Stereomotion suppression and the perception of speed: Accuracy and precision as a function of 3D trajectory

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The precision and accuracy of speed discrimination performance for stereomotion stimuli were assessed for several receding 3D trajectories confined to the horizontal meridian. It has previously been demonstrated in a variety of tasks that *detection* thresholds are substantially higher when subjects observe a stereomotion stimulus than when simply viewing one of its component monocular half-images—a phenomenon known as stereomotion suppression (C. W. Tyler, 1971). Using monocularly visible motion in depth targets, we found mean *speed discrimination* thresholds to be higher for stereomotion, compared with monocular lateral speed discrimination thresholds for equivalent stimuli, demonstrating a disadvantage for binocular viewing in the case of speed discrimination as well. Furthermore, speed discrimination thresholds for motion in depth were not systematically affected by trajectory angle; hence, the disadvantage of binocular viewing persists even when there are concurrent changes in binocular visual direction. Lastly, there was a tendency for oblique trajectories of stereomotion to be perceived as faster than equally rapid motion receding directly away from the subject along the midline. Our data, in addition to earlier stereomotion suppression observations, are consistent with a stereomotion system that takes a noisy, weighted difference of the stimulus velocities in the two eyes to compute motion in depth.

Keywords: binocular vision, 3D motion, motion in depth, interocular velocity difference, RDS

Introduction

It is no coincidence that, to our knowledge, evolution has not produced a single vertebrate species[1] with only one eye. Binocular vision affords humans and many other animals several significant advantages. For those whose visual fields overlap only minimally (e.g., rabbits and horses), having two eyes principally offers the advantage of extended angular coverage of the surrounding environment. For those animals whose visual fields do overlap substantially (e.g., cats and primates), through binocular summation we are effectively afforded two independent opportunities to see a stimulus in a given location that might otherwise be only marginally perceptible (see Blake, Sloane, & Fox, 1981, for a review). In addition, the binocular field of view allows the recovery of depth information through the small positional differences between each monocular image (binocular disparities). Binocular vision also facilitates the perception of objects' changing depth through stereomotion[2] cues.

There are, however, certain circumstances under which the use of two eyes proves detrimental to the performance of a visual task, as demonstrated in the phenomenon of stereomotion suppression (also referred to as stereomovement suppression). This involves the detection of the motion in depth of a stimulus undergoing a change of relative binocular disparity, with the two monocular images having unequal (signed) velocities (i.e., an interocular velocity difference). When the amplitude of motion in depth is set just below detection threshold, the monocular lateral motion becomes trivially detectable if the subject closes one eye (Tyler, 1971). Although binocular vision allows us to perceive motion in depth for relatively large amplitudes of motion, it appears to hinder us in the more general task of motion detection.

A similar phenomenon has been reported by Harris and colleagues (Harris, McKee, & Watamaniuk, 1998; Harris & Rushton, 2003; and Sumnall & Harris, 2000). Using a visual search paradigm, these authors showed that the detection of motion for a single dot translating laterally was possible among a larger number of stationary noise dots compared with the detection of the stereomotion of that dot moving in depth (when equated for monocular stimulus speed). This form of suppression occurs principally when stereomotion stimuli feature equal and opposite velocities in each monocular image, leading to a change of binocular disparity over time and a trajectory of motion that approaches or recedes from the subject directly along the midline. When the monocular speeds differ, an obliquely directed trajectory is produced (see Figure 1). Under these circumstances, the dot is almost equally detectable when moving (obliquely) in depth or when moving purely laterally in this visual search context, suggesting that different mechanisms may be at work when searching for direct versus oblique trajectories in noise (Harris et al., 1998;

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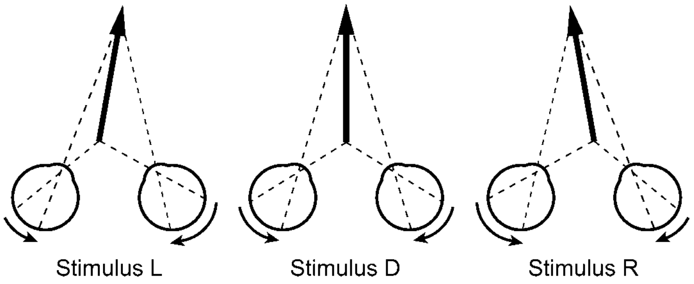

Figure 1. Three-dimensional trajectory and its relationship to monocular velocities. Oblique stimuli (L and R) feature a ratio of monocular velocities of −1:2 (or −2:1). The stimulus recedes from the eye with the slower motion. Stimulus D moves directly away from the subject along the midline and features identical monocular speeds. Figure not drawn to scale. In the experiment reported here, trajectory angles D and L (or R) differed by only 0.25 deg.

Harris & Sumnall, 2000; McKee, Watamaniuk, Harris, Smallman, & Taylor, 1997). However, in the original Tyler (1971) detection study, such oblique stimuli still suffered a substantial degree of stereomotion suppression and were only marginally more detectable than direct stimuli, as confirmed by Beverley and Regan (1975). So, unlike the visual search phenomenon, the original stereomotion suppression phenomenon for conventional detection is largely independent of trajectory angle, suggesting that the same mechanism is at work when detecting either direct or oblique trajectories.

An additional difference between the study by Tyler (1971) and those by Harris et al. is worth noting. Tyler compared monocular lateral motion thresholds and stereomotion thresholds. However, Harris et al. compared binocular lateral motion thresholds and stereomotion thresholds. The latter studies therefore allow the opportunity for binocular summation in the lateral motion condition (receiving identical monocular stimuli) that does not apply either to the stereomotion case (receiving differing monocular stimuli) or to the monocular case (receiving only a single instance of image motion). Conversely, in all of these earlier studies, it is possible that the stereomotion suppression could be a form of nonspecific binocular masking where two incongruent monocular motion signals interfere with each other, independent of any fused stereomotion signal.

In this study, we examined the phenomenon of stereomotion suppression to see whether it can be extended to the case of speed perception for both direct and oblique trajectories and whether the suppression effect is specific to stereomotion stimuli. We addressed this question by measuring just-noticeable differences (JNDs) and points of subjective equality (PSEs) for speed discrimination of motion in depth and monocular lateral motion.

