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Speed Discrimination Under Stabilized and Normal Viewing Conditions

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To determine whether speed discrimination improves when the retinal image is stabilized against the effects of eye movements, thresholds were measured under stabilized and normal viewing conditions. In the normal viewing conditions, eye movements were recorded and used to estimate retinal-image speeds. Stimulus reference speed for sinusoidal gratings varied from 0.5 to 8.0 deg/sec. Results showed that speed discrimination thresholds, expressed as Weber ratios, decreased with increasing stimulus speed for both the normal and stabilized viewing conditions. Stabilized viewing thresholds were higher than normal viewing thresholds only at the slowest stimulus reference speed. However, when speed discrimination thresholds were expressed as a function of the estimated retinal speed, there was no difference in thresholds for the stabilized and normal viewing conditions. A retinal-image model, whereby speed discrimination depends on retinal-image motion, explains the results. Copyright © 1996 Elsevier Science Ltd.

Speed discrimination Stabilized viewing Eye movements

INTRODUCTION

Psychophysical studies that investigate the properties of motion processing mechanisms often fail to accurately specify the stimulus. Most studies implicitly assume that the retinal image which provides input to a motion mechanism mirrors the distal stimulus. One problem with this framework is that the distal stimulus is not the only input to the retinal image; rather, retinal-image motion is the vectorial sum of the stimulus motion and the coincident eye movements.

Human observers cannot voluntarily inhibit eye movements when the visual field is composed entirely of moving targets and no fixation stimulus is provided (Kowler & McKee, 1987; Murphy *et al.*, 1975). Psychophysicists can reduce unwanted eye movements by using a stationary fixation point (Murphy *et al.*, 1975); but, the fixation mark may be problematic if it introduces relative spatial cues that confound the measured behavior. Other attempts to minimize eye movements may include restricting stimulus durations to times shorter than the putative latency of smooth pursuit eye movements, approximately 150–200 msec, and randomly varying the direction of stimulus motion. However, none of these procedures circumvent all eye movements. Anticipatory eye movements, which occur even when the stimulus motion direction and onset time vary randomly, are generated approximately 200–350 msec prior to the onset of a moving stimulus (Kowler & McKee, 1987; Kowler & Steinman, 1979a, b, 1981). Additional eye movements also can occur when an attempt is made to control movements by asking subjects to track targets moving at slow velocities. The corresponding eye movement recordings show noisy eye oscillations superimposed on smooth pursuit, with considerable variability in eye velocity (Kowler & McKee, 1987).

Given that the retinal image motion is a composite of the stimulus motion and the eye movement, a question arises as to whether eye movements affect the sensory representation for stimulus motion. One way to assess the precision of the sensory representation is to measure an observer's ability to detect small differences in the speed of moving stimuli. Such a speed discrimination task can be viewed as one of detecting the signal, defined here as the speed difference of the stimuli, in the presence of noise, defined as perturbations of the motion signal. Presumably, noise degrades the internal sensory representation and makes signal discrimination more difficult. Past studies (McKee, 1981; Orban *et al.*, 1984; Pantle, 1978) have shown that speed discrimination thresholds, when discussed in terms of the distal stimulus speed, decrease as a function of stimulus speed, and then asymptote for stimulus speeds of approximately 4 deg/sec and higher.

Using motion discrimination to determine the characteristics of the representation, the question can be formulated as such: for motion discrimination tasks that

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require the subject to judge the speed of the stimulus on the display screen, does precision increase when the retinal image is stabilized against the effects of eye movements? The non-invasive technique of using a stabilized image allows the experimenter to control the spatiotemporal properties of the retinal image, so that the retinal input is equivalent to the input that would be presented to a stationary eye.

If eye movements add noise to the sensory representation, speed discrimination performance should improve under stabilized viewing, because stabilization eliminates the effects of eye movements on retinal-image velocity and reduces the eye-movement associated noise. To test the hypothesis, we systematically manipulated the stimulus reference speed as we measured speed discrimination thresholds under stabilized and normal viewing conditions.

