

Stereothresholds for moving line stimuli for a range of velocities [☆]

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Abstract

This study examined the influence of lateral target motion on the stereothresholds for bright vertical lines at a range of velocities. Stimuli were presented for 200 ms with horizontal velocities from 0 to 12 deg/s. Observers' horizontal eye movements were recorded on additional trials, and confirmed that the velocity of retinal image motion closely matched the velocity of the stimulus. In three auxiliary experiments, stereothresholds were measured (1) after equating the detectability of targets that moved at different velocities, (2) for moving and stationary stimuli with durations between 20 and 200 ms, and (3) for stationary stimuli presented at eccentricities of 0.6 and 1.2 deg. The results indicate that stereothresholds are unaffected by velocities up to approximately 2 deg/s, but worsen in proportion to the velocity at higher speeds. The results of our auxiliary experiments demonstrate that the increase in stereothresholds during image motion cannot be attributed primarily to a reduction in the detectability of the stimulus, a decrease in the effective exposure duration, or non-foveal viewing. We conclude that the elevation of stereo thresholds during lateral motion is consistent with a shift in the sensitivity of the visual system toward lower spatial frequencies as a result of motion blur.

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1. Introduction

Binocular stereoacuity is an example of a hyperacuity that allows threshold spatial discriminations substantially finer than the spacing between the retinal photoreceptors. It is of both theoretical and practical interest to know how stereothresholds are affected by stimulus motion, which causes the retinal image to sweep sequen-

tially across a number of photoreceptors. Theoretically, retinal image motion represents a challenge to the neural mechanisms that are responsible for achieving fine stereopsis (Howard & Rogers, 2002; Westheimer, 1979). Practically, stereoacuity should withstand at least the range of retinal image motion that accompanies normal eye and head movements (e.g., Steinman, Levinson, Collewijn, & van der Steen, 1985) to be maximally useful during everyday tasks.

Westheimer and McKee (1978) reported that stereothresholds are essentially unaffected by lateral image motion in the two eyes up to the highest velocity that they tested of 2.5 deg/s. However, they found that thresholds are elevated substantially by much lower velocities of motion in depth, which produce changes in the absolute retinal image disparity (see also Ukwade, Bedell, & Harwerth, 2003a, 2003b). Subsequently, Morgan and Castet (1995) measured stereothresholds for low spatial frequency grating targets, during lateral

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motion at a wide range of velocities. Stereothresholds were relatively unaffected by lateral motion until the velocity of the targets exceeded a temporal frequency of approximately 30 Hz, corresponding to a velocity of almost 200 deg/s for 0.16 c/deg targets.

A number of inter-related factors could contribute to the degradation of stereothresholds during high-speed lateral retinal image motion. One consideration is that when a stimulus is in motion, its energy is spread over a spatio-temporal area. If this spread exceeds either the spatial or the temporal sensitivity windows of the receptive fields needed to produce the optimal performance, then the energy in the stimulus will not be summated completely. This reduction in the effective energy of the stimulus should reduce its detectability, thereby contributing to an elevation in the threshold (Halpern & Blake, 1988; Harwerth, Fredenburg, & Smith, 2003; Legge & Gu, 1989; Westheimer & Pettet, 1990).

A related factor is that when a stimulus moves, it remains within the most sensitive central fovea for only a brief duration. The resulting effective reduction of the stimulus duration would be expected to lead to an elevation of stereothresholds, which are known to worsen as exposure duration is decreased (Harwerth et al., 2003; Ogle & Weil, 1958; Patterson, 1990; Shortess & Krauskopf, 1961; Watt, 1987; Westheimer & Pettet, 1990).

In addition to limiting the duration that a stereotarget is in the fovea, image motion shifts the target to increasingly eccentric retinal locations over time. Because the thresholds for stationary stereotargets increase rapidly with retinal eccentricity (Fendick & Westheimer, 1983; Rawlings & Shipley, 1969; Westheimer & Truong, 1988), the elevation of stereothresholds during motion could be a consequence of the time-averaged extra-foveal image location.

A final factor that could contribute to the elevation of stereothresholds during movement of the stimulus is motion blur, which can be thought of as an effective smearing of a moving target's contrast as a result of visual persistence. Motion blur eliminates high spatial frequency information from a moving stimulus thereby producing a *de facto* shift of visual processing to channels tuned to lower spatial frequencies. Previously, Chung and co-workers (Chung & Bedell, 1998, 2003; Chung, Levi, & Bedell, 1996) proposed that a shift in spatial processing to channels tuned to lower spatial frequencies accounts for the degradation of Vernier and letter acuity during motion of the retinal image.

Because stereothresholds have not been studied for laterally moving, broad band targets at velocities greater than 2.5 deg/s, the principal purpose of this study was to investigate the effect of a wider range of retinal image motion on the stereothresholds for line targets. In addition, we performed several auxiliary experiments to assess the contributions of the factors listed above to the degradation of stereothresholds during stimulus motion.

2. Methods

2.1. Observers

Five observers participated in this study after voluntarily granting written informed consent. The University of Houston Committee for the Protection of Human Subjects reviewed the experimental protocol before any observers were enrolled. Each observer was corrected fully for his or her refractive errors, either with spectacles (MLR, HEB and RKR), contact lenses (SKR), or previous refractive surgery (PCF). Observer RKR had a corrected anisometropia of -3.00 DS. Each observer had best-corrected visual acuity of at least 20/20 in each eye, normal ocular motility, and no detectable ocular abnormalities. Stereoacuity was at least 40 arc-sec at near and 1 arc-min at distance, as determined clinically using random dot stereograms and the Wirt circle test, respectively. Although three of the observers (SKR, RKR and PCF) were naïve to the purposes of the study, all had some prior experience in performing psychophysical tasks.

