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Perceived speed of motion in depth is reduced in the periphery

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Abstract

The perceived speed of motion in depth (MID) for a monocularly visible target was measured in central and peripheral vision using a 2AFC speed discrimination task. Only binocular cues to MID were available: changing disparity and interocular velocity difference (IOVD). Perceived speed for monocular lateral motion and perceived depth for static disparity were also assessed, again in both central and peripheral vision. The purpose of the experiment was to assess the relative contributions of changing disparity and IOVD cues to the perceived speed of stereomotion. Although peripheral stimuli appeared to lie at approximately the same depth as their central counterparts, their apparent speed was reduced. Monocular/lateral and binocular/MID speeds were reduced to a similar extent. It seems that reduced apparent monocular speed leads to reduced perceived MID speed, despite the fact that the disparity system appears to be unaffected. These results suggest that the IOVD cue makes a significant contribution to MID speed perception. © 2000 Published by Elsevier Science Ltd.

Keywords: Motion in depth; Speed discrimination; Peripheral vision

1. Introduction

Consider the motion of an object approaching an observer along the median plane. Three major cues to the speed of the object are available. (1) Monocularly, the object's retinal image increases in size as it approaches, and the velocity of approach could be derived from the rate of change. However, it has been shown that for small, rapidly moving objects, monocular cues should be relatively ineffective compared to binocular cues (Regan & Beverley, 1979). (2) Binocularly, the depth of the object compared to its surroundings at any one time is signalled by the relative binocular disparity of its retinal images. As the object approaches, disparity changes and the rate of this change offers a potential cue to the rate of its motion. A unit sensitive to the changing output of a population of static disparity detectors tuned to different depths could encode this motion neurally. Such a system will be referred to as a 'changing disparity' system. (3) As depth changes, the two monocular images drift in opposite directions (in this instance their speeds are equal and both images move in a temporal direction). This cue to the speed of motion in depth (MID) could be encoded by the motion system, without the need for disparity sensitive mechanisms. A unit capable of assessing the difference in velocity of each monocular motion signal could be used to encode the speed of MID. Such a system will be referred to as an inter-ocular velocity difference (IOVD) system.

Disparity change and IOVD are always present in natural examples of MID, but psychophysicists have attempted to isolate them in the laboratory. There have been repeated demonstrations of MID perception in dynamic random dot stereograms (DRDS) which lack any monocular motion cues (Julesz, 1971; Norcia & Tyler, 1984; Regan, 1993; Cumming & Parker, 1994), suggesting that an IOVD is not critical to MID detection. Cumming and Parker (1994) and Gray and Regan (1996) have demonstrated that detection thresholds for DRDS stimuli are at least as good as those for an equivalent random dot stereogram containing monocular motion cues (RDS). The converse of a DRDS stimulus has recently been employed, having monocular motion signals, but no coherent disparity information. This was achieved by making the RDS patterns correlated in time, but not between stereo half-images. This stimulus is capable of supporting MID perception in

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appropriate conditions (Shioiri, Saisho & Yaguchi, 1998; Howard, Allison & Howard, 1998; Allison, Howard & Howard, 1998). It would seem that changing disparity is not crucial for MID detection either.

It has been suggested that IOVD plays a pivotal role in the encoding of MID speed, since RDS speed discrimination thresholds are lower than those for DRDS (Harris & Watamaniuk, 1995). However, the generality of this result has been challenged by others (Portfors-Yeomans & Regan, 1996; Portfors & Regan, 1997), who find equivalent performance for cyclopean (DRDS) and monocularly visible stimuli. Portfors-Yeomans and Regan attribute the difference to the fact that Harris and Watamaniuk's stimulus passed through the fixation plane, and hence the DRDS was momentarily undetectable. When assessed either in front of, or behind the horopter, DRDS speed discrimination performance was very much improved. However, the 'monocularly visible' targets in these experiments were not RDSs. Instead they were DRDSs targets moving in depth on either a blank or a static noise background. This mode of presentation meant that individual dots in the display did not carry IOVD information, and the stimulus patch as a whole carried either a reduced contrast first order monocular motion signal, or a second order motion signal only. It is possible that with a conventional RDS stimulus superior speed discrimination performance may have been apparent.

Another study by the referent authors attempted to tease apart the two cues in a stimulus in which both are available. Portfors-Yeomans and Regan (1997) demonstrated that speed discrimination performance is equivalent for oblique MID stimuli with trajectories within the horizontal meridian and in the vertical meridian. This, they argue, implies the use of changing disparity only. For a stimulus with an oblique trajectory in the horizontal meridian, monocular velocity signals will both be horizontal, but unequal. For a stimulus with an oblique trajectory in the vertical meridian the visual system does not have immediate access to any IOVD information, since monocular motion in both eyes is oblique. However, it is not difficult to imagine a system which is capable of resolving an oblique motion into its horizontal and vertical components, before feeding the former into a MID stage. A system capable of such an operation would also predict the results obtained by these authors.