PSYCHOPHYSICAL TASK

Method

Subjects. One inexperienced and two experienced psychophysical observers (the authors, KT and SH) voluntarily participated in the experiment. All three observers had normal or corrected-to-normal vision, with visual acuities ranging from 20/13 to 20/17.

Stimulus and apparatus. The stimuli were generated by a graphics display board (Cambridge Research Systems), controlled by an IBM compatible AT computer. The stimulus, a vertically oriented, 3.0 c/deg sine-wave grating, was displayed on a Joyce DM2 monitor with a refresh rate of 100 Hz. The screen was masked with a circular aperture that measured 17.5 cm in diameter. The display subtended a visual angle of 5.6 deg at the viewing distance of 2.0 m. Space average luminance of the grating was 80 cd/m^2. The contrast, defined as $[(L_{\max} - L_{\min})/(L_{\max} + L_{\min})] \times 100$, was 30%.

The observer viewed the display with the right eye, and the left eye was covered with a translucent patch. The head was stabilized with a bite bar and headrest. Images were stabilized with an optical image stabilizer driven by an SRI Generation-V dual-Purkinje-image (DPI) eyetracker (Crane & Steele, 1985; Crane, 1994). The DPI eyetracker uses reflections from the first and fourth Purkinje images to measure eye movements. The eyetracker has an accuracy of about 1 minarc and a frequency response of approximately 500 Hz. Analog signals representing rotations of the eye are fed into an SRI two-dimensional visual stimulus deflector (Crane & Clark, 1978). Rotating mirrors, controlled by servomotors, deflect the image vertically and horizontally to compensate for eye movements; the compensatory feedback mechanism of the stabilizer allows the experimenter to control the spatiotemporal characteristics of the retinal image, and serves to eliminate the retinal-image effects of eye movements. The time delay for the stimulus deflector is < 2 msec.

The stabilization–calibration procedure, done prior to each test session under stabilized viewing, was as follows: the observer manually adjusted the eyetracker in three dimensions with a remote control, to align approximately the visual stimulus and the eye (the Generation-V eyetracker has three motors that move the stage, on which the instrument is mounted, in three dimensions). Once this was done, the instrument, with an automatic focus and autostaging capability, automatically aligned the eyetracker to the optimal position [see Crane (1994) for details]. To ensure that the image was precisely stabilized on the retina, and to provide a criterion for an adequate stabilization, the observer used a remote control to calibrate the horizontal and vertical gains. Both gains were adjusted by aligning a stabilized point-target on the display monitor with a fixation grid placed directly in front of the eye. As Crane has noted (1994, p. 58), this method is quite sensitive, because vernier acuities are used to judge the gain settings. The autostaging and focus servosystems were turned off prior to the start of the trials, which was necessary to preclude artifacts in the recordings. If the observer lost lock on the stabilized image, data collection was suspended until lock was re-established; this occurred for $< 5\%$ of the sessions. For the normal viewing conditions, the observer viewed the stimuli through the optics of the eyetracker, with the optical scanners turned off.

Design and procedure. Five reference speeds, 0.5, 1.0, 2.0, 4.0 and 8.0 deg/sec, were factorially combined with two viewing conditions, stabilized and normal viewing. The duration of each motion stimulus was randomly chosen from a Gaussian distribution with a mean of 500 msec and a standard deviation equivalent to 10% of the mean, to obscure duration and distance cues. A fixation cross on the center of the screen was used at the start of each testing session to facilitate optical adjustments, but no fixation mark was used during the test trials.

The minimum detectable difference in speed was determined by a two-alternative, forced-choice procedure. Two moving patterns were presented in successive intervals. In one randomly selected interval, the stimulus grating moved at a reference speed. In the other interval, the stimulus grating moved at a test speed, defined as the reference speed plus a delta speed. The direction of motion, right or left, was randomly determined for each trial, but remained the same for the two intervals. The intertrial interval was approximately 3 sec. The observer's task was to judge which interval contained the faster moving stimulus. Auditory feedback was provided. The delta speed (the difference between the reference speed and test speed) was changed according to a staircase method. The delta speed was set initially at 50% of the reference speed; two consecutive correct judgments decreased the delta by half or by the smallest step possible. A single incorrect response increased the delta in a similar way. Data collection began after the third reversal, or once the delta reached 0.05. The test session was terminated after data were collected for 40 reversals.