2.2. Experiment 1A: Stereothresholds for moving line stimuli

The stimuli were pairs of 0.2 arc-min (nominally) by 30 arc-min bright vertical lines presented against a dark background on a vector oscilloscope (Hewlett Packard, Model 1311B with P31 phosphor). One pair of vertically separated lines was presented to each eye, at a refresh rate of 240 Hz. The experiments were performed in darkness to minimize peripheral fusional cues. The targets were viewed by the observer through a mirror haploscope (Ukwade & Bedell, 1999). Head and chin rests were used to stabilize the observer's head position.

Polarizing filters were placed in front of both the haploscope and the oscilloscope, so that each eye saw one lateral half of the oscilloscope at the test distance of 3.95 m. Each eye's polarized view was seen after reflection by one fixed and one rotatable mirror. The rotatable mirrors were mounted on galvanometers (General Scanning, Inc., Model G325D) that were placed close to each eye. A pair of scanner controllers (General Scanning, Inc., Model CCX-650) provided the input signals to these galvanometers. The input voltages to the controllers came from 2 digital-to-analog channels of a Scientific Solutions Labmaster board, mounted in a pc compatible computer. Binocular conjugate retinal image motion in the two eyes was achieved by synchronously moving the galvanometer-driven rotatable mirrors in front of each eye with a constant velocity ramp waveform, randomly either to the left or to the right. Prior to the start of the study, the haploscope was aligned by projecting a pair of parallel laser beams through the mirrors in the right- and left-eye channels onto the

fixation target displayed for each eye on the oscilloscope screen. The offsets of the galvanometer-driven mirrors were adjusted mechanically and electronically to produce zero vergence demand for the test distance of 3.95 m. By equating the dynamic deflections of the projected laser spots on the oscilloscope screen, the two mirrors were calibrated to produce identical image velocities in response to a linear voltage change.

The pair of lines presented to each eye was separated vertically by either 5 arc-min or 20 arc-min. Horizontal retinal image disparity was produced by introducing a horizontal offset between the top and bottom lines in each stereo pair that was in opposite directions in the two eyes. Stereothresholds were measured during lateral stimulus motion that ranged in velocity from 0 to 12 deg/s.

The luminance of each stationary line was measured from a distance of 19 cm, using a Prichard Spectra Photometer with a 2 arc-min measuring aperture and an auxiliary lens. The luminance of each line was approximately 30 cd/m², after correcting for the attenuation produced by the polarizing filters. Each target presentation had a duration of 200 ms, calibrated by placing a United Detector Technology photocell (Model 10 DP) directly against the face of the oscilloscope. This photocell was used also to measure the temporal asynchrony between the presentation of the top and the bottom stimulus lines, which was found to be less than 1 ms.

Before each trial, the observer fixated on the outline of a 0.2×0.2 deg square that was centered on each half screen of the oscilloscope, and made sure that the fused outline was clear and sharp. When the observer was ready to initiate a trial, he or she pressed the fire-button on a joystick, at which time the fixation target was turned off. After a dark interval of 246 ms, the line stimuli were presented on the oscilloscope for a duration of 200 ms during the middle portion of a 500-ms ramp-motion waveform. The trajectory of ramp-produced image motion was always symmetrical with respect to the position of the previously visible fixation target. Both the duration of the line stimuli and the randomly selected direction of mirror motion (left vs. right) on each trial were chosen to minimize the influence of pursuit eye movements, which have been reported to have a latency of approximately 200 ms for targets that move unpredictably (O'Mullane & Knox, 1999; Rottach et al., 1996). The dark interval that preceded the onset of the stereotargets ensured that any transients associated with the onset of mirror movement would not affect the quality of the image motion. Following the offset of the stimulus and after the mirror ceased its deflection, the observer was asked to indicate with a joystick whether the position of the lower test line was nearer or farther than the top line.

An experimental run consisted of a block of 70 trials. The pairs of lines were presented 10 times in random order at each of seven different disparities: three equally

spaced values of crossed disparity, three equally spaced values of uncrossed disparity, and zero disparity. In addition, the lateral position of the lower line seen by each eye was jittered from trial to trial to minimize monocular position cues. The amount of position jitter was in the same direction and equal in both the eyes, and was selected randomly from 0, $\pm 1/3$, $\pm 2/3$ or ± 1 times the disparity that was being presented. The stationary fixation target reappeared as soon as the observer made a response, and served as a ready signal for the next trial. The different velocities of stimulus motion were tested in separate blocks of trials, scheduled in a random order. No feedback was provided for correct or incorrect responses. To avoid fatigue, testing was conducted in short sessions on different days.

Because stereothresholds improve with practice, (Fendick & Westheimer, 1983; Wittenberg, Brock, & Folsom, 1969) the observers underwent practice sessions with and without motion of the stimuli until no further improvement in the stereothreshold was observed. This practice consisted of approximately eight blocks of trials for MLR, SKR, and RKR, and fewer for the highly practiced observers, HEB and PCF. After the completion of practice, the percentage of “far” responses for each block of trials was subjected to probit analysis to yield one estimate of the stereothreshold, corresponding to a change from 50% to 84% on the psychometric function. The mean thresholds and standard errors were calculated from at least three replications per condition for each observer.