This study aims to discover whether IOVD influences the perception of MID speed in a stimulus containing both monocular motion signals and continuously changing disparity, by comparing the perceived speed of MID in central vision and in the periphery. It has long been known that the perceived rate of frontoparallel motion is reduced in the peripheral visual field (Lichtenstein, 1963; Campbell & Maffei, 1979, 1981; Tynan & Sekuler, 1982; Johnston & Wright, 1986; Schlykowa, Ehrenstein, Cavonius & Arnold, 1993). If the speed of MID is derived exclusively through IOVD, then monocular speed signals will be reduced for a stimulus approaching in the periphery, leading to a predictable reduction in the apparent rate of MID. However, if we assume that there is no systematic effect of eccentricity on perceived depth, speed perception based on changing disparity alone should be veridical. An intermediate perceived velocity might reflect an interaction between these two systems.

2. Experiment 1

2.1. Methods

2.1.1. Apparatus and stimuli

A PC-compatible computer equipped with a super-VGA display card was used to generate the left and right halves of each stereo image side-by-side on a NEC Multisync Plus colour monitor. Subjects viewed the two images through a mirror stereoscope (adjusted to give convergence appropriate for the viewing distance of 1.8 m, whilst maintaining the line of sight as normal to the display surface, to avoid unwanted disparities). A partition was placed in the median plane between the stereoscope and the screen, to ensure that each eye saw only the appropriate monocular image. The mean luminance of the screen was 50 cd/m^2, and all tests took place in a darkened room. Responses were recorded from a two-button response box connected to the computer's game port. Subjects wore their best optical corrections for all conditions.

The background pattern comprised 50% density bright/dark dots at a Michelson contrast of 80%, each subtending 3.62 (H) $\times$ 4.16 (V) min arc. Each dot field was presented in a 'viewport' measuring 2.66 (H) $\times$ 1.24 (V) deg arc displayed at screen mean luminance immediately above a small high contrast fixation cross, located in a rectangle also at mean luminance. These were in identical positions in each stereo half image, and hence were located binocularly in the fixation plane (see Fig. 1). Nonius lines were also provided on each side of the cross as a fixation aid and a vergence control. The targets themselves were random dot patterns (same size, density and contrast as the background) subtending 1.93 (H) $\times$ 1.08 (V) deg arc. These could be displayed at various positions within each viewport to simulate various speeds, disparities and binocular directions without overlapping any part of the background dot pattern.

2.1.2. Subjects

There were five subjects: three women and two men between the ages of 20 and 30. All had normal or corrected to normal vision, and though two of the subjects were experienced psychophysical observers, they were all naïve as to the purposes of the experiment. All subjects received payment at an hourly rate.

2.1.3. Design and procedure

A two-factor repeated measures design was used in all experiments, employing the method of constant stimuli. Here we assume that the subjects will make comparisons between test and standard stimuli within each trial independently. The two factors were stimulus location (central, C, and peripheral, P), and x-axis speed (five speeds, see below), or disparity, or MID speed. In condition C, both the test and standard stimulus appeared in the same central location (just above the fixation cross), whilst in condition P, the standard appeared centrally and the test stimulus was placed 4 deg arc above the standard, as shown in Fig. 1. All tests included randomly interleaved trials from conditions C and P, generating separate psychometric functions. Three different tasks were performed in separate experiments: monocular speed discrimination, depth discrimination (crossed and uncrossed disparities), and MID speed discrimination.

2.1.4. Screening for stereoanomalous observers

Before subjects began the experiment, each participated in tests to confirm that none of them were stereo-blind or stereomotion-blind. These tests were simple disparity or MID direction discriminations performed at all of the static disparities and speeds of MID used in the experiment. Subjects viewed a stimulus that was randomly assigned either a crossed or an uncrossed static disparity, and were asked to respond by pressing buttons on the response box corresponding to 'near' or 'far'. Similarly, in the stereomotion blindness test subjects viewed either an approaching or a receding MID stimulus and were required to respond appropriately. All of the subjects used in this study performed at 95% correct or better in all tests.