To anticipate, we found evidence of stereomotion suppression for speed perception for all trajectory conditions. This was shown in the form of elevated speed JNDs for stereomotion stimuli compared with those found for matched monocular stimuli, whether the non-viewing eye was simply patched or experienced equivalent visual noise. This finding is consistent with a stereomotion mechanism that computes differences in monocular image velocities in a manner that adds substantial noise. We also found shifted PSEs showing that oblique motion in depth is generally perceived faster than direct motion of the same speed.

Methods

Stereomotion display

Stereoscopic stimuli were created by alternately displaying the monocular half-images on an Image Systems 240-Hz monitor (120 Hz per eye) using P46 fast phosphor, driven by a Matrox G400 video card. These were viewed through high-speed (switching time 50 μs), high-transmittance (30%), ferroelectric shutter glasses also running at 240 Hz that were synchronized to the vertical refresh of the monitor. Pilot tests confirmed that at the speed, luminance, and contrast levels used, there was no perceptible flicker or bleed-through of the unwanted monocular image, and motion appeared smooth and continuously linear. Stimuli with simulated direct trajectories appeared to move directly away from the observer at constant speed as intended, indicating that the extremely brief interocular onset asynchrony (4 ms) caused no perceptible Pulfrich-like phenomenon (see Ross, 1974; Tyler, 1971).

The general stimulus arrangement is depicted in Figure 2. The visible area of the screen subtended 7.3 deg × 6.2 deg. With a resolution of 700 × 640 pixels, this resulted in an effective resolution of 96 × 103 pixels per degree at the viewing distance of 2.5 m. The mean luminance of the screen was 12.5 cd/m^2, and all tests took place in a room essentially devoid of extraneous light. Responses were recorded using a two-button mouse. Subjects wore their usual optical corrections for all experimental sessions.

Identical random dot background patterns comprised 50% density bright/dark dots at a Michelson contrast of 20%, each subtending 2.5 × 3.7 arcmin (4 pixels square) in each half-image. The background pattern in each eye comprised two 7.3 deg × 0.66 deg strips centered 1 deg above and below a small, bright, central fixation ring. These features were located binocularly in the fixation plane, being in identical positions for each half-image. Moving stimuli were random dot stereogram patterns (same size, density, and contrast as the background), which filled the vertical gap between the background strips. All patterns extended horizontally to the edges of the image to minimize any effects of stereomotion signals arising from binocularly unmatched regions (e.g., Brooks & Gillam, 2005) or stereo from motion-defined boundaries (e.g., Lee, 1970).

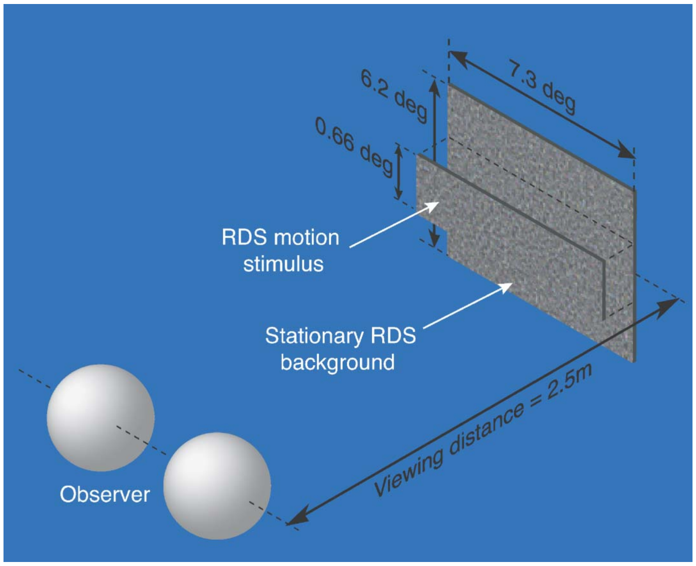

Figure 2. Stimulus presentation arrangement. Figure not to scale. See text for details.

A relative disparity pedestal of zero was used; that is, moving stimuli passed through the plane of the background dots at the midpoint of their motion. All retinal half-images translated nasally (i.e., in opposite directions in each half-image) with monocular half-image speeds in each stimulus presentation either equal (direct stimuli) or featuring a velocity ratio of −2:1 (oblique stimuli). This simulated a real-world trajectory angle inclined at ±0.25 deg with respect to the midline (see Figure 1). The real-world trajectory angle, β, can be calculated using Equation 1, given left and right monocular (signed) image velocities, ω_{L} and ω_{R}, respectively, the interpupillary distance, I, and the viewing distance, d (Regan, 1993).

$$\beta = \tan^{-1}\left[\frac{I(\omega_{\mathrm{R}}+\omega_{\mathrm{L}})}{2d(\omega_{\mathrm{R}}-\omega_{\mathrm{L}})}\right]. \tag{1}$$

The component of motion in depth velocity parallel to the midline is given by Equation 2 (Regan, 1993).

$$\mathbf{v}_z = \frac{d^2(\omega_{\mathrm{R}}-\omega_{\mathrm{L}})}{I}. \tag{2}$$

The difference between $\mathbf{v}_z$ and the total motion in depth velocity, or $\mathbf{v}$, is negligible (<0.001%) for the small trajectory angle used here. The amplitude of the velocity difference between the monocular motions in the two eyes (i.e., $\omega_{\mathrm{R}} - \omega_{\mathrm{L}}$, a direct correlate of $\mathbf{v}_z$) for the standard stimulus was set at 0.622 deg/s (equivalent to a $\mathbf{v}_z$ value of 1.04 m/s), regardless of whether it was direct (D) or oblique (L and R). Nine possible values of test stimulus speed were used within interleaved one-up–one-down adaptive staircases. For test stimulus D, possible speeds of retinal motion experienced simultaneously by each eye ranged between 0.178 deg/s and 0.466 deg/s toward the nasal side, which correspond to actual $\mathbf{v}_z$ values between 0.60 and 1.56 m/s. For test stimulus L, speeds in the left/right eyes ranged between 0.124/0.249 and 0.355/0.710, which correspond to real-world $\mathbf{v}_z$ values between 0.63 and 1.79 m/s. These speeds were presented to the opposite eyes for test stimulus R. All stimuli were visible for 600 ms, with an inter-stimulus interval of 600 ms. It has previously been demonstrated that subjects do not use the cue of total displacement to make stereomotion speed judgements under our stimulus conditions but respond to the speed per se (Brooks & Stone, 2004; see also Brooks, 2002a; Brooks & Mather, 2000; Harris & Watamaniuk, 1995; Portfors-Yeomans & Regan, 1986).