2.3. Experiment 1B: Assessment of eye movements

In Experiment 1A, the velocity of retinal image motion corresponds to the velocity of the stimulus only insofar as the eye remains stationary during each trial. To evaluate the observers' eye movements, horizontal eye position was recorded using an infrared limbal eye tracker (ASL model 200) during the presentation of two-line stereotargets at velocities of 4, 8, and 12 deg/s. Each presentation of the stereotargets was identical to that described above for Experiment 1A. Analog signals from the eye tracker were digitized at 1000 Hz using a Scientific Solutions Labmaster card and saved, along with a signal of mirror motion, on a separate personal computer from the one that generated the stimuli. In order to obtain more robust signals from the infrared limbal eye tracker, the refractive errors of the three observers who wore spectacles in Experiment 1A (RKR, MLR and HEB) were corrected with soft contact lenses in this study. Calibration of the eye tracker was carried out before and after eye movements were recorded at each stimulus velocity. During calibration, the observer looked sequentially between stationary targets that were separated horizontally by 4.34 deg. As in Experiment 1A, the head was restrained with head and chin rests.

Eye movements were measured for a total of 20 trials for each stimulus velocity. As in Experiment 1A, the line stimuli were presented randomly with rightward or leftward motion on each trial. After each trial, the observer indicated with a joystick whether the lower line was “nearer” or “farther” when compared to the top line. However, because only 20 trials were presented for each velocity of the stimulus, estimates of the stereothreshold were not determined from these psychophysical data.

Analysis of the eye movement data was conducted off-line. First, any trial that included a blink was rejected. The recorded eye-position signals for each eye were then averaged for the first six acceptable trials for each direction and velocity of stimulus motion. Each observer's average horizontal eye position in degrees was plotted as a function of time, for each combination of stimulus velocity and direction of motion.

2.4. Experiment 2: Stereothresholds for equally detectable moving line stimuli

Monocular detection thresholds were determined for one pair of line targets separated by a 20 arc-min vertical gap, by introducing neutral filters of increasing density (0.1 log unit steps) in front of one eye. The non-viewing eye was occluded. Using a bracketing technique, the neutral filter through which the stimulus could be detected approximately 50% of the time was taken as an estimate of the detection threshold. As in Experiment 1, the line targets moved randomly to the right or the left on each trial. Detection thresholds were determined for observers MLR and HEB, for stimulus velocities of 0, 4, 8, and 12 deg/s.

Each observer's stereothresholds were then re-measured for the same set of stimulus velocities using equally detectable line targets with a 20 arc-min vertical gap. We define equally detectable stimuli as stimuli that are presented at equal multiples of their detection thresholds. Specifically, stereothresholds were determined after inserting neutral density filters in front of *both* eyes to equate the detectability of the line stimuli that moved at 0, 4, and 8 deg/s to that of the unattenuated line stimuli that moved at 12 deg/s. Otherwise, the set up and procedures for this experiment were the same as for Experiment 1A.

2.5. Experiment 3: Effect of stimulus duration on stereothresholds

Stereothresholds were measured for pairs of line stimuli with a 20 arc-min vertical gap, for durations of 20, 40, 80, 120, and 200 ms and velocities of 0 and 8 deg/s. Stationary line stimuli were presented at the same location as the previously visible fixation target. Moving line stimuli were presented randomly in rightward or leftward motion, with a trajectory that was centered

on the location of the extinguished fixation target. Each combination of stimulus velocity and duration was assessed in separate blocks of trials for observers HEB and PCF.

2.6. Experiment 4: Effect of retinal eccentricity on stereothresholds

The stimuli used this experiment were the identical to the stereotargets used in Experiment 1A, except that the pairs of lines were presented statically for 200 ms, rather than in motion. After the central fixation target was turned off, stationary pairs of lines were presented at an eccentric location corresponding to the end point of the motion trajectory for a target velocity of 6 or 12 deg/s. Based on the 200-ms stimulus duration in Experiment 1, these end points were 0.6 and 1.2 deg to the left and right of the extinguished fixation target, for velocities of 6 and 12 deg/s respectively. Each block of trials determined the stereothreshold at one of the above two eccentricities using a stimulus with a 20 arc-min vertical gap. Data were obtained for two practiced observers (MLR and HEB).

3. Results

3.1. Stereothresholds for moving line stimuli

Stereothresholds are plotted as a function of the stimulus velocity for all of the observers in the top and bottom panels of Fig. 1, for 5 and 20 arc-min separations between the line stimuli, respectively. As reported by Westheimer and McKee (1978), the stereothresholds are unaffected by velocities of lateral motion up to approximately 2 deg/s. However, the stereothresholds for both line separations increase monotonically with higher velocities up to 12 deg/s. As indicated in Fig. 1a and b, the average stereothreshold increases by a factor of approximately 8 when the stimulus velocity increases from approximately 2–12 deg/s.

The stereothresholds measured for a target velocity of 0 deg/s do not differ significantly for the stimuli with 20 vs. 5 arc-min gaps (paired $t_{df=4}=0.86$; $p=0.43$). The absence of a pronounced effect of gap size on stereothresholds is consistent with previous reports that stereothresholds increase non-monotonically as a function of target separation (Berry, 1948; Stigmar, 1970; Westheimer & McKee, 1979).