2.1.5. Monocular speed discrimination

The five levels of 'x-axis speed' were chosen carefully to fulfil certain performance criteria: (i) accurate monocular speed discrimination; (ii) accurate MID speed discrimination when presented simultaneously; (iii) absence of diplopia at the beginning and end of the MID sequence; and (iv) subjectively smooth apparent motion. Pilot work led us to use speeds of 0.105, 0.175, 0.263, 0.350 and 0.394°/s. A 2AFC procedure was used. On each trial two targets were presented monocularly to the same eye, one moving at 0.263°/s (the 'standard') and one moving at one of the five speeds shown above (the 'test'). The test could appear either first or second in the sequence with equal probability on each trial. Meanwhile, the non-stimulated eye viewed the normal background and blank viewport at mean luminance. The subject was asked to indicate with the response box which stimulus appeared to travel faster. Retinal images always moved in a temporal direction. Stimulus duration was 800 ms with an inter-stimulus interval (ISI) of 200 ms. The next trial was initiated after the subject's response, following an inter-trial interval of 1000 ms. Each subject performed 400 judgements, 40 in each of the ten stimulus conditions. These were completed in one day in blocks of 100 trials, each of which lasted approximately 10 min.

Fig. 1. General screen arrangement. Drawing not to scale. See text for detailed parameters.

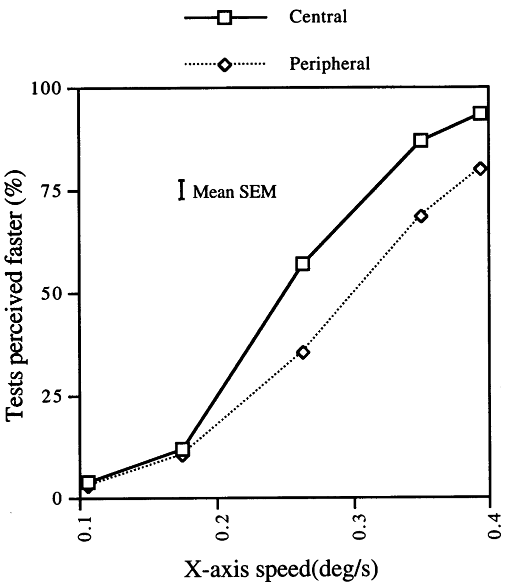

Fig. 2. Monocular speed discrimination for central and peripheral stimuli. Psychometric functions are plotted versus the test speed.

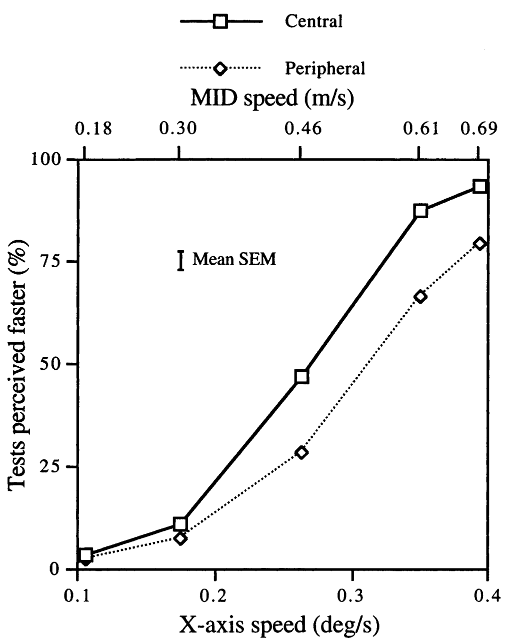

Fig. 3. MID speed discrimination tasks for central and peripheral stimuli. Psychometric functions are plotted versus the test speed.

2.1.6. MID speed discrimination

The stimuli for the MID speed discrimination trials were similar to the monocular images in the monocular speed discrimination trials, except that a perfectly correlated stereo pair of images was shown to each eye simultaneously moving at the same speed, but in opposite directions. This simulated MID with a trajectory directly between the observers' eyes. The five levels of MID speed to which these monocular speeds correspond were 0.18, 0.3, 0.46, 0.61 and 0.69 m/s at the viewing distance used. The initial and final positions of all stimuli were equidistant from the fixation plane, and as such, the mean disparity was zero. In all other respects, the procedure was identical to the monocular speed discrimination task.

2.1.7. Depth discrimination

Crossed and uncrossed disparities were investigated in separate blocks of trials. The two standard disparities ($\pm$ 12.6 min arc) were chosen to match the disparities of the starting and finishing positions of the stimulus in the MID speed discrimination test. Test disparities were 5, 8.4, 12.6, 16.8, and 18.9 arc min. In each trial there were two stimulus intervals of 800 ms, separated by an ISI of 200 ms, containing the two stimuli. The test could appear either first or second with equal probability on each trial. The subject was asked to indicate with the response box which stimulus appeared to be closer, after which the next trial was initiated following an inter-trial interval of 1000 ms. Each subject performed 400 trials for both crossed and uncrossed disparity, 40 in each of the ten stimulus conditions. These were completed over a number of days in blocks of 100 trials, each of which lasted approximately 10 min.

