparison, we tested position sensitivity using a single static sinusoidal line having a variable spatial frequency (sinusoidal periods/degree of visual angle). In this case the observer was not required to detect motion, but to detect a deviation from collinearity or straightness. Such a stimulus has been previously investigated by Tyler (1973) and appears to be related to vernier acuity. Two such stimuli having different spatial frequencies are shown in the inset of Fig. 6.

General procedures

Two practiced observers, the authors, were used throughout the study. Thresholds were obtained by the method of adjustment, varying the amplitude of the stimulus by a logarithmic potentiometer placed between the AM function generator and the X axis input (see Fig. 1A). At least 4 separate settings were obtained for each plotted point.

Viewing distance was kept at 114 cm, the room illumination was maintained at a low photopic level, and the observer was instructed to restrict fixation to the center of the screen.

RESULTS

Experiment 1—Detection of relative movement in the random-dot display bypasses position sensitivity

To test the supposition that movement in the random-dot display is mediated by velocity sensitive elements rather than by position sensitive mechanisms, we relied on the fact that the peak velocity of any sinusoidally oscillating point in the display increases in proportion to temporal frequency ($d \sin \omega t / dt = \omega \cos \omega t$). The peak velocity of a 1 Hz oscillating motion for example is 10 times that of a 0.1 Hz oscillation, given a constant amplitude. Thus, if the detection were mediated by a motion system, requiring a minimum threshold velocity rather than a minimum displacement, proportionately less amplitude would be necessary as the temporal frequency was increased, at least over some significant range. On the other hand, if the detection were based solely on position, there would be no dependence of threshold on temporal frequency.

The dependence of threshold amplitude on temporal frequency was determined for a constant spatial frequency of movement (3 c/deg). Figure 3 shows that over the range between 0.1 and 1.0 Hz, thresholds fall steadily and conform well to the slope of -1 on the log-log representation. Because points along this part

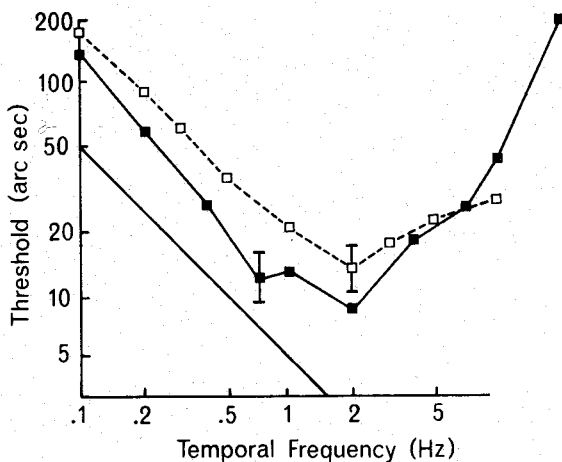


Fig. 3. Motion threshold amplitude vs temporal frequency for random-dot moving grating (3 c/deg). Note that between 0.1 and 1 Hz, the relation is reciprocal, indicating movement rather than position sensitivity. Observer KN (open symbols), observer CWT (filled symbols) for this and subsequent figures. Diagonal line represents slope of -1 .

of the function all represent movements having the same peak velocity, the result indicates that motion detection in the random-dot grating is determined exclusively by the peak velocity in the stimulus. Thus it confirmed our original supposition that the observer would be unable to detect local deformations in the random-dot pattern even though they were fixated in foveal vision. As such, the measurement of motion sensitivity using random dots appears to bypass the contaminating effects of position sensitivity.

Experiment 2—Contamination by position information

Before describing a spatial characteristic of motion sensitivity, we first provide a contrasting example where an attempted measure of motion sensitivity is highly contaminated by recognizable position information. For this we used the moving sinusoidal line (described in Methods) modulated with the identical standing wave motion. Unlike the random-dot pattern, it shows a recognizable change in appearance as it goes through successive stages of movement (see inset of Fig. 4) and the experiments indicate that the relation between threshold amplitude and temporal frequency is very different. The function is essentially flat over the 0.1–1 Hz range just where the thresholds for the moving gratings fell by a factor of 10 (see Fig. 4).