3.2. Eye movements in response to moving stereotargets

Fig. 2 shows average eye movement traces for observer MLR in response to rightward and leftward motion of the stereotargets at a velocity of 12 deg/s. Smooth pursuit eye movements are first apparent approximately 175

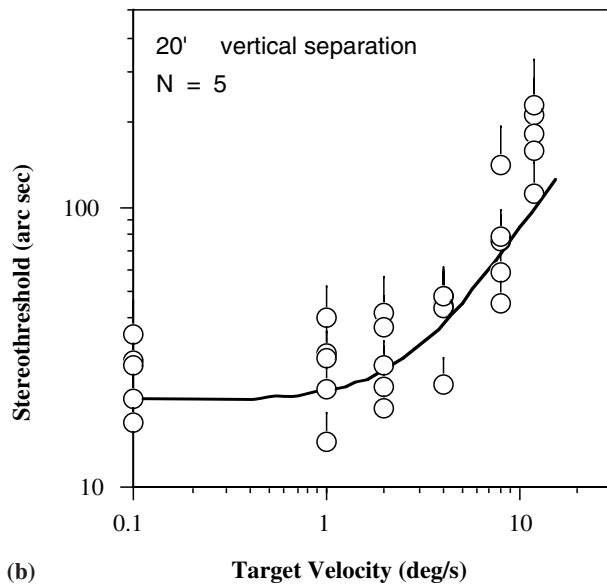
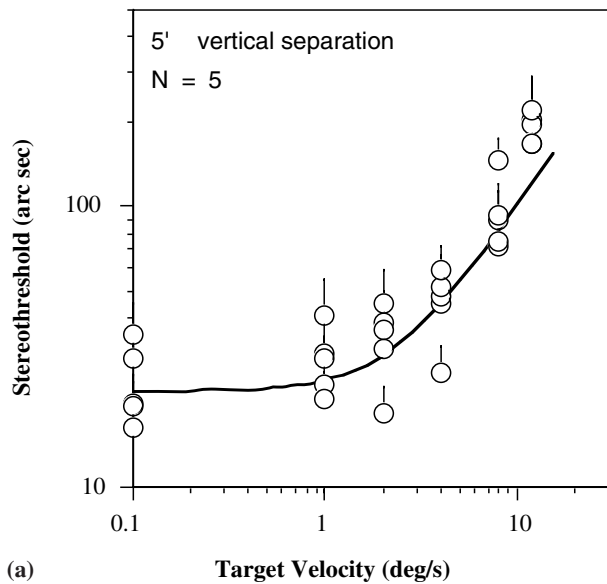


Fig. 1. Average stereothresholds, in arc-sec, for five observers are plotted as a function of stimulus velocity, in deg/s, for target lines with 5 (a) and 20 arc-min (b) vertical separations. Solid lines represent the best fitting line to the data in each panel, using Eq. (2) in the text. The error bars are ± 1 SEM for each observer. Note that the stereothresholds for stationary targets are plotted at 0.1 deg/s on the x-axis.

ms after the onset of stimulus motion, but their velocity is substantially less than that of the stimulus. The transient increase in eye velocity that occurs shortly after the end of the stimulus presentation indicates the presence of a saccade, after which the eye velocity falls approximately to the speed of the previous stimulus motion. The averaged eye movement traces for each of the observers in response to the different velocities of rightward and leftward motion of the stereotargets were qualitatively similar. Either the observers exhibited minimal pursuit eye movements that started near the end of the

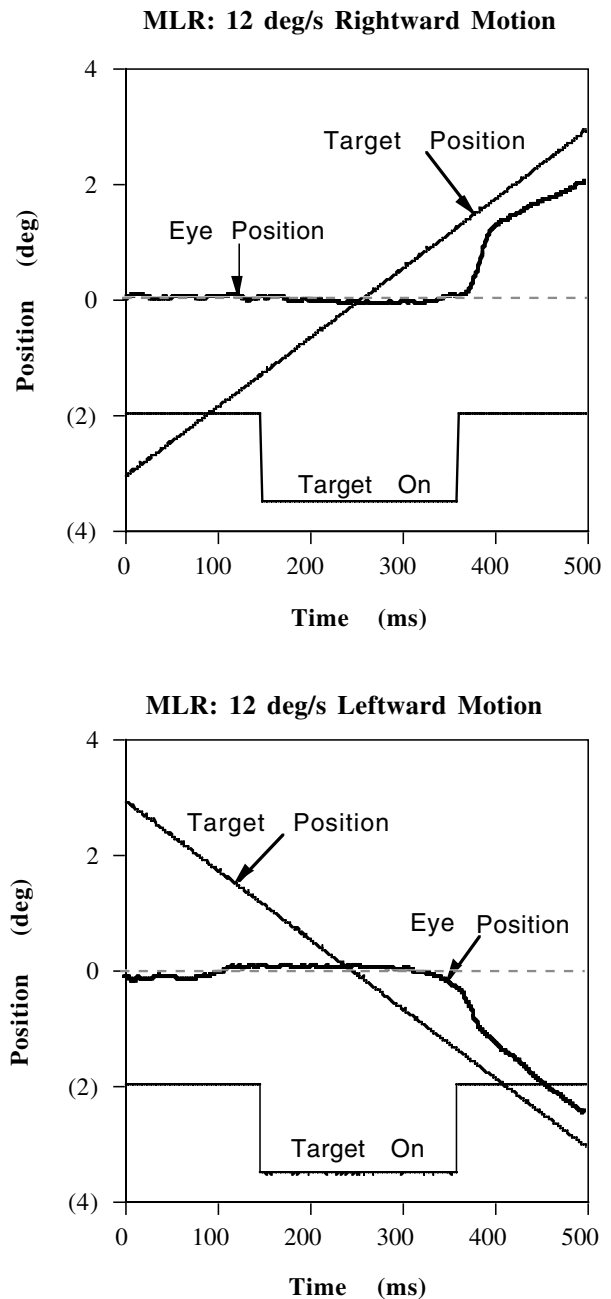


Fig. 2. Averaged eye position traces for observer MLR are shown for rightward (top panel) and leftward (bottom panel) target motion at 12 deg/s. The diagonal lines indicate the change in target position over time, after reflection from the galvanometer-driven mirrors. The 200-ms time interval during which the stereotargets were visible is represented by the downward deflection of the target trace. Each eye position trace represents the average eye position vs. time for 6 trials.