2.2. Results

Results are pooled between all five experimental subjects, unless stated otherwise. Though small individual differences did exist in various conditions, the same general pattern was evident in all observers.

2.2.1. Monocular speed discrimination

Psychometric functions for the monocular speed discrimination task are shown in Fig. 2. The mean PSE for central stimuli was 0.249°/s, close to the actual standard speed of 0.263°/s. The function for peripheral stimuli shows a clear shift to the right, and yields a higher mean PSE of 0.310, representing a 24% difference in perceived speed. Since previous research has allowed us to clearly predict the direction of such a difference, a one tailed t-test was used to compare means, showing that the difference is statistically significant ($P = 0.044$).

2.2.2. MID speed discrimination

Psychometric functions are shown in Fig. 3. Here, the abscissa represents the monocular speeds used, for ease of comparison with Fig. 2; equivalent MID speeds are indicated at the top of the graph. In the central condition, the mean PSE is 0.268°/s (actual standard speed: 0.263°/s). In the peripheral condition, the plot shows a marked shift to the right, similar to that described for monocular speed discrimination, with a PSE of 0.309°/s. This represents a 15% shift in PSE. A one-tailed t-test yielded a statistically significant effect of stimulus location ($P = 0.039$).

PSE values for both speed discrimination tasks are represented in Fig. 4. PSEs for all subjects, conditions and tasks were entered into a 2×2 within subjects ANOVA. This showed a statistically significant effect of location ($P = 0.28$). Neither the main effect of 'motion-type' (monocular or MID) nor the interaction effect neared significance ($P > 0.05$).

2.2.3. Depth discrimination

Psychometric functions for depth discrimination tasks can be seen in Fig. 5. The data from conditions in central vision show mean PSEs of 11.77 and 11.94 arc min in the crossed and uncrossed conditions respectively, close to the true standard disparity of 12.60 min. For peripheral conditions, the respective PSEs were 10.80 and 12.43 arc min. This represents a 9% decrease in perceived distance from the observer for crossed disparity, and a 4% decrease for uncrossed, relative to apparent distance in the fovea. PSEs for each of the depth discrimination tasks and conditions are shown in Fig. 6. Each of these four PSEs for each subject was submitted into a 2×2 within subjects ANOVA. This test showed no significant main effects or interactions.

2.3. Discussion

Monocular speed discrimination results above faithfully replicate a well established property of peripheral vision: that the perceived speed of a pattern is reduced as a function of eccentricity. The 24% difference in perceived speed recorded here is in broad agreement with previous demonstrations of the effect with similar stimuli (Tynan & Sekuler, 1982; Schlykowa et al., 1993).

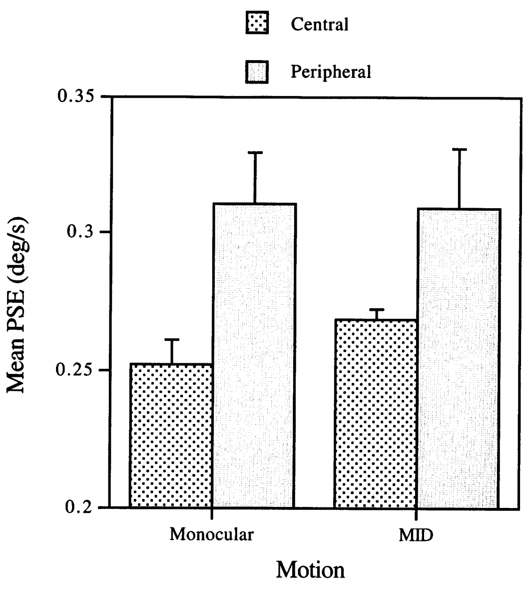

Fig. 4. PSE data for central and peripheral stimuli in monocular and MID speed discrimination experiments. The vertical bars mark +1 SE.