Discussion: Experiments 1 and 2

Although Experiments 1 and 2 both use moving stimuli, it is clear that only Experiment 1 measures motion sensitivity. In Experiment 2 there is an obvious and recognizable change in the appearance of the line as it moves and this occurs irrespective of how slowly the process proceeds. In other words, recognizable shape or position rather than movement determine the threshold, so the sinusoidal line stimu-

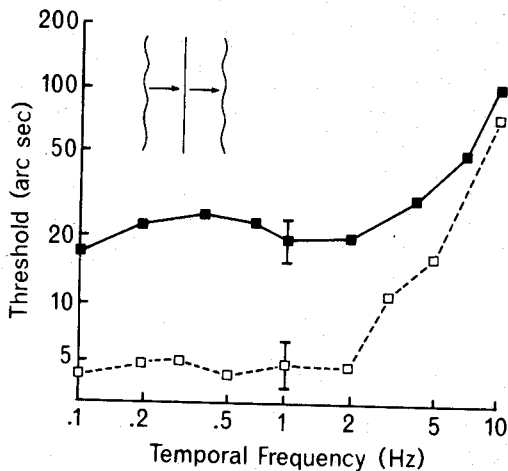


Fig. 4. Threshold amplitude vs temporal frequency for a 3 c/deg movement of a single luminous line. Inset shows how this changes appearance during some phases of the movement cycle. Although movement is identical to that used for the random-dot moving stimulus (see Fig. 3), the function between 0.1 and 1 Hz is flat. This indicates the dominance of position rather than motion information for this moving line stimulus.

lus is clearly the wrong stimulus to examine motion sensitivity, and it suggests that other moving line stimuli are similarly suspect. For example, one of the classical studies in motion parallax sensitivity (Graham *et al.*, 1948) used a pair of vernier lines moving at different velocities. It is unclear whether the observers were indeed sensing the motion or whether the detection threshold was determined by a series of successive vernier acuity judgments. In another example, Tyler and Torres (1972) measured differential movement at the fovea between two adjacent parallel lines (separated by 15 min) and found that instead of a slope of -1 relating log threshold amplitude and log temporal frequency, the slope was approximately $-1/2$. They attributed this reduction in slope to the confounding effects of motion with position sensitivity. Their supposition gains credence when considering some recent experiments of Westheimer (1977) who has shown that observers are remarkably good at judging the relative distances between lines and could thus use this information to infer motion. It should be clear that line stimuli can be heavily laden with recognizable position information and that unless some particular precautions are taken (see later—Experiment 5), they are generally unsuitable as a probe to characterize motion sensitivity.

Experiment 3—Spatial characteristics of human motion sensitivity

Equipped with the moving random-dot grating, which is a stimulus that can dissociate motion from position sensitivity, we were in a favorable position to examine the spatial properties of motion sensitivity. To do this, we varied the spatial frequency of motion and measured threshold displacements. It should be

emphasized that by spatial frequency we refer to the spatial frequency of movement (f_s in equation 1) and not the spatial frequency of a luminance distribution as it is often used in studies with sinusoidal contrast gratings.

Because the best response of the movement system is around 2 Hz (see Fig. 3, also Tyler *et al.*, 1972; Nakayama and Tyler, 1978b), we fixed this temporal parameter and varied spatial frequency. The threshold results are plotted in Fig. 5.

Several features of this spatial tuning function should be noted. The first is that the sensitivity to differential motion can be extremely good, requiring only 5–6 arc sec of differential displacement. This is a figure that compares very well to that obtained for vernier acuity and other hyperacuity targets (Westheimer 1979). The second feature is that the motion threshold is lowest at the lowest spatial frequencies tested and is progressively elevated for movement spatial frequencies greater than about 0.7 c/deg. Thus, contrary to conclusions drawn by earlier studies (Brown, 1931), increased proximity of differentially moving points, as represented by the higher spatial frequencies of movement, do not offer advantages in the detection of relative motion. In fact, sensitivity improves as the distance between the areas of maximum differential movement increase.