Observers performed in each condition twice. Viewing

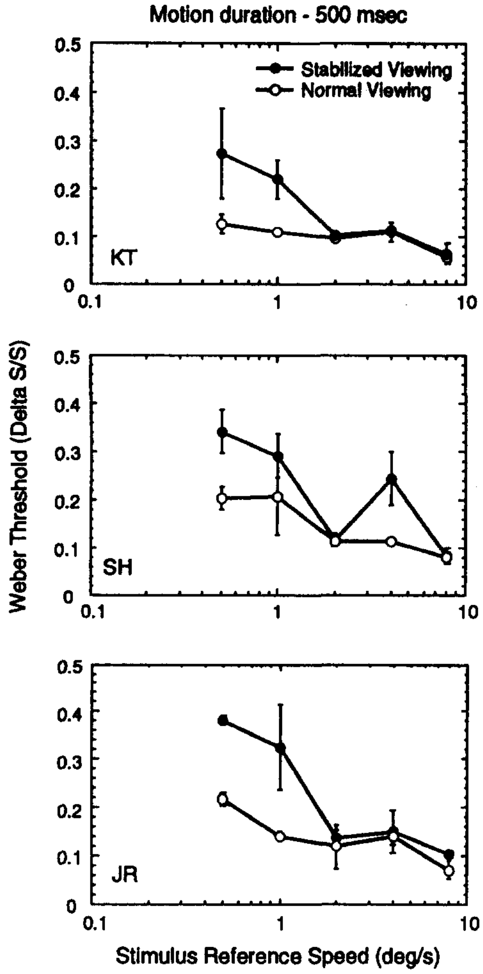

FIGURE 1. Weber thresholds (defined as Delta S/S, where Delta S corresponds to threshold delta speed and S refers to stimulus reference speed) for three subjects are plotted as a function of reference speed. The open symbols represent performance for the normal viewing condition and the solid symbols represent thresholds for the stabilized viewing condition. Error bars = ± 1 SD for the two means.

condition (i.e., stabilized or normal) was counterbalanced across two blocks of trials for each observer. Five stimulus conditions, corresponding to the five levels of stimulus reference speed, were randomly ordered within each block of trials. Only one stimulus condition was presented during a single test session, which typically lasted 30 min.

The speed discrimination threshold for each testing session was computed as the average of the 40 reversals generated from the staircase procedure. The value obtained with our statistical procedure is comparable to the delta speed of 70.7% correct discrimination. The two threshold values per test condition were averaged to provide a mean threshold value and standard deviation.

Results and discussion

Speed discrimination results under stabilized and normal viewing conditions, as a function of stimulus reference speed, are shown for each subject in Fig. 1. The data are plotted as Weber fractions (i.e., Delta S/S, where Delta S corresponds to the threshold delta speed and S refers to the reference speed of the stimulus) for the five reference speeds. Data for normal viewing trials are represented by the open symbols, and data for stabilized viewing trials are plotted as the solid symbols. The error bars represent ± 1 SD for the two means. Figure 2 plots the mean data of the three subjects, and the error bars represent ± 1 SEM.

As Figs 1 and 2 illustrate, speed difference thresholds for the normal viewing conditions show a general decrease with increasing reference speed. Subjects, on average, required an 18% speed difference for a reference speed of 0.5 deg/sec, but needed only a 7% speed difference for a reference speed of 8 deg/sec. The speed discrimination thresholds obtained under normal viewing conditions are approximately the same as those reported in other speed discrimination studies using similar conditions (e.g. McKee, 1981; McKee & Welch, 1985; Orban *et al.*, 1984; Pantle, 1978).

The speed difference thresholds for the stabilized viewing conditions, in general, show the same trend as the thresholds obtained under the normal viewing conditions: thresholds are highest for the slowest reference speeds and lowest for the fastest reference speeds, approximately 33 and 8%, respectively. Note that at the slowest reference speed, 0.5 deg/sec, the stabilized viewing thresholds are almost two times higher than the thresholds for the normal viewing conditions for all three subjects. Discrimination performance for stabilized viewing approaches that of normal viewing when the reference speed is >1.0 deg/sec, with the exception of SH at 4.0 deg/sec.