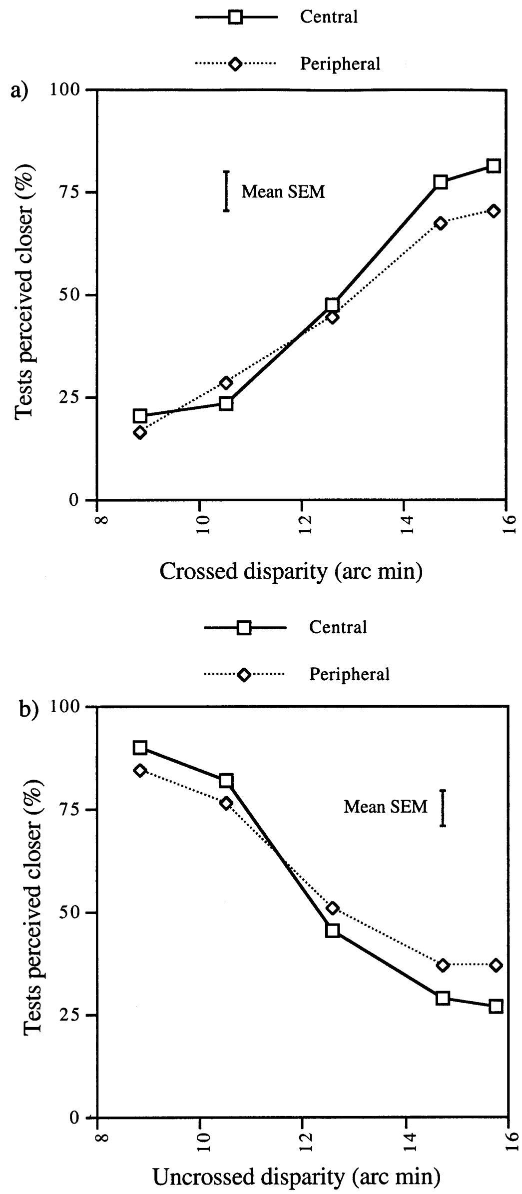

Fig. 5. Depth discrimination tasks at (a) crossed and (b) uncrossed disparities for central and peripheral stimuli. Psychometric functions are plotted versus the test disparity.

The results of the depth discrimination experiments at both crossed and uncrossed disparities are, to our knowledge, the first experimental data reported on the effects of eccentricity on perceived depth. There was no systematic effect of eccentricity on perceived depth. Since in this experiment the peripheral stimulus was placed in the upper portion of the subject's visual field, one might expect the pictorial depth cue of 'height' (Gibson, 1950; Ittelson & Kilpatrick, 1951; Bruce & Green, 1990; Levine & Shefner, 1991) to influence perceived depth. No such bias was found, however, indicating that either the height of an image only has influence in conjunction with another depth cue such as linear or detail perspective (Rock, 1984), or that the unambiguous disparity cues dominated the perception of depth.

The observation that in all tasks psychometric functions seem a little less steep for peripheral stimuli is in line with previous reports that discrimination thresholds vary with eccentricity, both for speed (McKee & Nakayama, 1984) and for depth (Siderov & Harweth, 1995; see also Blakemore, 1970).

The results of the MID speed discrimination show that a peripheral stimulus approaching the subject will appear slower than an otherwise identical central stimulus. In this case the shift was of 15%. If perceived MID velocity were computed by a mechanism sensitive only to the changing disparity of the stimulus, then no bias should have been apparent. If MID speed were perceived solely on the basis of IOVDs, we would expect the same degree of misperception in this task as in the monocular speed discrimination task. The reduced effect for MID may indicate that changing disparities exerted at least some influence on judgements. However, the small difference in the degree of misperception in each task was not significant.

Alternative explanations for the results must not be overlooked. It has recently been suggested that attention is critical for the accurate perception of smooth stereomotion (Tyler & Kontsevich, 1995), whilst it is assumed that monocular speed perception is a pre-attentive process. In all of the tasks performed, 75% of the stimuli appeared centrally, with only 25% being presented in the periphery. This could lead to the preferential allocation of focal attention towards the centre of the visual field. If this lack of attention in the periphery led to a degraded MID percept, this might

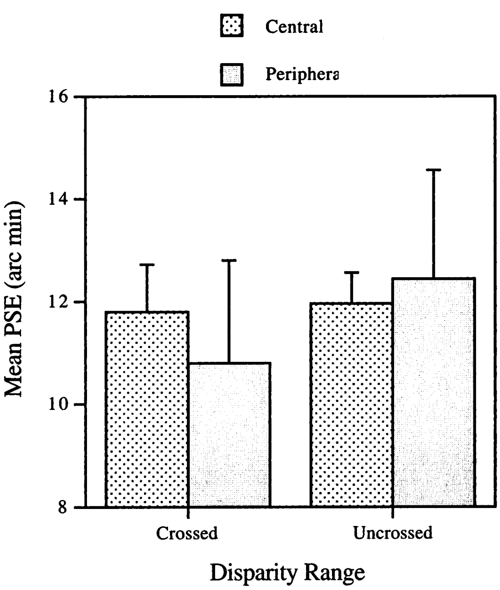

Fig. 6. PSE data for central and peripheral stimuli in both crossed and uncrossed disparity discrimination tasks. The vertical bars mark + 1 SE.

have been manifested as a change in perceived speed. The same need not be true for perceived monocular speed, which is unaffected by attention. It is possible that the reductions in perceived speed for monocular motion and MID could come from entirely independent sources. In order to address these concerns, we repeated Experiment 1 with a single subject, including a pre-cue to subsequent stimulus location. Data from these tests were qualitatively and quantitatively similar to those presented earlier. We conclude that the differences described above cannot be attributed to attentional effects.