Experiment 4—Spatial characteristics of human position sensitivity

Before discussing the results regarding the spatial characteristics of motion sensitivity, it is important to consider them in relation to the characteristics of differential position sensitivity. To accomplish this comparison along a comparable spatial metric, we used the periodic vernier acuity target consisting of a single static sinusoidal line. To obtain thresholds for position sensitivity, we had the observer determine the

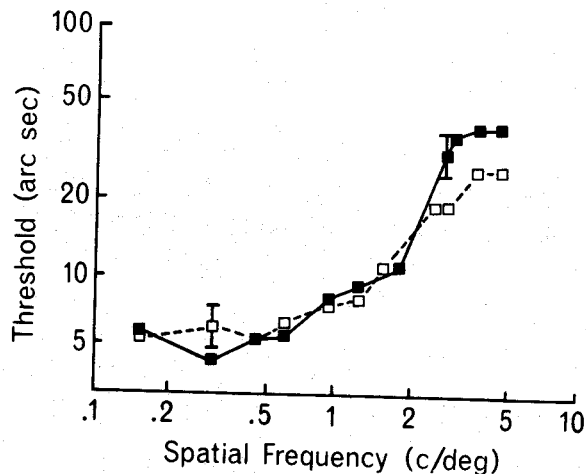


Fig. 5. Movement threshold amplitude as a function of movement spatial frequency (f_s) for a random-dot moving grating. Temporal frequency is 2 Hz. Note that the sensitivity is not diminished at the lowest spatial frequencies tested.

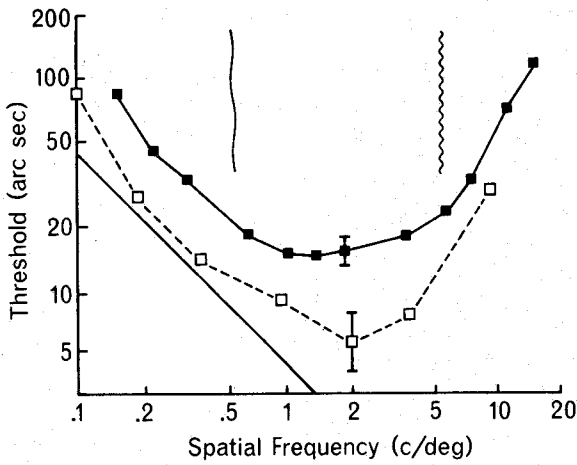


Fig. 6. Position threshold amplitude as a function of spatial frequency using a periodic vernier acuity task. Inset above the plotted function shows the appearance of the static line showing a low and a high frequency sinusoidal displacement profile. The observer is to set the amplitude of this sinusoidally modulated line so that it is just noticeably different from a straight line. Note that in contrast to motion seen in the random-dot grating (as in Fig. 5), the lowest thresholds are at a relatively high spatial frequency. At the lowest spatial frequency tested, position thresholds are 5–10 times higher than motion thresholds (compare Figs 5 and 6).

smallest sinusoidal amplitude that would produce a perceptible deviation from collinearity or straightness in the static line. These threshold settings are plotted against spatial frequency in Fig. 6 and replicate the results obtained by Tyler (1973). Several features deserve special mention, particularly as they differ significantly from the spatial characteristics of motion sensitivity depicted in Fig. 5. First is the fact that the shapes of the curves are completely different. Position sensitivity peaks at a relatively high spatial frequency, about 2 c/deg, and there is an inverse relationship

between spatial frequency and threshold over the range of 0.2–2 c/deg. Because points along this portion of the function share the same peak angular deviation from the vertical, it supports the emerging view that vernier and other static hyperacuity tasks are determined by orientation sensitive mechanisms (Andrews, 1973; Tyler, 1973). The second feature of interest is that sensitivity for position at these very low spatial frequencies is far worse than that for motion sensitivity, with a difference up to tenfold. A comparison of the lowest frequency portions of Figs 5 and 6 shows that position sensitivity is very poor at 0.2 c/deg where motion sensitivity is at its best. The third result is the extent to which position sensitivity is clearly superior to motion sensitivity at the higher spatial frequencies. Position sensitivity is still increasing as spatial frequency is increased while motion sensitivity is clearly decreasing.