stimulus presentation or did not begin to track the motion at all until after the stimulus disappeared. Because the observers' eye velocity approximated the velocity of the stimulus only *after* the target disappeared, we conclude that the retinal image motion produced by the stereotargets in our experiments can be represented closely by the physical velocity of the stimulus motion.

3.3. Stereothresholds for equally detectable moving line stimuli

The log relative luminance thresholds of observers MLR and HEB to detect line stereotargets (20 arc-min gap) moving at velocities between 0 and 12 deg/s are summarized in the second and third columns of Table 1. Stereothresholds were re-measured through binocular neutral-density filters (last two columns of Table 1) that adjusted each moving target to either 0.9 (observer MLR) or 0.7 (observer HEB) log units above the observer's detection threshold. As shown in Fig. 3, the stereothresholds for equally detectable targets changed very similarly with velocity as the stereothresholds for targets of equal luminance, as measured in Experiment 1A.

3.4. Effect of stimulus duration on stereothresholds

Fig. 4 compares the average stereothresholds of two observers as a function of exposure duration, for a stationary stimulus and a stimulus moving at 8 deg/s. Consistent with the results shown above in Fig. 1, the stereothresholds are elevated substantially by stimulus motion. In agreement with previous reports for stationary targets, the stereothresholds are elevated also by a reduction in the presentation duration (Harwerth et al., 2003; Ogle & Weil, 1958; Patterson, 1990; Shortess & Krauskopf, 1961; Watt, 1987; Westheimer & Pettet, 1990). The thresholds for the stationary and moving stereotargets increase essentially in parallel as duration decreases, with no indication that the influence of stimulus motion is reduced at short compared to long durations. As considered in more detail below in the Section 4, these results are *not* consistent with the suggestion that the stereothreshold for a target in motion is limited by the time that the target is imaged at the most sensitive central region of the two foveas.

3.5. Effect of retinal eccentricity on stereothresholds

Table 2 presents the average stereothresholds for observers MLR and HEB for stationary stimuli, presented ± 0.6 and ± 1.2 deg laterally to the fovea. Separate thresholds are reported for targets with 5 and 20 arc-min vertical separations. For each separation only a single

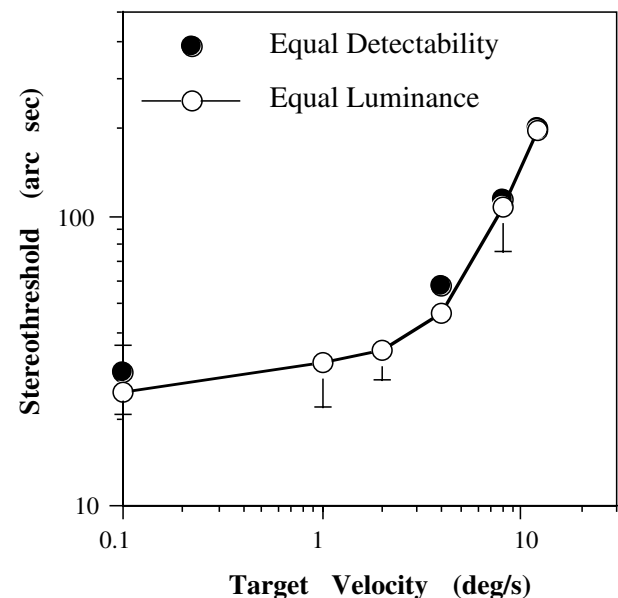


Fig. 3. Average stereothresholds, in arc-sec, for equally detectable line stimuli are plotted as a function of the stimulus velocity, in deg/s, for observers MLR and HEB (filled circles). For comparison, average stereothresholds for targets of equal luminance are plotted for the same two observers from Experiment 1A (unfilled circles). Error bars are ± 1 SEM, across observers. The stereothresholds for stationary targets are plotted at 0.1 deg/s on the x-axis.

threshold value is shown for each eccentricity of the target, as the data were obtained by interleaving presentations randomly to the left and the right of the previously visible fixation stimulus. Also included in Table 2 are the average stereothresholds for observers MLR and HEB during stimulus motion, from Experiment 1A. Because a moving target traverses a distance that is equal to its duration times its speed, note that the trajectory of a stereotarget that moves for 200 ms at 12 deg/s extends ± 1.2 deg on either side of the fovea.