3. Control observations

A number of control observations were made in order to test other possible explanations of results in the above experiment. In Experiment 1, the duration of all stimuli was held constant at 800 ms, and as such it is possible that subjects were in fact responding not on the basis of image speed per se, but instead on the basis of displacement distance. To test for this possibility, observations were made using stimuli in which presentation duration varied at each velocity, to remove the displacement cue. In addition, the disparity discrimination task was repeated at smaller disparities, to test the possibility that a misperception occurred only at certain disparities.

3.1. Methods

For the purposes of this experiment, one subject only was used. Subject SF, a 30-year-old female, had contributed data to Experiment 1. She was experienced in psychophysical observation, but naïve as to the purposes of the experiment.

For speed discrimination tests a zero-correlation design was adopted in order to break the connection between stimulus speed and displacement. As before, the duration of the standard stimulus was 800 ms, and five different test speeds were used. The duration of the test stimulus was varied in order to create five orthogonal sub-conditions of constant displacement. In order to do this the duration was reduced for faster speeds and increased for slower speeds. As such, there was no correlation between speed and displacement in this experiment. This also meant that subjects could no longer produce appropriate results by simply responding on the basis of displacement. Psychometric functions could be plotted with test speed on the abscissa, collapsing data across displacement conditions, and with test displacement on the abscissa, collapsing across speed conditions. This would allow us to see on which stimulus property the subject based her responses. Full details of speed, displacement and duration parameters

Table 1
Stimulus duration parameters (ms) for each speed and displacement condition (control observations)

Speed (°/s)	Displacement (°)				
	0.079	0.14	0.21	0.28	0.315
0.105	800	1333	2000	2667	3000
0.175	480	800	1200	1600	1800
0.263	320	533	800	1067	1200
0.35	240	400	600	800	900
0.394	213	356	533	711	800

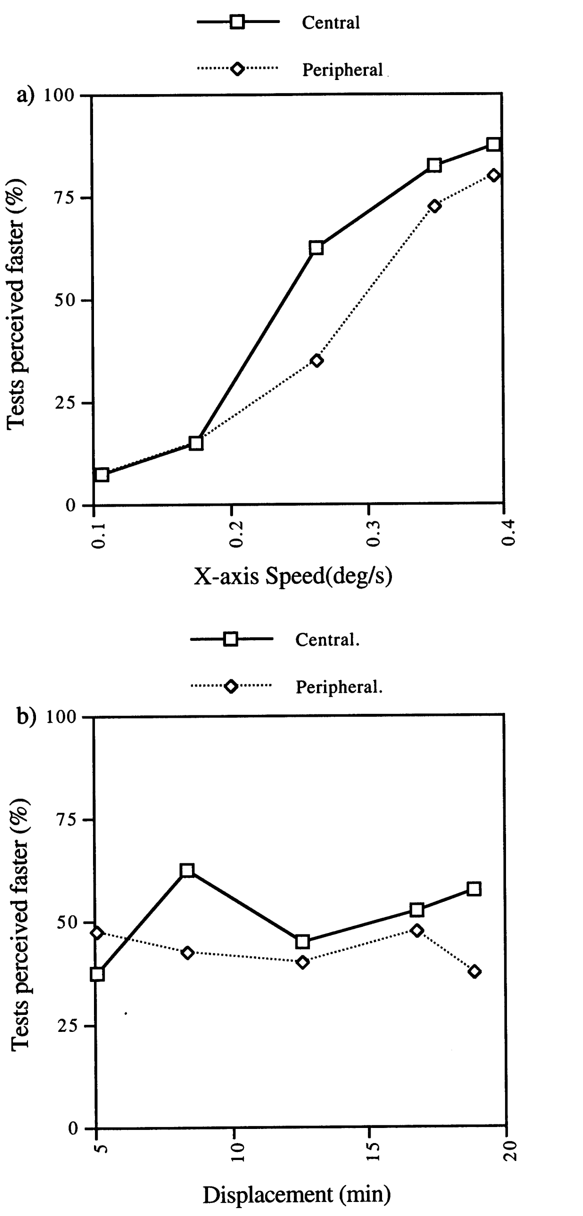

Fig. 7. Results for the monocular speed discrimination task plotted against (a) test stimulus speed and (b) test stimulus displacement (control observations).

for all conditions can be seen in Table 1. In all other respects the procedure was as described above for Experiment 1.