Experiment 5—Low spatial frequency line stimuli can also isolate differential movement mechanisms

The preceding comparisons between motion and position sensitivity provide further insight as to how motion and position mechanisms will determine thresholds. If a target has recognizable position cues and the distance over which these recognizable differences in position are small, then position sensitivity will dominate as its threshold will be lower than the motion threshold. This occurred when a relatively high spatial frequency of 3 c/deg was used (Fig. 4). There is no indication of motion sensitivity at this spatial frequency as this is close to the optimal spatial frequency to stimulate position sensitivity as shown by the function depicted in Fig. 6.

On the other hand, if we choose a moving line stimulus requiring the comparison of position over a large distance, the position system would be poorly stimulated and the results would again be determined

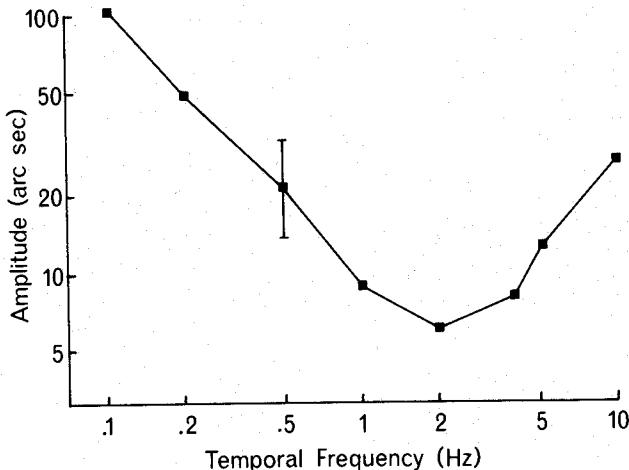


Fig. 7. Threshold amplitude vs temporal frequency for a moving sinusoidal line (moving according to equation 1) and having a spatial frequency of only 0.2 c/deg. Note that in comparison to the line stimulus having the higher spatial frequency (as shown in Fig. 4), the relation between threshold amplitude and frequency is reciprocal, indicating that the threshold depends on motion sensitivity.

by sensitivity to velocity. To test this idea, we measured motion thresholds of a moving sinusoidal line exactly as in experiment 2, except that a much lower spatial frequency was employed (0.2 c/deg, equivalent to one sinusoidal cycle/screen). In comparison to Experiment II (described in Fig. 4), the relation between threshold displacement and temporal frequency was reciprocal, indicating motion rather than position sensitivity (see Fig. 7). Even though it is a line stimulus, with recognizable position features, the spatial configuration of the stimulus is not optimal for position sensitivity and thereby permits motion sensitivity to dominate. An analogous result has been described by Westheimer (1979) where he showed that the threshold displacement of a hopping line is somewhat lower than the threshold difference required to note a static difference in distance in cases when the two reference lines were relatively far apart.

DISCUSSION

Separate organization of motion and position sensitivity

In physical terms, motion is always correlated with a change in position. As a consequence, one might initially suppose that relative motion coding is a process derived after the coding of relative position. This is a serial view and it suggests that motion sensitivity might share at least some characteristics with relative position sensitivity.

It should be clear that the results of the present study contradict this expectation. Of primary importance is the fact that motion and position sensitivity have completely different spatial tuning functions. Static position sensitivity appears best when the distance between differential displacements is relatively small, showing a peak in the spatial frequency curve at 2 c/deg. Thus the best comparisons are made over a peak-to-peak range of 15 arc min. Motion sensitivity, on the other hand, is at its best even at the low value of 0.2 c/deg.* As such, it is remarkable in its ability to make a differential comparison of a tiny displacement (5 arc sec) over a very large retinal distance, exceeding 4000 arc sec. Because differential motion sensitivity is so much better than position sensitivity when the comparison is made over these very large distances

(compare the low spatial frequency portions of Figs 5 and 6), it is unlikely to be derived from the psychophysically measured position sensitivity. We suggest it represents a distinct form of hyperacuity and can be best seen as a system wired in parallel to position sensitivity. Preliminary investigations show that differential motion sensitivity also differs in its lack of tolerance to retinal image motion (Nakayama, 1979), a result which stands in contrast to the findings obtained for acuity and hyperacuity targets (Westheimer and McKee, 1975).