Four subjects (L.S., B.B., C.N., and L.L.) contributed data in all conditions, whereas two others (A.K. and S.S.) contributed data for the stereomotion conditions only. Each subject had normal or corrected-to-normal vision and passed preliminary screening tests for stereo deficiencies involving correctly reporting the sign of static disparity displays and the direction of motion of stereomotion displays over a range of disparities and speeds. Except for one subject (the author L.S.), all subjects were naive as to the purpose of the experiment but were experienced at performing psychophysical tasks before beginning practice sessions.

Stereomotion speed discrimination

We used a yes–no paradigm, sequentially presenting standard and test intervals in a randomized order, following which the subject indicated whether the first or second stimulus appeared to travel more rapidly, regardless of its specific trajectory. JNDs and PSEs for stereomotion speed discrimination were computed for each of five relative trajectory conditions. To avoid the possibility that subjects could perform the task on the basis of the rate of lateral motion, each stimulus pair featured a directly receding stimulus. Such trajectories involve no lateral translation, and hence, responding on the basis of this inappropriate cue would cause the staircase to fail to converge and prevent a JND from being established. Each condition involved one stimulus with trajectory D (either test or standard) and another stimulus with trajectory D, L, or R. As such, the five possible standard:test combinations were D:D, D:L, D:R, L:D, and R:D. Subjects completed three to five sessions of testing, with each session consisting of four blocks, and each block lasting approximately 12 minutes. Each block contained five randomly interleaved staircases (with each terminating after 12 reversals), one for each of the five trajectory conditions associated with the five trajectory pairs above.

Data were analyzed for each subject individually. Responses from trials in a given condition were combined across the four blocks, and a cumulative Gaussian curve was fitted to the data by probit analysis (Finney, 1971). Both the midpoint (PSE) and the semi-interquartile difference (JND) of the underlying Gaussian distribution were free parameters in the curve fitting routine. PSEs and JNDs were averaged across sessions, and their associated standard errors were calculated. Statistical significance was assessed using ANOVAs, with specific comparisons performed using planned linear contrasts.

Monocular/lateral speed discrimination

Methodological details of our monocular/lateral speed discrimination task differ from those of our stereomotion task only in the following respects. One monocular half-image from the motion in depth stimuli described above was presented to the dominant eye (in all four of our subjects, it happened to be the right eye). The other eye received no coherent motion signal. For two subjects (B.B. and L.S.), this involved simply patching the non-dominant (left) eye, whereas for the other two (C.N. and L.L.), a dynamic noise masking stimulus was presented to the left eye. This manipulation was performed to establish whether any observed suppression is specifically linked to a stereomotion percept or whether the effect persists during equivalent binocular stimulation devoid of any associated stereomotion percept. If stereomotion suppression were due to some kind of nonspecific masking of one monocular motion signal by the other eye's incongruent signal, then no suppression effect would be evident when one eye views dynamic noise, since monocular and binocular thresholds would both be equally adversely affected. In an additional control, subject L.S. also performed the monocular speed discrimination task using the monocular half-image corresponding to the eye featuring the faster monocular motion and the noise mask in the other. It should be noted that, if anything, the use of the noise mask would tend to increase thresholds for monocular speed discrimination, and thus decrease the chances of finding evidence for stereomotion suppression.

The mask was a series of independent random dot images having the same contrast, dot size, and density as the monocular halves of the stereo image, changing at a rate of 120 Hz. Subjects perceived clear lateral motion with the masked monocular motion stimuli, despite the presence of the dynamic mask. Either three (subject C.N.) or six (L.S., B.B. and L.L.) sessions were conducted, during which the data acquisition and analysis procedures were identical to those described above for stereomotion speed discrimination.

Results

Precision

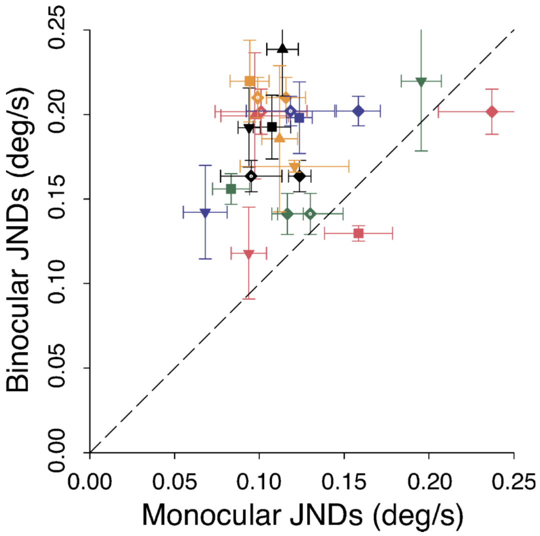

Figure 3. Speed discrimination JNDs for monocular motion (*x*-axis) plotted in terms of the equivalent stereomotion speed, against those for stereomotion (*y*-axis). Symbols ◇, □, ▽, △, and ⟐ represent subjects L.S. (patch), B.B. (patch), C.N. (noise) L.L. (noise), and L.S. (faster motion; noise), respectively. Relative trajectory conditions DD, DL, DR, LD, and RD are represented by points colored black, green, red, blue, and orange, respectively. Error bars represent ±1 *SEM*. Two outliers—points for observer L.L., high above the line—were omitted for clarity (DL: 0.242, 0.417; LD: 0.092, 0.327).