For depth discrimination tasks, all details were identical to Experiment 1, except for the fact that all standard and test disparities were halved.

3.2. Results

3.2.1. Monocular speed discrimination

Speed discrimination results for SF can be seen plotted against stimulus speed and against stimulus displacement in Fig. 7. A characteristic psychometric function is revealed for the plot of percent perceived faster versus speed, whereas for percent perceived faster versus displacement, performance hovers around chance levels. There is also a clear difference in performance between central and peripheral data, with peripheral stimuli being judged faster on fewer occasions. The size of this difference is similar in this case to that shown in Experiment 1, as is the slope of the psychometric function (see Fig. 2). The similarity of the pattern of responding in each case implies that subjects were in fact judging speed per se rather than displacement throughout Experiment 1.

3.2.2. MID speed discrimination

Plots for MID speed discrimination, plotted against test speed and test displacement can be seen in Fig. 8. Here, the situation is as described above for monocular speed discrimination. The psychometric functions plotted against test speed shows that peripheral stimuli are once again perceived faster on fewer occasions, by a similar margin to that shown in Experiment 1 (see Fig. 3). Data plotted against test displacement shows responding at or around chance levels.

3.2.3. Depth discrimination

The results of depth discrimination tests at smaller disparities are shown in Fig. 9 for crossed and uncrossed disparity. Both graphs show the expected psychometric function, with a slightly less steep slope than the equivalent data in Experiment 1, and no systematic difference in performance between central and peripheral conditions.

3.3. Discussion

In general, the control tests performed in this section do not change our analysis of the results of Experiment 1, and we can be confident in the conclusions reached in the discussion above. The speed discrimination plots for both monocular and MID stimuli show that subjects do perform discriminations of stimulus speed per se, rather than basing their decisions on displacement, and that even when durations are varied, the same misperception of velocity is shown in both cases. It is also clear that target eccentricity, at the levels tested here, has no systematic effect on perceived depth, over a large range of disparities.

4. General discussion

The effect of eccentricity on the perceived speed of binocularly defined MID is clearly consistent with the idea that the IOVD cue contributes to the perception of stereomotion velocity. Though the misperception of speed is very slightly smaller in the case of MID versus monocular/lateral motion, the lack of any significant difference represents our inability to find clear evidence of the influence of changing disparity.

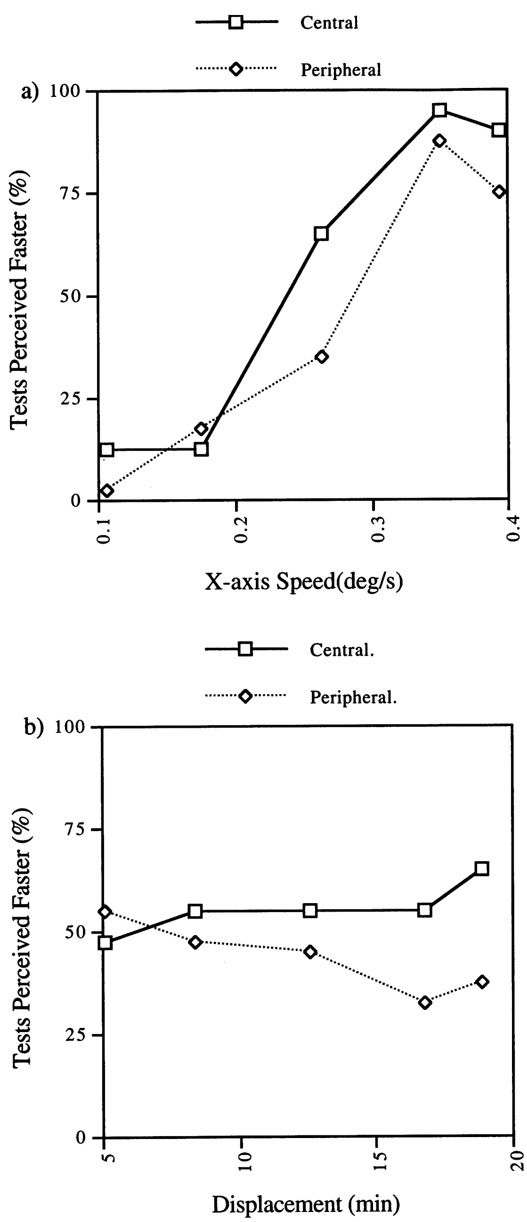

Fig. 8. Results for the MID speed discrimination task plotted against (a) test stimulus speed and (b) test stimulus displacement (control observations).