A repeated measures Analysis of Variance (ANOVA) showed a statistically significant main effect for stimulus reference speed, $F(4,8) = 37.41$, $P < 0.000$, a significant main effect for viewing condition, $F(1,2) = 82.28$, $P < 0.012$, and a significant reference speed $\times$ viewing condition interaction, $F(4,8) = 6.71$, $P < 0.001$. To localize the source of the reference speed $\times$ viewing condition interaction, we performed a simple main effects test of viewing condition at each level of reference speed. The results showed a significant viewing condition effect only

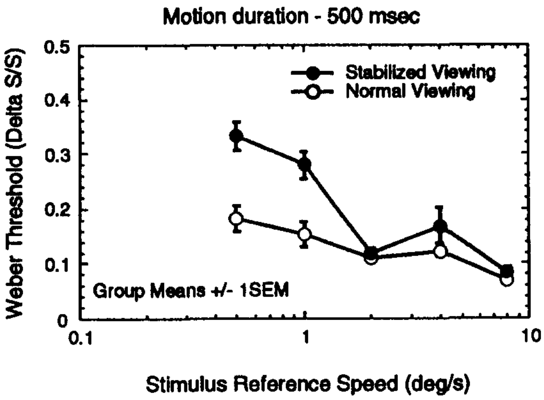

FIGURE 2. Mean Weber thresholds (Delta S/S) as a function of reference speed. The open and solid symbols represent performance for the normal viewing and stabilized viewing conditions, respectively. Error bars = ± 1 SEM.

at the 0.5 deg/sec reference speed, $F(1,2) = 354.31$, $P < 0.003$.

In summary, we found that speed discrimination thresholds are dependent upon the stimulus reference speed, with the highest Weber thresholds obtained at the slowest stimulus speeds. This is true for both normal viewing and stabilized viewing conditions. Comparing speed discrimination thresholds obtained under stabilized viewing to thresholds obtained under normal viewing, we found the stabilized viewing thresholds are higher than normal viewing thresholds at the slowest reference speed.

EYE MOVEMENTS

Stabilized viewing thresholds were higher than the normal viewing thresholds when analyzed in terms of distal-stimulus speed, as typically is done for studies of speed discrimination. To determine whether the difference in speed discrimination performance between the stabilized and normal viewing conditions could be explained on the basis of retinal-image speed, we compared the thresholds for the two viewing conditions after adjusting for the change in retinal speeds. The retinal speed in the stabilized viewing trials closely approximates the speed of the grating on the display monitor, whereas the retinal speed in the normal viewing trials is the vectorial sum of the stimulus motion and coincident eye movements. In order to estimate the retinal speeds in the normal viewing conditions, we used the measured eye movements for two subjects that were generated while they performed the discrimination task. If speed discrimination is dependent upon the retinal-image speed, and eye movements merely alter the retinal-image velocity, then thresholds plotted in terms of retinal-image speed should be comparable for the stabilized and normal viewing conditions.

Method

Eye movements were measured on two observers (the authors) as they performed the speed difference judgments for reference speeds of 0.5, 1.0, 2.0, 4.0 and 8.0 deg/sec (KT), and for reference speeds of 0.5 and 4.0 deg/sec (SH), using a motion duration of 500 msec.

Stimulus and apparatus. Horizontal movements of the right eye were recorded with an SRI Generation-V DPI eyetracker. The left eye was covered with a translucent patch and the head was stabilized with a bite bar and headrest. The voltage analogs of horizontal eye position were fed to a 12-bit analog-to-digital converter every 10 msec. The digital voltages then were stored on an IBM AT computer for off-line analysis. Average eye velocity per motion sequence was computed as the slope of eye position over time. Data for the first 150 msec, which reflect the putative latency of onset, were not included in the eye velocity calculation. Saccades were eliminated from the analyses in a manner similar to that of Dursteler and Wurtz (1988). Specifically, prior to analyzing the eye records, a threshold velocity of 14 deg/sec was designated, so that calculated eye velocities that exceeded the threshold level were eliminated from the eye record. To ensure that all saccades had been removed, each eye movement record was visually examined. Those data sets that still contained a saccade (< 2% of the total eye records) were eliminated from further analysis.