To compare motion in depth speed discrimination with monocular lateral speed discrimination, we tested four observers under matched monocular and stereomotion conditions. In line with previous stereomotion suppression studies, data for monocular speed discrimination were treated in the same way as stereomotion data, that is, as if the omitted monocular motion signal was present. This allows us to express JNDs for both conditions in degrees of disparity per second and to directly compare the two. If thresholds are lower in monocular conditions, this constitutes evidence of stereomotion suppression.

Across all trajectory conditions, monocular speed discrimination was more precise than the corresponding stereomotion speed discrimination. Figure 3 plots the binocular JNDs as a function of the corresponding monocular JNDs. Of the 25 data points in Figure 3, 23 were above the line of slope 1 and intercept 0 (dashed line) and only 2 were below the line, yet not significantly so. For all observers, the difference between the monocular and binocular JNDs was highly significant in individual 2 × 5 ANOVAs, L.S.: $F(1,4) = 22.768$, $p = .009$; B.B.: $F(1,4) = 19.929$, $p = .011$; C.N.: $F(1,2) = 58.346$, $p = .017$; L.L.: $F(1,4) = 25.862$, $p = .007$, regardless of whether they had experienced an eye patch or the dynamic noise mask with their non-dominant eye or whether they had viewed the faster half-image or the right half-image. On average, monocular JNDs were lower by a factor of 1.8 ± 0.1 (*SEM* across observers and trajectories). The mean monocular

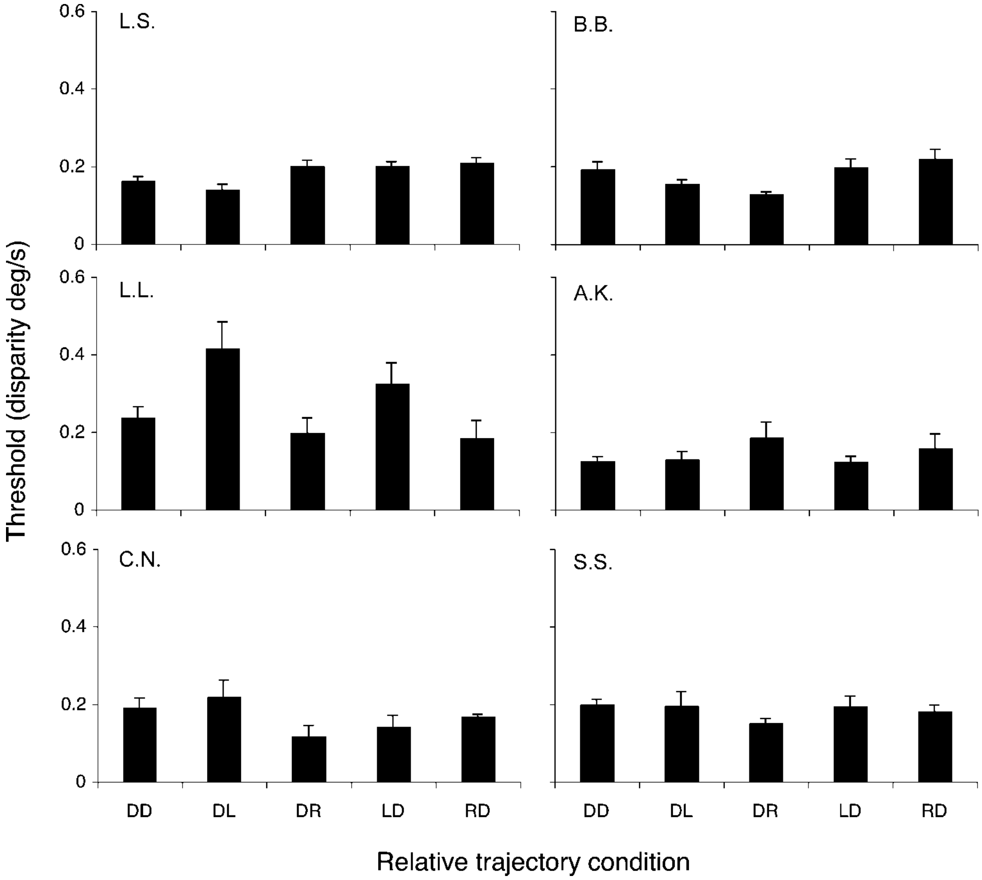

Figure 4. Stereomotion speed discrimination JNDs. The histogram bars represent stereomotion thresholds for all six observers under all five trajectory conditions. These show no systematic pattern of variation. Error bars represent ±1 *SEM*.

speed JND across subjects and relative trajectory condition was 0.12 ± 0.01 deg/s (*SEM* across four observers). The mean stereomotion JND across relative trajectory condition was 0.20 ± 0.02 deg/s (*SEM* across the same four observers). These findings demonstrate robust stereomotion suppression for speed discrimination.

We saw no systematic variation in stereomotion JND with relative trajectory angle. To increase our statistical power with respect to this negative result, we tested two additional subjects (A.K. and S.S.) in our stereomotion speed discrimination task. Despite this effort, there was no significant effect of trajectory angle on JND across our six observers, $F(1,5) < 1$, $p > .05$. Furthermore, individual comparisons revealed that the JNDs for oblique motion were not significantly different from that of condition DD for five of the six observers (ANOVA with linear contrasts; DD vs. average of all other conditions: $p > .05$). However, for one subject (L.S.), thresholds were significantly higher for oblique motion, $F(1,4) = 9.795$, $p = .035$. Stereomotion speed discrimination thresholds are plotted as histograms in Figure 4 for all six subjects and all five trajectory conditions. We conclude that there is little effect of trajectory on the JND of stereomotion speed discrimination.

Accuracy

Unlike the JND data, the PSE data showed a more systematic effect of trajectory, albeit with some intersubject variability. The PSEs for RDS stereomotion stimuli are plotted in Figure 5. For all subjects, speed comparisons between stimulus pairs with different trajectories were not made veridically. Although PSEs varied, at least to some extent, as a function of trajectory angle, all subjects achieved a reliable and somewhat accurate speed match between direct stimuli (where the average of monocular half-image velocities was zero) and oblique stimuli (where the average of monocular velocities was 0.1 deg/s). This finding confirms that no subject attempted to make his or her judgements on the basis of an average of the monocular velocity signals.