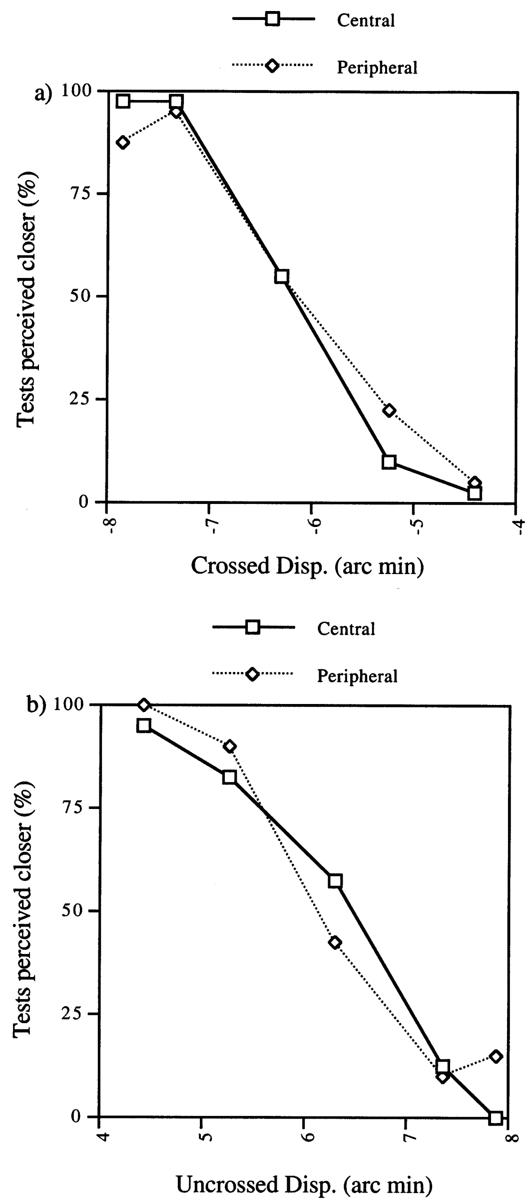

Fig. 9. Depth discrimination results for (a) crossed and (b) uncrossed disparities (control observations).

It is of course possible that the changing disparity signal is derived from disparity units other than those which are used to discriminate between static disparities for stationary images. Indeed, some authors have suggested the existence of separate and parallel disparity processing streams (e.g. Tyler, 1990). In this proposal, the 'interblob' projections of the parvocellular stream perform static disparity judgements, while stereo processing for moving stimuli would be computed in the magnocellular stream. Though this does not appear to be the most parsimonious account, it does allow the possible alternative explanation that our two speed misperceptions have independent roots, and are not causally linked. However, though these disparity units for stationary and moving images may be distinct, they both rely on the same basic stimulus property: the difference in relative position in the two eyes. It seems very unlikely that the latter mechanisms would show an eccentricity-dependent response, post binocular combination, in exactly the same way that the monocular speed mechanisms do, despite the eccentricity invariance of static disparity detectors.

The idea that IOVDs dominate the perception of stereomotion speed conflicts with the findings of Portfors-Yeomans and Regan, (1996); see also Portfors & Regan, 1997), who compared cyclopean and non-cyclopean stimuli (though there may be doubts about the usefulness of the monocular motion signals provided in these studies: see Section 1). The criticism levelled at the Harris and Watamaniuk (1995) paper could not be directed at the data presented here. Since Harris and Watamaniuk's DRDS stimulus passed through the fixation plane, it became invisible for a brief period. Portfors-Yeomans and Regan point to this brief loss of visibility as the cause of the poor performance in DRDS speed discrimination. Rather than simply eliminating the IOVD cue to changing depth, our study caused a deliberate misperception in the monocular speed system, such that any decision based upon this mechanism would reveal non-veridical performance. Though our stimulus did pass through zero relative disparity, unlike the stimuli mentioned above it was constantly visible, since it was presented in a viewport.

We may still be able to reconcile all results with the idea that when the stimulus passes through zero relative disparity, IOVD has a greater influence on MID speed perception. This would account for the continued good discrimination using RDS (compared with their temporally uncorrelated counterparts) near zero relative disparity, but relatively small differences between the two stimuli at larger disparities. It would be interesting to see what influence a change in the mean disparity of our stimuli would have on our results. It is also possible that changing disparity information was degraded by the decreased stereoacuity associated with peripheral stimuli, particularly those with a high spatial frequency (Siderov & Harweth, 1995). Indeed, the slopes of Fig. 5 show a trend towards decreased depth discrimination performance. This too might have led the system to be more reliant on IOVD. It remains to be seen whether IOVD is used in the computation of 3D velocity for other stimuli.

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