Consistent with earlier studies (Fendick & Westheimer, 1983; Rawlings & Shipley, 1969; Westheimer & Truong, 1988), the average stereothresholds in Table 2 worsen with eccentricity for both 5 and 20 arc-min separations between the line targets. Nevertheless, the stereothresholds measured for extrafoveally presented stationary stimuli remain substantially better than those for moving stimuli, even under the highly conservative

Table 1

Log relative detection thresholds for line stereotargets and neutral-density (ND) filters used before both eyes to equate the detectability of targets at velocities between 0 and 12 deg/s

Target velocity (deg/s)	Log relative detection threshold		Neutral density filters to equate detectability	
	Observer MLR	Observer HEB	Observer MLR	Observer HEB
0	-1.8	-1.5	0.9	0.7
4	-1.5	-1.2	0.6	0.4
8	-1.2	-1.0	0.3	0.2
12	-0.9	-0.8	0.0	0.0

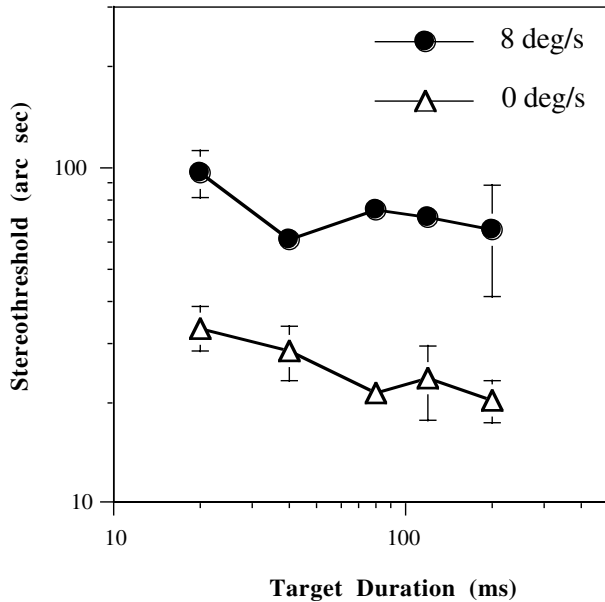


Fig. 4. Average stereothresholds in arc-sec are plotted for observers PCF and HEB as a function of exposure duration, in ms, for stationary line stimuli (unfilled triangles) and for stimuli that move at 8 deg/s (filled circles). The vertical separation between the stereotargets was 20 arc-min. Error bars represent ± 1 SEM, across observers.

Table 2
Average stereothresholds (± 1 SEM) for MLR and HEB, for stationary eccentric stimuli and for stimuli in motion

Eccentricity (deg)	Stereothreshold (arc-sec), lines with 5 arc-min gap	Stereothreshold (arc-sec), lines with 20 arc-min gap
<i>Stationary line targets</i>		
± 1.2	60.4 ± 24.3	52.3 ± 21.9
± 0.6	31.0 ± 15.6	36.4 ± 18.8
0.0	24.2 ± 6.2	24.7 ± 7.8
<i>Moving line targets</i>		
12	199.2 ± 71.1	198.3 ± 59.2
8	108.2 ± 43.7	108.4 ± 52.2
4	46.5 ± 14.7	46.3 ± 7.8

assumption that the threshold for a moving target is determined by the retinal eccentricity corresponding to the end point of its motion trajectory.

3.6. Intrinsic blur analysis of stereothresholds during image motion

In Section 1, we identified the production of motion blur as one possible explanation for the motion-related elevation of stereothresholds. In order to evaluate this explanation, we performed an intrinsic blur analysis on the stereothresholds obtained for our observers in

Experiment 1A. The assumption that underlies this analysis is that the stereothresholds for moving stimuli are limited by two independent sources of noise: (1) *intrinsic* noise or “blur” within the visual system and (2) *extrinsic* blur that results from motion of the target’s image across the retina.

Intrinsic blur is assumed to reflect a combination of the neural and non-neural blur in the visual system that interferes with the extraction of binocular disparity signals. Focusing inaccuracies and fixation errors are two factors that contribute to the non-neural component of intrinsic blur. Motion of the stimulus is assumed to produce additional *extrinsic* blur, the magnitude of which would be expected to increase directly in proportion to the velocity. Under the assumption that intrinsic and extrinsic blur are additive, we would expect stereothresholds (1) to be unaffected by image velocities for which the amount of extrinsic motion blur is relatively small, and (2) to increase systematically with velocity when the magnitude of extrinsic blur equals or exceeds the intrinsic blur. Both of these expectations can be derived from the formula:

$$\text{Threshold} = K(\sigma_{\text{ext}}^2 + \sigma_{\text{int}}^2)^{0.5} \quad (1)$$

Here, K is a constant and σ_{ext} and σ_{int} are the extrinsic and intrinsic blur of the visual system, respectively.

To estimate the magnitude of the intrinsic blur for the stereo tasks performed in Experiment 1, we used the following equation, which can be obtained by substituting the expression, $\text{Th}_0/\sigma_{\text{int}}$, for K in Equation (1) above and re-arranging:

$$\text{Threshold} = \text{Th}_0(1 + [s_{\text{ext}}/s_{\text{int}}]^2)^{0.5} \quad (2)$$

Here, Th_0 is the stereothreshold when the extrinsic blur is zero (i.e., when the stimulus velocity is 0 deg/s) and s_{ext} and s_{int} are estimates of the extrinsic and intrinsic blur of the visual system, respectively, as related to disparity processing. Similar equations were used previously to analyze various sources of intrinsic noise or blur in the visual system (Barlow, 1957; Levi & Klein, 1990; Watt & Hess, 1987; Watt & Morgan, 1984). Based on our assumption that the extrinsic blur, s_{ext} , increases linearly with the velocity of the stimulus (V), we substituted V for s_{ext} , when we used the above equation to fit our data. From the equation, it is apparent that in the condition when the extrinsic and intrinsic blur are equal, the stereothreshold will be $\text{SQRT}(2)$ larger than the value of Th_0 .