The nonveridical matches revealed a tendency for oblique trajectories to be perceived as faster than equally fast directly receding motion. Across observers, the speed of oblique trajectories was overestimated in 20 of 24 cases (two-tailed binomial test, $z = 3.266$, $p = .0011$). To assess the significance of this effect for each individual subject, the JND data were transformed to represent differences from the veridical speed, where overestimations in oblique

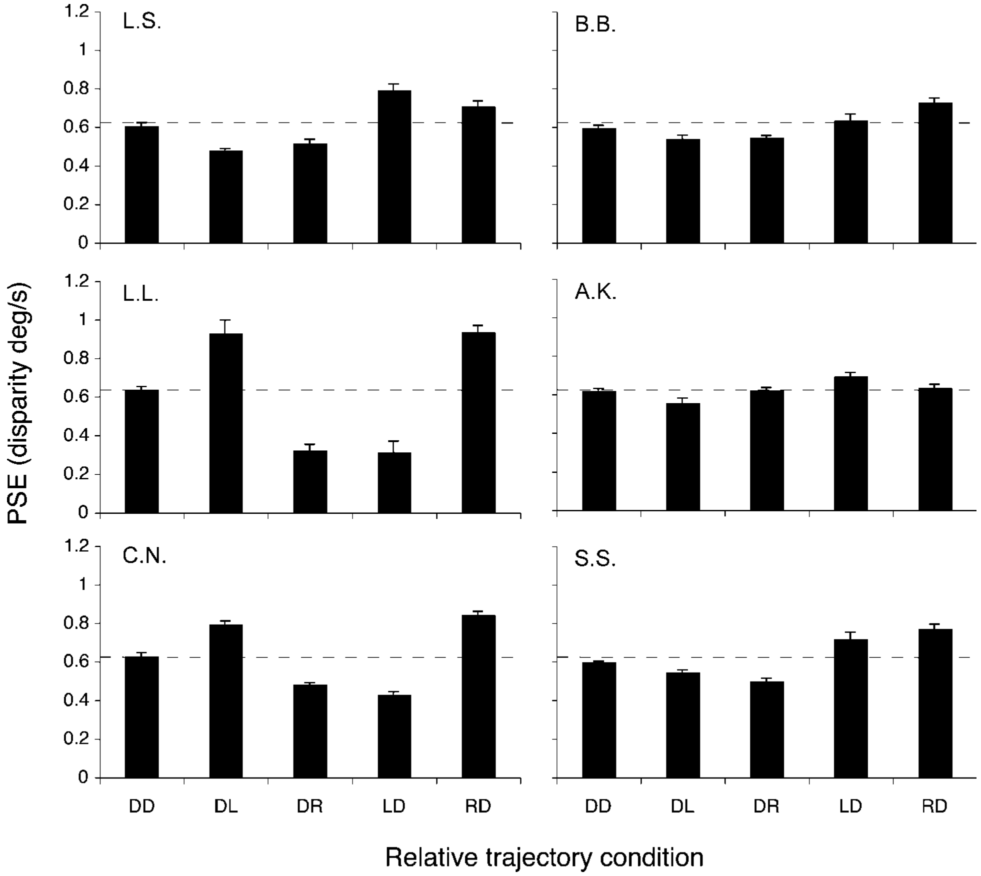

Figure 5. Stereomotion speed discrimination PSEs. Data are shown for all six observers in five relative trajectory conditions (histogram bars). Error bars represent ±1 *SEM*. A percept of faster motion for oblique stimuli is represented by values below 0.622 deg/s for conditions DL and DR and by values above 0.622 for LD and RD. Although four subjects (L.S., B.B., A.K., and S.S.) show this pattern clearly, this is true only for two conditions each for two subjects (C.N. and L.L.).

speed were coded as positive and underestimations were coded as negative. For four observers, the speed of oblique trajectories was significantly overestimated relative to that of direct stimuli in 1 × 4 ANOVAs, L.S.: $F(1,4) = 119.959$, $p < .0005$; B.B.: $F(1,4) = 13.888$, $p = .020$; A.K.: $F(1,4) = 8.894$, $p = .041$; S.S.: $F(1,4) = 270.948$, $p < .0005$. However, in the other two subjects, oblique stimuli were only perceived as faster in half of the conditions, and hence, the general pattern of overestimation was not significant for these individuals.

Discussion

Tyler first reported the phenomenon of stereomotion suppression in 1971. Using stimuli whose monocular images oscillated in counterphase, simulating sinusoidal motion in depth, he showed that when the amplitude of stereomotion in the binocular image was set just below detection threshold, motion can still be easily detected in either monocular half-image when viewed in isolation. The experiment reported here extends the phenomenon of stereomotion suppression from the domain of threshold motion detection to the domain of suprathreshold speed perception. For directly or obliquely receding stimuli, speed discrimination JNDs were significantly higher for motion in depth than for either monocular lateral motion component alone, showing that in this task, two eyes are once again worse than one. Simply put, just as Tyler (1971) demonstrated that a barely detectable degree of stereomotion becomes easily detectable as lateral motion with one eye closed, we have demonstrated that, in general, a barely detectable difference in stereomotion speed becomes an easily detectable difference in lateral speed when using only one eye. Furthermore, the fact that all observers tested on lateral speed discrimination with a monocular noise mask showed significant stereomotion suppression indicates that this effect is not mediated by nonspecific binocular interactions but rather by a mechanism that processes stereomotion per se.