To determine the noise level of the eyetracker, eye movement records were collected using an artificial eye, which produced first and fourth Purkinje images adjusted to average levels. Eye positions along the horizontal meridian were sampled at the same rate and stored in the same manner used for recording subjects' eye movements. The noise level, operationalized as the standard deviation of the measures, was 0.35 minarc (cf., Kowler & McKee, 1987).

The conversion from voltage to degrees of visual angle was calibrated for each observer. Twenty-five equally spaced points, extending out to 6 deg horizontally and vertically, were displayed individually on a CRT display screen positioned 2 m in front of the observer. To calibrate each point, a central dot appeared and the observer pushed a button when she fixated the point. Then the central dot disappeared and a calibration dot appeared. Again, the observer pushed a button when she fixated the point. At that time, the voltage and screen position of the dot were recorded.

Design and procedure. As in Experiment 1, the observer's task was to judge which of two successive intervals contained the faster moving stimulus. Again, the direction of motion for each grating stimulus was randomly determined for each trial, but remained the same for the two intervals. Test conditions also were randomly ordered. The delta speed for the test stimulus was determined by the same staircase procedure

TABLE 1. Eye speed as a function of stimulus reference speed

Stimulus speed (deg/sec)	Subject	Mean eye speed (deg/sec)	SD eye speed	Mean gain	Retinal speed (deg/sec)	Number of trials
0.5	KT	0.63	0.23	1.26	0.13	110*
1.0	KT	0.63	0.17	0.63	0.37	57
2.0	KT	1.10	0.26	0.55	0.90	56
4.0	KT	1.32	0.37	0.33	2.68	99*
8.0	KT	2.37	0.44	0.30	5.63	87
0.5	SH	0.73	0.28	1.46	0.23	44
4.0	SH	1.48	0.73	0.37	2.52	58

*Data computed from two sets of trials.

than the slowest reference speed in our study by a factor of five. Furthermore, subjects reported that the stimuli never appeared to fade during test sessions. It also is unlikely that a reduction in the effective stimulus contrast due to image stabilization can account for the increased thresholds at slow speeds, since past studies have shown that speed discrimination is essentially independent of suprathreshold changes in contrast (McKee *et al.*, 1986; Turano & Pantle, 1989).

We predicted that if eye movements add noise that degrades the sensory representation, then stabilized viewing should produce lower speed discrimination thresholds than normal viewing, since image stabilization would diminish, if not eliminate, the eye-movement associated noise. Our results showed the opposite effect. One noise-related explanation for higher thresholds under stabilized viewing may be the stabilization procedure itself: the mirrors of the image stabilizer, which deflect the stimulus to compensate for eye movements, move the stimulus with respect to the observer; if the motion of the external stimulus serves as a source of noise and masks speed information, then the relatively unpredictable displacements of the stimulus caused by eye movements could hinder discrimination. According to our data, masking would be efficacious only for the slowest reference speeds. One reviewer noted that the argument is plausible, given that speed judgments for slower stimuli appear to require longer stimulus durations (e.g., McKee & Welch, 1985; Orban *et al.*, 1984), and longer durations are coupled with the increased likelihood of eye movements. Following this argument, one would expect that eye movements and the consequential masking effect could be reduced with shorter stimulus durations. However, evidence from our lab, using the identical stabilization procedure with a briefer stimulus (i.e., approximately 200 msec), showed that thresholds for slow stimulus speeds under stabilized viewing still were significantly worse than those under normal viewing. Although we cannot definitively dismiss the possibility that objective speed (i.e., stimulus speed plus displacements produced by the servo-controlled mirrors) accounts for the difference only at the slow speeds, we favor an explanation based on retinal-image speed. Stabilized viewing thresholds were comparable to those obtained with normal viewing, when we equated the two measures in terms of retinal velocity. The retinal motion governed performance; and, the retinal motion was equally effective, whether it derived from stimulus motion or stimulus motion combined with eye movements [cf., Murphy (1978) who reached the same conclusion for contrast sensitivity measures].