The best fits to the average stereothresholds from Experiment 1A are represented by the solid lines in Fig. 1. When the vertical separation between the stimulus lines was 5 arc-min, the mean estimated value of intrinsic blur for the stereo task is 2.16 deg/s. For stimuli that are separated by 20 arc-min, the mean estimated value of intrinsic blur for the stereo task is 2.71 deg/s.

These estimates of intrinsic blur for targets with 5 and 20 arc-min vertical separations do not differ significantly (paired $t_{df=4} = 1.95$; $p = 0.12$).

4. Discussion

The data from our experiments show that stereothresholds are essentially unaffected by stimulus velocities up to approximately 2 deg/s, but increase monotonically at higher velocities, up to at least 12 deg/s. These results are consistent with those of Westheimer and McKee (1978), who reported that conjugate retinal image motion up to 2.5 deg/s produced little or no elevation of the stereothreshold for line targets. By measuring our observers' eye movements, we demonstrated that the velocities of our stereotargets represent a close approximation to the velocities of retinal image motion.

In Section 1, we identified four factors associated with retinal image motion that could contribute to the elevation of stereothresholds: (1) a reduction in the detectability of the stimulus, (2) a reduction of the effective exposure duration of the stimulus, (3) imaging of the stimulus at eccentric locations on the retina, and (4) an attenuation of high spatial frequency information in the stimulus by motion blur. Although these four factors are related to one another, in the following paragraphs we will consider the separate impact of each factor in turn.

Previous investigations showed that stereothresholds are high when the stimulus luminance is low, but improve toward a low, asymptotic value as the luminance increases (Berry, Riggs, & Duncan, 1950; Mueller & Lloyd, 1948). For example, the results of Berry et al. (1950) indicate that foveal stereothresholds improve about fourfold as the luminance of the stimulus increases from 0.1 to approximately 15 cd/m², but that a further increase in luminance has little effect. Stereothresholds also improve as the contrast of the stimulus increases. For example, Legge and Gu (1989) found that stereothresholds for sine-wave targets vary approximately inversely with the square root of the Michelson contrast, for contrasts between 0.01 and 1. Although Cormack, Stevenson, and Schor (1991) reported that stereothresholds for random-dot targets depend only weakly on the level of *suprathreshold* contrast, they also showed that stereothresholds decline rapidly as the random dot stimuli approach their contrast threshold.

The luminance-detection threshold for the line targets used in our experiments increased approximately eightfold between 0 and 12 deg/s. Earlier studies reported similar or smaller changes in the detection thresholds for discrete targets that moved within this range of velocities (Burr, 1981; Chung et al., 1996; van den Brink & Bouman, 1957). However, the results of our Experiment 2 indicate that equating the detectability of the sta-

tionary and moving stereotargets reduces the velocity-dependent elevation of stereothresholds only by about 0.1 log units. These data indicate that, at least for the conditions of our experiment, the reduction of stimulus detectability during motion contributes little to the elevation of stereothresholds.

Neither can the degradation of stereothresholds by motion be accounted for by the limited duration, or "dwell time," of the moving target images within the central fovea, where stereothresholds are most acute. If stereothresholds were limited by the "dwell time" of the moving target images within the central fovea, then the thresholds for moving and stationary targets should be essentially identical for short durations, i.e., until the stimulus duration exceeds the foveal "dwell time" for moving targets. Further, the stereothresholds for moving and stationary targets should diverge at long durations, because no additional improvement should occur in the thresholds for moving stereotargets if their duration is extended beyond the foveal "dwell time." Contrary to these expectations, the stereothresholds for a stationary stimulus and a stimulus that moves at 8 deg/s change essentially in parallel as a function of the exposure duration (Fig. 4). These results indicate that the stereothreshold for a target in motion is not limited by the time it remains available for processing within a fixed central region of the fovea. Previously, Morgan, Watt, and McKee (1983) found essentially no elevation of the threshold for a Vernier target that moved at 3 deg/s if the duration of this target was reduced from 250 to 25 ms. When the duration of the moving stimulus was 25 ms, it is highly unlikely that the Vernier threshold was limited by the target's "dwell time" in the central fovea, as the *total* angular excursion was only ± 2.3 arc-min.

The motion of a stereotarget displaces the target's images from the central foveas which, by itself, would be expected to result in an increase in these thresholds (Fendick & Westheimer, 1983; Rawlings & Shipley, 1969; Westheimer & Truong, 1988). However, as shown by the results of our Experiment 4, the degradation of stereothresholds for eccentric stationary stimuli is small compared to the elevation of these thresholds during motion. Note that the comparisons that we made in Experiment 4 are very conservative, as they assume that stereothresholds for moving targets are determined by the eccentricity that is reached at the *endpoints* of the motion trajectory. Under the more plausible assumption that the "effective" eccentricity of a stereo stimulus in motion is the *average* of the retinal locations traversed (i.e., the "effective" eccentricity is approximately 0.6 deg for a 200-ms stimulus that moves across the fovea at 12 deg/s), then retinal eccentricity contributes even less to the elevation of stereothresholds during motion. Previous investigators concluded that retinal eccentricity does not account fully for the elevation of *Vernier*

thresholds during stimulus motion (Chung & Bedell, 1998; Morgan et al., 1983).