In only 2 of 25 cases in Figure 3 did data fall below the line of unity, suggesting that some stereomotion thresholds were lower than associated monocular thresholds. These two examples come from subjects L.S. (black symbols) and B.B. (green symbols) for condition DR (triangles). This apparent inconsistency in the stereomotion suppression effect can be explained by considering the monocular motion stimulus parameters used in these conditions. Since different trajectories involve different monocular velocities, the omission of the right monocular half-image will, in some conditions, leave the faster half image remaining, and sometimes the slower. When viewing condition DR with the right eye only, a medium speed standard must be discriminated in speed from the slower of the two test half-images. It is likely that this was the cause for the absence of observable stereomotion suppression in these two cases, as it is known that for very low speeds, lateral motion JNDs become very large (McKee, 1981; Thompson, 1983). To see if these two points were indeed due to low speed and not to the specific trajectory condition, one subject (L.S.) was re-run on the monocular speed discrimination task in which he was presented with the faster half-image in one eye and a noise mask in the other (see Figure 3, gray symbols). In that case, all points lie substantially above the line of unity showing stereomotion suppression for all trajectory conditions. From these data and from first principles, we infer that, under oblique conditions where the motion in one monocular half-image becomes sufficiently slow (i.e., in the extreme case, motion aimed directly toward or away from one eye generates a retinal speed of zero in that eye), closing the eye that views the faster half-image cannot reveal stereomotion suppression for speed discrimination (or motion detection for that matter).

Stereomotion suppression and the interocular velocity difference

The difference between the velocities in the two monocular images for any object moving in depth can aid the perception of trajectory angle (see Equation 1) and velocity (Equation 2) in 3D due to a stereomotion cue known as the interocular velocity difference. The crucial stage of this computation involves the subtraction of left and right monocular image velocity signals. The interocular velocity difference cue has received support from a number of experimental studies on the detection of motion in depth (Allison, Howard, & Howard, 1998; Fernandez & Farell, 2005; Howard, Allison, & Howard, 1998; Shioiri, Saisho, & Yaguchi, 2000). For suprathreshold situations, it has been shown that the IOVD cue greatly influences the accuracy (Brooks, 2001, 2002a, 2002b; Brooks & Mather, 2000) and precision (Brooks & Stone, 2004; Harris & Watamaniuk, 1995) of stereomotion perception and is a strong candidate to explain our findings. Although the phenomenon of stereomotion suppression for speed discrimination might at first seem to argue against the use of this cue for stereomotion speed perception, this conclusion would be premature. As it is likely that the neural process of subtracting two monocular velocities would introduce additional noise, there is good reason for us to expect that JNDs produced by any interocular velocity difference system would indeed be higher than those for the perception of speed for monocular motion.

Visual search studies, however, have led some authors to suggest that the two monocular velocities are not subtracted but are instead averaged (Harris et al., 1998; Harris & Rushton, 2003; Sumnall & Harris, 2000; Westheimer, 1990). Harris et al. (1998) argue that this explanation "could account for Tyler's classic finding." In the averaging scheme, the equal and opposite monocular speeds featured in directly approaching or receding stereomotion cancel each other out. This, it is argued, produces inferior performance for binocular compared to monocular conditions, since the average becomes zero—the same as for an entirely motionless stimulus. However, when monocular speeds differ, such as for trajectories directed obliquely in depth, their average is non-zero, allowing easier detection. This theory is able to explain why stereomotion suppression is less apparent for oblique motion in depth in their visual search task, although it cannot explain why Tyler (1971) found clear stereomotion suppression in his detection task even with oblique trajectories.

More recently, Brooks and Stone (2004) have shown that velocity averaging cannot account for the estimation of stereomotion speed. Instead, they postulate that an interocular velocity difference mechanism features a noisy binocular combination stage where monocular velocities are subtracted from each other. This theory predicts that stereomotion suppression should be equally evident across all trajectories, which is what we observed.

An explanation of stereomotion suppression based on velocity averaging, however, makes predictions quite different from those observed. Firstly, according to this theory, thresholds for the non-DD conditions should be lower due to the pairing of a direct stimulus with one whose velocity average is non-zero and, hence, whose speed is calculable on the basis of this statistic. This would lead to weaker stereomotion suppression effects for conditions DL, DR, LD, and RD compared with that for DD. This pattern was not observed in our JND data. However, it could be argued that a cognitive difficulty in comparing the speeds of stimuli with different trajectories raises the threshold in the four oblique conditions and masks any difference between the direct and oblique conditions that would otherwise be apparent. We believe that this is unlikely, since the difference between the trajectories of our stimuli was only 0.25°. Furthermore, it is important to remember that the average of the two monocular image velocities—the rate of change of binocular visual direction (BVD)—was always zero for all direct trajectories, since BVD was unchanging regardless of the amplitude of $\mathbf{v}_z$. Given that all trials featured at least one direct trajectory, use of the rate of change of BVD alone would therefore have caused the psychophysical staircases to fail to converge. This was never observed.

In the visual search experiments, stereomotion suppression was reduced or was nonexistent for oblique stimuli. It is possible that oblique stimuli were detected with ease because of their lateral motion. In their search task, the target is the only dot with the motion in depth, but it is also the only dot featuring continuous lateral motion (or a rate of change of BVD). It may well be the case that under these circumstances, performance is indeed mediated by a process, averaging the two monocular velocities as the velocity of lateral movement is computed. We propose that, although the motion of objects with oblique trajectories may, in some conditions, be better *detected* by the lateral component of their motion (the velocity average computation), our 3D speed discrimination is a task better suited to revealing the details of the binocular motion in depth mechanism *per se* as it requires that the z component of motion be taken into account. Our data here and previous data (Brooks & Stone, 2004) suggest that a 3D motion mechanism, involving additional noise above and beyond that of 2D monocular motion processing, generates stereomotion suppression, independent of the presence or absence of a change in BVD.

Anisotropies in stereomotion perception

Perception of stereomotion speed was not perfectly veridical, with subjects showing a general tendency to perceive oblique trajectories as faster than direct stimuli. Thus, it is clear that motion in depth speed is not calculated by simply reading out the interocular velocity difference formula given in Equation 2.