Receptive field interpretation

The spatial characteristics of motion sensitivity can be interpreted physiologically if we assume that there are movement-specific neurons having very large receptive fields and that these neurons are driven by input subunits having high sensitivity and small receptive fields. Such units have been analyzed in detail in single unit studies (Barlow and Levick, 1964; Michael, 1968). It must be assumed that subunits having the opposite motion preference will generate inhibition rather than excitation at the level at which integration occurs. Such a neuron could be sensitive to very small displacements as it integrates over a large area but would have reduced outputs if there were also movements in the opposing direction within the receptive field. It would respond best to spatial frequencies of movement which had half periods larger than the receptive field diameter. If we consider the fact that movement sensitivity falls off above 0.7 cycle/deg (see Fig. 5), we can conclude that these integrating receptive fields for motion are as large as 2° in extent, even in the human foveal region. A similar conclusion was reached by Richards (1971) on the basis of motion aftereffect data.

REFERENCES

- Andrews D. P., Butcher A. K. and Buckley B. (1973) Acuities for spatial arrangements in line figures: human and ideal observers compared. *Vision Res.* **13**, 599-620.
- Aubert H. (1886) Die Bewegungsempfindung. *Pflügers Arch. ges. Physiol.* **39**, 347-370.
- Barlow H. B. and Levick W. R. (1964) The mechanism of directionally selective units in rabbit's retina. *J. Physiol.* **178**, 477-504.
- Brown J. F. (1931) The thresholds for visual movement. *Psychol. Forsch.* **14**, 249-232.
- Graham C. H., Baker K. E., Hecht M., Lloyd V. V. (1948) Factors influencing thresholds for monocular movement parallax. *J. exp. Psychol.* **38**, 205-223.
- Leibowitz H. (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.
- Michael C. R. (1968) Receptive fields of single optic nerve fibers in a mammal with an all cone retina. II: Directionally selective units. *J. Neurophysiol.* **31**, 257-267.
- Nakayama K. (1979) Common image motion severely disrupts motion parallax sensitivity. *J. opt. Soc. Am.* **69**, 1487.
- Nakayama K. and Tyler C. W. (1978a) Spatial characteristics of foveal movement sensitivity in random-dot gratings. *Invest. Ophthalm. visual Sci. Suppl.* p. 288.

* A question arises as to whether the motion of the dots relative to the edge of the screen at 3° eccentricity is sufficient to account for the very low movement thresholds obtained at the lowest spatial frequencies. We reject this interpretation for two reasons. First, we compared differential motion (0.2 c/deg) with whole field motion in a separate experiment using forced-choice feedback procedures. The whole-field motion threshold for KN was 12 arc sec, more than twice the 5 arc sec figure obtained for differential movement (or higher by 4 standard errors of the variability). Thus thresholds determined by the peripheral edge comparison are far too high to explain the lowest thresholds seen in Fig. 5.

Furthermore, even in the sinusoidal line stimulus which is 3° away from the edge of the screen, relative motion thresholds have the same low value of 5 arc sec at 0.2 c/deg (see Fig. 7).

- Nakayama K. and Tyler C. W. (1978b) Relative motion induced between stationary lines. *Vision Res.* **18**, 1663-1668.
- Richards W. (1971) Motion detection in man and animals. *Brain Behav. Evol.* **4**, 162-181.
- Rogers B. and Graham M. (1979) Motion parallax as an independent cue for depth perception. *Perception* **8**, 125-134.
- Tyler C. W. and Torres J. (1972) Frequency response characteristics for sinusoidal movement in the fovea and periphery. *Percept. Psychophys.* **12**, 232-236.
- Tyler C. W. (1973) Periodic vernier acuity. *J. Physiol.* **228**, 637-647.
- Westheimer G. (1977) Spatial frequency and light spread descriptions of visual acuity and hyperacuity. *J. opt. Soc. Am.* **67**, 207-212.
- Westheimer G. and McKee S. P. (1975) Visual acuity in the presence of retinal image motion. *J. opt. Soc. Am.* **65**, 847-850.
- Westheimer G. (1979) The spatial sense of the eye. *Invest. Ophthalm. visual Sci.* **18**, 893-912.