A retinal-image motion model appears sufficient to explain the present result. Yet, in other motion studies (e.g., Pola & Wyatt, 1989; Royden *et al.*, 1992), the contribution of the extraretinal signal is implicated*. Royden *et al.* examined subjects' ability to judge heading direction during tracking eye movements. They found that judgments were more accurate during executed eye movements than simulated eye movements, when eye speeds were greater than approximately 1 deg/sec, or when there was no visible horizon to serve as a potential cue. The results were interpreted in terms of the extraretinal signal contributing to the decision-making process in the condition where the subject executed eye movements. Royden *et al.* suggest that the extraretinal signal may contribute to motion perception under conditions where there is motion ambiguity.

Wertheim (1981, 1987; Wertheim & Van Gelder, 1990) also has discussed the role of extraretinal signals, in that motion perception is dependent upon the magnitude of the difference between the retinal signal and the extraretinal signal, not the extraretinal signal, *per se*. (Wertheim estimates the extraretinal signal velocity to be the same as the eye velocity.) In our study, this is the same as the difference between the stimulus speed and the eye speed, but only in the normal viewing condition. In the stabilized viewing condition, the retinal image speed is equivalent to the speed of the stimulus on the monitor. Wertheim's model differs from the retinal-image motion model implicated here, which predicts that performance is based on the retinal-image speed. Our results, which show similar thresholds for the normal and stabilized viewing conditions when the two are equated in terms of retinal speed, are difficult to explain with Wertheim's model.

Further studies are needed to distinguish which tasks can and cannot be explained in terms of retinal-image motion. If it can be demonstrated that extraretinal signals play a role in some motion perception tasks, then further research is needed to determine the operating range of the extraretinal signal and the nature of the signal. That is, it remains unclear whether the extraretinal signal is qualitative, such as an on/off code, or quantitative, such as a velocity code that incorporates a speed and a direction, or merely speed information.

In conclusion, the results of this study show that speed discrimination thresholds for slow stimulus speeds, expressed as Weber ratios relative to stimulus speed, are higher when measured with image stabilization than when measured under normal viewing conditions. When equated in terms of retinal speed, there is no difference between the stabilized viewing and the normal viewing thresholds. A retinal-image motion model is a parsimonious explanation for the results.

*Information about eye movements may be conveyed through a feedback loop (i.e., an extraretinal signal that may be a copy of the efferent signals sent to the oculomotor system, or proprioceptive feedback from the eye muscles).

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described previously. The only modification to the procedure was that the test session was terminated after 16 reversals.

Results and discussion

Table 1 is a summary of the eye movement data obtained at the indicated reference speeds. The columns, from left to right, show the reference speeds, subject identification, mean eye speeds, standard deviation of the eye speeds, gains (i.e., ratio of eye movement speed to distal stimulus speed), average retinal speeds, and the number of trials. Retinal-image speed (i.e., distal speed minus eye speed) was calculated only for the portion of the motion sequence in which the grating moved at the reference speed.

Eye speed showed a general increase with increasing distal-stimulus speed. The average eye speed for the 4.0 deg/sec stimulus speed was approximately twice the eye speed for the 0.5 deg/sec stimulus speed. However, the *gain* decreased with increasing stimulus speed. This result is consistent with the findings of Murphy (1978) and Martins *et al.* (1985). In our study, the average gain for the 0.5 deg/sec stimulus speed was >1, indicating that the eye moved at a faster speed than the distal stimulus. But the average gain for the 4.0 deg/sec stimulus speed was approximately one-third of the distal speed. Gain was approximately four times greater for the 0.5 deg/sec stimulus speed compared to the 4.0 deg/sec stimulus speed.