Here, subjects were asked to respond on the basis of total 3D velocity, $\mathbf{v}$, but we set the same $\mathbf{v}_z$ for our standard stimuli regardless of trajectory. This was not considered a problem because of the small value of β (the trajectory angle relative to the median plane) and, hence, the negligibly small physical difference (<0.001%) between $\mathbf{v}$ and $\mathbf{v}_z$ for our oblique stimuli. However, although it was not explicitly measured in this experiment, subjects reported an overestimated stimulus trajectory angle (i.e., they perceived the angle to be larger than 0.25 deg for conditions L and R), informally confirming the results of Harris and Dean (2003). It may be that the variation in speed PSEs with relative trajectory condition is related to this misperception. For a fixed $\mathbf{v}_z$, a larger perceived value of trajectory angle, β, is consistent with an increase in the perceived lateral velocity of the stimulus, $\mathbf{v}_x$, and, hence, with an increase in the perceived total velocity, $\mathbf{v}$, since $\mathbf{v} = \mathbf{v}_x + \mathbf{v}_z$. If perceived total velocity were on the basis both components (a veridically perceived $\mathbf{v}_z$ and an exaggerated $\mathbf{v}_x$), an overestimation of trajectory angle would accompany a larger difference between perceived $\mathbf{v}$ and perceived $\mathbf{v}_z$, and hence, the shift in PSEs indicating that oblique motion in depth appears faster. (The same would be true if $\mathbf{v}_z$ were underestimated and if $\mathbf{v}_x$ was perceived veridically.)

The misperception of trajectory angle may be related to the known distortion of intervals in depth relative to frontoparallel horizontal (or vertical) distances. In several experiments, it has been shown that stereoscopic objects at moderately large viewing distances such as ours appear compressed in depth, although the details of this vary across experimental stimuli (Howard & Rogers, 2002; Tittle, Todd, Perotti, & Norman, 1995). Here, the lack of vertical disparities could cause erroneous scaling of disparities (or stereomotion signals: see Equations 1 and 2) by an improperly estimated viewing distance. However, Harris and Dean (2003) showed that perceived trajectory errors do not vary consistently with viewing distance.

More relevantly, the speed of direct stereomotion also seems to be misperceived in a similar way. Brenner, van den Berg, and van Damme (1996) asked subjects to match the speed of a directly approaching stereomotion target using a binocular motion stimulus that traveled only laterally. Subjects consistently underestimated the speed of the former relative to the comparison stimulus, such that a fast motion in depth appeared to be equal in speed to a slow binocular lateral motion. One possible cause for such an effect and for the increase in perceived trajectory and speed of oblique stimuli is cue conflict. The effectiveness of the signal from conventional stereomotion cues (specifying $\mathbf{v}_z$) may be attenuated by conflicting motion in depth cues (e.g., looming and change of contrast), which explicitly signal a lack of motion in depth. However, this would not affect the perceived lateral motion of the stimulus. If the depth component of 3D speed is underestimated relative to its lateral speed (whether the origin of that misperception is in the compression of z space or z speed or even in the expansion of x space or x speed), the logical consequence would be an overestimation of the object's trajectory angle, as described by Harris and Dean (2003), and an overestimation of the speed of oblique trajectories, as observed here. Lastly, given the recent finding that the classic 2D "oblique effect" of enhanced direction discrimination along the cardinal axes is associated with an expansion of direction space around the x- and y-axes (Krukowski & Stone, 2005), it is tempting to think that the 3D phenomena described by Harris and Dean and seen here represent a generalization of that 2D oblique effect to the z-axis and to 3D motion.

The stereomotion anisotropies noted here and in previous reports (Harris & Dean, 2003) may be related to the observation by Beverley and Regan (1975) that the discrimination of trajectory is superior for oblique stimuli compared with their direct equivalents. Using a combination of techniques, they found evidence that an ensemble of "neural mechanisms 'tuned' to different left:right ratios could provide a physiological basis for sensing the direction in which an object moves in three-dimensional space," and whose comparative outputs determine the motion in depth percept (Beverley & Regan, 1975). The authors further state, "Our results suggest that, when processing movement information, the brain does not give equal weight to all left:right ratios" (Beverley & Regan, 1973). Computationally, such a scheme might be simulated by introducing a different weighting for the two velocities into Equation 2. Thus, a weighted velocity-differencing scheme might accommodate much of the data reporting anisotropies in stereomotion perception.

Conclusion

This study extends the phenomenon of stereomotion suppression to the realm of speed discrimination for a range of stimulus trajectory angles. A stereomotion speed perception mechanism that uses a weighted ensemble of relatively noisy interocular velocity difference filters, each tuned to a specific range of 3D trajectory angles, may be able to explain much of the published data.

Note added in proof

Since the submission of this manuscript, a paper has been published that describes a systematic directional anisotropy for motion in depth (Lages, 2006). This study includes data showing that, consistent with our findings, oblique trajectory are perceived as faster.

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Footnotes

[1] Invertebrate species can be found with only one primitive photosensitive organ or feature. For example, euglenids—primitive single-cell organisms—have an "eye spot" at one end. At the opposite end, a flagellum (a whip like structure) allows them to propel themselves towards a light source. Considering multi-celled organisms, several species of crustacea (including the aptly named Cyclops) feature a median (nauplius) eye, usually containing a cluster of eye-cups and a handful of receptors (Land, 1984).

[2] Like the majority of authors cited in this article, we use the term stereomotion to refer to motion toward or away from an observer. This should not be confused with the use of this term to describe frontoparallel motion of a stimulus defined by binocular disparity, e.g., Lu & Sperling, 2001; Patterson, 1999.

References

Allison, R. S., Howard, I. P., & Howard, A. (1998). Motion in depth can be elicited by dichoptically uncorrelated textures [Abstract]. *Perception, 27*(Suppl.), 46.