It remains possible that more than one of the three factors considered above contributes simultaneously to the degradation of stereothresholds during stimulus motion. As already noted, the factor of stimulus detectability can essentially be ruled out, as our observers' stereothresholds were almost the same before and after equating the detectability of the targets. The two remaining factors of "dwell time" within the central fovea and stimulus eccentricity are based on incompatible assumptions about the retinal site that fundamentally limits the stereothresholds for moving targets. In particular, the "dwell time" explanation assumes that the stereothresholds for moving targets are determined in the centralmost fovea, whereas the explanation based on stimulus eccentricity assumes that these stereothresholds are determined outside the fovea. Consequently, these two factors cannot be additive. We conclude that the three factors that we considered so far are not adequate, either individually or in combination, to account for the bulk of the increase in stereothresholds during motion.

Previously, Chung and her colleagues (Chung & Bedell, 1998, 2003; Chung et al., 1996) concluded that the degradation of both Vernier and letter acuity during motion is attributable primarily to a shift in the spatial mechanisms that mediate these tasks, i.e., from spatial mechanisms tuned to high spatial frequencies to mechanisms tuned to lower spatial frequencies. The basis for this shift in spatial scale is the systematic change in the spatio-temporal properties of the human visual system for stimuli that are moving vs. stationary (Kelly, 1979; Robson, 1966). In particular, visual mechanisms tuned to high spatial frequencies are more sensitive to stationary or slowly moving targets, whereas the mechanisms tuned to lower spatial frequencies are more sensitive to stimuli that move at moderate or high velocities. Earlier, Patterson (1990) proposed a similar account for the systematic changes in stereothresholds that he measured when grating targets were presented for different durations or modulated at different temporal frequencies. This explanation is compatible also with the results of Morgan and Castet (1995), who emphasized the temporal rather than the spatial resolution of the visual system to account for the limitations of stereothresholds that they observed for rapidly moving targets.

A closely related explanation for the elevation of stereothresholds during motion is the introduction of blur or smear in the moving stimulus (Burr & Morgan, 1997; Morgan & Benton, 1989), presumably as a consequence of visual persistence. Motion blur would be expected to elevate thresholds because, like optical blur, it attenuates the high-spatial-frequency information in the stimulus that is necessary to yield optimal spatial thresholds. Larger spatial filters would be more sensitive to the disparity information that remains in the blurred

stimulus than the smaller spatial filters that mediate optimal stereothresholds (Glennester & Parker, 1997; Julesz & Miller, 1975; Prince, Eagle, & Rogers, 1998).

As discussed in Section 3.6, above, the threshold for stationary stereotargets is assumed to be limited by the *intrinsic* noise and blur within the visual system that influences disparity detection. The values of intrinsic blur that we estimated from the stereothresholds in our study are specified in terms of the stimulus velocity, in deg/s. However, these values can be converted to spatial extents of blur if the duration of visual persistence is known. We estimated this duration in a separate experiment by measuring the stereothresholds for horizontally moving line targets that were separated *horizontally* instead of vertically (Ramamurthy, Bedell, & Patel, 2002). Like the stereothresholds for vertically separated targets shown in Fig. 1, the stereothresholds for horizontally separated targets also increase systematically with the velocity of the stimulus. In addition, for each velocity tested the stereothresholds for horizontally separated targets increase dramatically when the separation becomes smaller than some critical value. We propose that this dramatic increase in the stereothreshold for a pair of horizontally separated targets occurs when motion blur from the leading target significantly overlaps the trailing target. Previously, Morgan and Benton (1989) offered a similar explanation for the influence of stimulus motion on spatial-interval discrimination. If this explanation is correct, then we can estimate the duration of visual persistence for each velocity of motion from the horizontal separation at which the stereothreshold begins to rise. Our results show that this critical horizontal separation between the stereotargets increases with the velocity of motion, but for each velocity tested the critical separation corresponds to a duration of approximately 80 ms.

Averaged across the two vertical target separations that we used in Experiment 1A, the estimate of intrinsic blur that we calculated from our observers' stereothresholds is 2.44 deg/s. Using an estimate of 80 ms for the duration of visual persistence, this value of intrinsic blur corresponds to a spatial extent of 11.7 arc-min. Note that this value represents the *full* extent of the extrinsic motion blur that has the same effect on the stereothreshold as the intrinsic blur within the visual system.

Previous studies determined the influence of extrinsic Gaussian blur on the stereothresholds for *stationary* targets (Stigmar, 1971; Wilcox, Elder, & Hess, 2000). For example, Stigmar (1971) found that the stereothresholds for stationary line targets remain unaffected up to a blur half-width between 3.7 and 7.6 arc-min. Because the half-width of a Gaussian corresponds to 1.35 standard deviations (SDs), these data imply that the SD of the intrinsic blur that limits the extraction of disparity signals is equal to approximately 4.2 arc-min. Although the spatial distributions of Gaussian blur and motion

blur are distinctly different, we can nevertheless approximate the influence of motion blur on stereothresholds by estimating the SD of this blur distribution. Using the approximation that the range of an arbitrary distribution corresponds to roughly 4 SDs, motion blur with a total spatial extent of 11.7 arc-min is estimated to have a SD on the order of 2.9 arc-min. This value is in reasonable agreement with the estimate of 4.2 arc-min obtained from Stigmar's study. Our estimate of 2.9 arc-min is also consistent with findings that the stereothresholds for spatially narrow-band targets improve only up to a spatial frequency between 2.5 and 4 c/deg (Hess, Liu, & Wang, 2002; Legge & Gu, 1989; Schor & Wood, 1983; Siderov & Harwerth, 1995), at which frequencies the SD of a single spatial period is on the order of 3.75 to 6 arc-min. The similarity between our estimate of intrinsic blur and those derived from previous studies that used stationary stereotargets is consistent with the conclusion that stereothresholds for laterally moving line targets are elevated primarily as a result of motion blur.

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