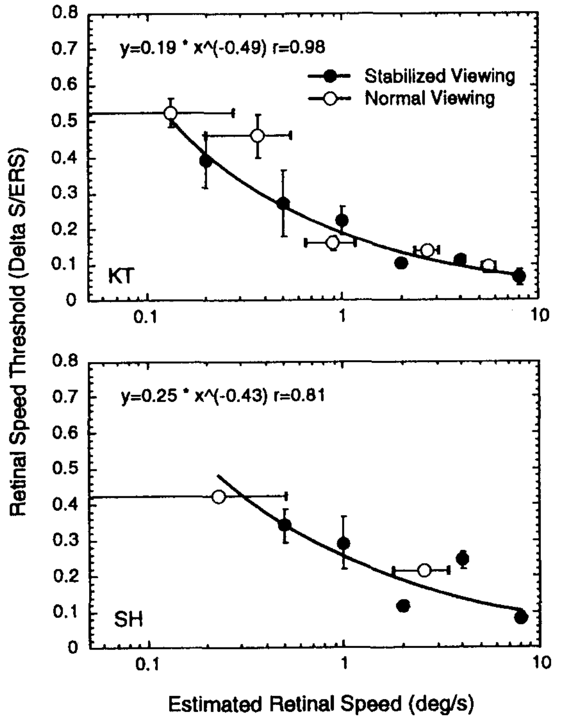

FIGURE 3. Speed discrimination thresholds (Delta S/ERS, where Delta S corresponds to the threshold delta speed and ERS refers to the estimated retinal-image speed) for two subjects, plotted as a function of the estimated retinal speed. The open symbols represent performance for the normal viewing condition; the solid symbols, replotted from Fig. 1, represent thresholds for the stabilized viewing condition. See text for details. Error bars = ± 1 SD. Solid lines represent the best-fit power functions for the stabilized viewing data.

The gains presented here differ from the gains reported in studies in which the subjects were instructed to pursue a moving target (Kowler & McKee, 1987) or maintain their line of sight (Murphy, 1978). Previous evidence has suggested that low gains would be predicted, if the subjects were not trying to track the moving stimuli (cf., Murphy *et al.*, 1975; Steinman *et al.*, 1969). However, gains > 1 would not be expected, because subjects cannot use voluntary effort to track faster than the target (Steinman *et al.*, 1969). The higher-than-expected gains for the 0.5 deg/sec condition may be due to a number of reasons. For one, the test speed always was greater than the reference speed, which may have produced a context effect. Kowler and McKee (1987) reported a context effect, whereby pursuit eye movements were faster when target stimuli were presented with other stimuli moving at higher velocities. Second, our study required subjects to make speed judgments about the distal stimulus, whereas the previous studies did not use a speed judgment task. Other explanations may concern differences in target type, gratings rather than small spot targets, or interactions between saccades and accompanying smooth pursuit movements.

Speed discrimination results obtained under normal viewing conditions are plotted in Fig. 3 as a function of the average retinal speed calculated from the eye movement recordings. Here thresholds are computed as Delta S/ERS, where Delta S corresponds to the threshold delta speed and ERS refers to estimated retinal-image speed, not distal-stimulus speed. Other graphing conventions used for Fig. 1 are used here. Stabilized viewing data for both subjects from Fig. 1 are replotted in Fig. 3. Subject KT performed an additional speed discrimination test at a reference speed of 0.2 deg/sec, in order to estimate the function of the stabilized viewing thresholds at a lower speed. The solid line represents the best-fit power function for the stabilized viewing condition. When considered within the framework of retinal speed rather than stimulus speed, the normal viewing thresholds closely match the stabilized viewing thresholds.

GENERAL DISCUSSION

The results of our study show that for slow stimulus speeds, speed discrimination thresholds, when expressed as a Weber ratio relative to the stimulus reference speed, are significantly higher when measured with image stabilization than the thresholds obtained with normal viewing.

One may hypothesize that the decreased performance for very slow stimulus speeds under stabilized conditions occurred because the slowly moving stimuli appeared to fade, and, therefore, the effective contrast was reduced. This explanation is unlikely for several reasons. Kelly (1979) measured contrast sensitivity thresholds for stabilized, drifting gratings over a broad range of spatiotemporal frequencies. The results showed that fading occurs at velocities < 0.1 deg/sec, speeds slower

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