Beverley, K. I., & Regan, D. (1973). Evidence for the existence of neural mechanisms selectively sensitive to the direction of movement in space. *Journal of Physiology, 235,* 17–29. [PubMed] [Article]

Beverley, K. I., & Regan, D. (1975). The relationship between discrimination and sensitivity in the perception of motion in depth. *Journal of Physiology, 249,* 387–398. [PubMed] [Article]

Blake, R., Sloane, M., & Fox, R. (1981). Further developments in binocular summation. *Perception & Psychophysics, 30,* 266–276. [PubMed]

Brenner, E., Van den Berg, A. V., & Van Damme, W. J. (1996). Perceived motion in depth. *Vision Research, 36,* 699–706. [PubMed]

Brooks, K. (2001). Stereomotion speed perception is contrast dependent. *Perception, 30,* 725–731. [PubMed]

Brooks, K., & Mather, G., (2000). Perceived speed of motion in depth is reduced in the periphery. *Vision Research, 40,* 3507–3516. [PubMed]

Brooks, K. R. (2002a). Interocular velocity difference contributes to stereomotion speed perception. *Journal of Vision, 2*(3), 218–231, http://journalofvision.org/2/3/2/, doi:10.1167/2.3.2. [PubMed] [Article]

Brooks, K. R. (2002b). Monocular motion adaptation affects the perceived trajectory of stereomotion. *Journal* *of Experimental Psychology: Human Perception and Performance, 28,* 1470–1482. [PubMed]

Brooks, K., & Stone, L. (2002). Monocular artifacts and the perception of stereomotion speed [Abstract]. *Journal of Vision, 2*(7), 329a, http://journalofvision.org/2/7/329/, doi:10.1167/2.7.329.

Brooks, K. R., & Gillam, B. J. (2005). Perceived motion-in-depth from changes in the extent of binocularly unmatched regions. *Australian Journal of Psychology, 57*(Suppl.), 46.

Brooks, K. R., & Stone, L. S. (2004). Stereomotion speed perception: Contributions from both changing disparity and interocular velocity difference over a range of relative disparities. *Journal of Vision, 4*(12), 1061–1079, http://journalofvision.org/4/12/6/, doi:10.1167/4.12.6. [PubMed] [Article]

Fernandez, J. M., & Farell, B. (2005). Seeing motion in depth using inter-ocular velocity differences. *Vision Research, 45,* 2786–2798. [PubMed]

Finney, D. J. (1971). *Probit analysis*. Cambridge: Cambridge University Press.

Harris, J. M., & Dean, P. J. (2003). Accuracy and precision of binocular 3-D motion perception. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 869–881. [PubMed]

Harris, J. M., & Rushton, S. K. (2003). Poor visibility of motion in depth is due to early motion averaging. *Vision Research, 43,* 385–392. [PubMed]

Harris, J. M., & Sumnall, J. H. (2000). Detecting binocular 3D motion in 3D noise: No effect of viewing distance. *Spatial Vision, 14,* 11–19. [PubMed]

Harris, J. M., & Watamaniuk, S. N. (1995). Speed discrimination of motion-in-depth using binocular cues. *Vision Research, 35,* 885–896. [PubMed]

Harris, J. M., McKee, S. P., & Watamaniuk, S. N. (1998). Visual search for motion-in-depth: Stereomotion does not "pop out" from disparity noise. *Nature Neuroscience, 1,* 165–168. [PubMed]

Howard, I. P., Allison, R. S., & Howard, A. (1998). Depth from moving uncorrelated random dot displays. *Investigative Ophthalmology and Visual Science, 31,* S669.

Howard, I. P., & Rogers, B. J. (2002). *Seeing in depth*. Ontario, Canada: I. Porteous.

Krukowski, A. E., & Stone, L. S. (2005). Expansion of direction space around the cardinal axes revealed by smooth pursuit eye movements. *Neuron, 45,* 315–323. [PubMed]

Lages, M. (2006). Bayesian models of binocular 3-D motion perception. *Journal of vision,* 6(4), 508–522, http://journalofvision.org/6/4/14/, doi: 10.1167/6.4.14. [PubMed] [Article]

Land, M. F. (1984). Crustacea. In M. A. Ali (Ed.), *Photoreception and vision in invertebrates* (pp. 401–438). New York: Plenum.

Lee, D. N. (1970). Binocular stereopsis without spatial disparity. *Perception and Psychophysics, 9,* 216–218.

Lu, Z. L., & Sperling, G. (2001). Three-systems theory of human visual motion perception: Review and update. *Journal of the Optical Society of America A, Optics, Image, Science, and Vision, 18,* 2331–2370. [PubMed]

McKee, S. P. (1981). A local mechanism for differential velocity detection. *Vision Research, 21,* 491–500.

McKee, S. P., Watamaniuk, S. N. J., Harris, J. M., Smallman, H. S., & Taylor, D. G. (1997). Is stereopsis effective in breaking camouflage for moving targets? *Vision Research, 37,* 2047–2055. [PubMed]

Patterson, R. (1999). Stereoscopic (cyclopean) motion sensing. *Vision Research, 39,* 3329–3345. [PubMed]

Portfors-Yeomans, C. V., & Regan, D. (1996). Cyclopean discrimination thresholds for the direction and speed of motion in depth. *Vision Research, 36,* 3265–3279. [PubMed]

Regan, D. (1993). Binocular correlates of the direction of motion in depth. *Vision Research, 33,* 2359–2360. [PubMed]

Ross, J. (1974). Stereopsis by binocular delay. *Nature, 248,* 363–364. [PubMed]

Shioiri, S., Saisho, H., & Yaguchi, H. (2000). Motion in depth based on inter-ocular velocity differences. *Vision Research, 40,* 2565–2572. [PubMed]

Sumnall, J. H., & Harris, J. M. (2000). Binocular three-dimensional motion detection: Contributions of lateral motion and stereomotion. *Journal of the Optical Society of America A, Optics, Image, Science, and Vision, 17,* 687–696. [PubMed]

Thompson, P. (1983). Discrimination of moving gratings at and above detection threshold. *Vision Research, 23,* 1533–1538. [PubMed]

Tittle, J. S., Todd, J. T., Perotti, V. J., & Norman, J. F. (1995). Systematic distortion of perceived three-dimensional structure from motion and binocular stereopsis. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 663–678. [PubMed]

Tyler, C. W. (1971). Stereoscopic depth movement: 2 Eyes less sensitive than one. *Science, 174,* 958–961. [PubMed]

Westheimer, G. (1990). Detection of disparity motion by the human observer. *Optometry and Vision Science, 67,* 627–630. [PubMed]