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Depth thresholds of motion parallax as a function of head movement velocity

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Abstract

The lower parallactic depth threshold is determined by (a) the ratio of relative image velocity to head velocity when the head moves fast (> 13 cm/s) and (b) the motion threshold when the head moves slow (< 13 cm/s). These two results are explained by a single system that codes the ratio of relative image velocity to head velocity, using the same image velocity signal as that used for motion perception. In this explanation, ratios coded from low relative image velocities, which are slightly higher than the motion threshold, produce a perception of depth only when the head moves slowly. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Motion parallax; Depth threshold; Head movement; Motion threshold

1. Introduction

What determines the lower threshold for perceiving depth from motion parallax? To answer this question, we adopt the definition of motion parallax as 'the relative movement of images across the retina resulting from movement of the observer' (Rogers & Graham, 1979). With this definition, we focus on the following visual information as possible determinants of the lower parallactic depth threshold: (a) relative image velocity; and (b) the ratio of relative image velocity to head velocity. By 'relative image velocity', we mean the difference in velocity of two images on different regions of the retina, and by 'head velocity', we mean the velocity of the head relative to exocentric coordinates. We use the term 'velocity' instead of 'speed' to emphasize our assumption that the visual system uses information about the direction and the speed of both retinal–image motion and head motion when 'computing' parallactic depth.

The literature suggests that relative image velocity determines the parallactic depth threshold. Our recent studies (Ono & Ujike, 1994; Ono, Sato, Shioiri, & Ujike, 1998) showed that: (a) a motion aftereffect, or MAE, produced a percept of depth when it was combined with a head movement, and (b) becoming insensitive to motion increased the parallactic depth threshold. These findings suggest that parallatic depth perception and motion perception use the same 'front end', namely, a retinal image motion detector, thus implying that relative image velocity determines the parallactic depth threshold. In support of this, Nagata (1984) found that the depth threshold specified in terms of relative image velocity remains constant across different head velocities.

The literature also suggests that the ratio of relative image velocity to head velocity determines the parallactic depth threshold. Rogers and Graham (1982) and Steinbach, Ono, and Wolf (1991) used a special case of the ratio, namely 'equivalent disparity', to describe the threshold. (For the purpose of this paper, equivalent disparity is defined as: the ratio of relative image velocity to head velocity multiplied by the constant, inter-ocular distance.) This definition is based on the geometrical prediction that equivalent disparity is proportional to the magnitude of parallactic depth, inde-

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pendent of either relative image velocity or head velocity. The definition is consistent with perception; the magnitude of perceived depth varies as a function of equivalent disparity (Rogers & Graham, 1979; Ono, Rivest, & Ono, 1986). This suggests that the visual system uses the ratio of relative image velocity to head velocity to produce percepts of depth and to determine the depth threshold. Moreover, our studies (Ono & Ujike, 1994; Ono et al., 1998) showed that depth produced by an MAE reappeared with a slow head movement after the depth produced by an MAE with a fast head movement disappeared. This implies that the ratio of image velocity signaled by a decaying MAE to head velocity must exceed a critical value for depth to be perceived, and thus suggests that the ratio of relative image velocity to head velocity is the determinant.

To examine which possible determinant is operating, we measured parallactic depth thresholds as a function of head velocity. With a single head velocity, it is not possible to differentiate between the two determinants. With more than one head velocity, however, one can differentiate between the two determinants by examining a plot of the thresholds specified by relative image velocity against head velocity. A slope of one would indicate that the ratio is the determinant of the threshold, whereas a slope of zero would indicate that relative image velocity is the determinant. Accordingly, we varied the velocity of lateral head movements systematically and measured the lower parallactic depth threshold, employing a relatively large range of ratios and relative image velocities.

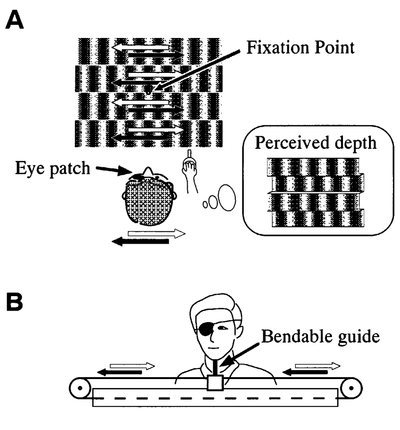

Fig. 1. (A) Schematic diagram of how the parallactic depth threshold was measured. Relative motion between the four bands of sinusoidal gratings was yoked to the observer's lateral head movements, as illustrated by the black and white arrows. During the head movement, the observer adjusted the ratio of relative image velocity to head velocity by turning the knob attached to the potentiometer, until no depth was seen. (B) Bendable guide under the observer's chin, which controlled the lateral head movements.

2. Experiment 1

Depth thresholds were measured with different amplitudes and frequencies of sinusoidal head movements, and were analyzed in terms of peak relative image velocities as a function of peak head velocity.

2.1. Method

2.1.1. Observers

Two observers, one female (MU) and one male (HU, the first author) participated. Observer, MU, had normal acuity, and HU wore glasses to correct for myopia. Both observers were experienced in psychophysical experiments, and MU was naïve as to the purpose of the experiment.

2.1.2. Apparatus and stimulus

The stimulus was generated by a Macintosh II computer and was displayed on a 13 inch AppleColor High Resolution Monitor, at a frame rate of 60 Hz. The display area was 640 × 480 pixels or 23 deg × 17 deg, and was surrounded by a piece of black cardboard (89 × 64 deg). The stimulus consisted of four bands of sinusoidal gratings (20 cycles each) with mean luminance of 23.8 cd/m^2, contrast of 85%, and 8 bit luminance levels for each of the red, green and blue phosphors. The bands (each 23 deg × 4 deg) were separated vertically by a gap (0.35 deg), and a fixation point (diameter 0.22 deg) was located at the center of the display. The stimulus was viewed monocularly from a distance of 57 cm in a dimly illuminated room. Movement of each grating was yoked to the observers' horizontal head movements, and was such that it produced a relative horizontal motion between adjacent gratings (see Fig. 1A). By varying the gratings' luminance profiles, it was possible to displace the gratings laterally in steps of one-64th of a pixel. The delay between the movement of the observers' head and the movement of the gratings was well within the 17 ms frame period of the monitor.

A computer-driven bendable rod (see Fig. 1B) guided the observers' head movements. The rod (or guide) was bendable for two reasons. First, it ensured that observers moved their head actively for all of the experimental conditions because they were unable to rest their chin on the rod, as they would be able to on a chin rest. Second, any bending of the guide signaled that the head had deviated from the desired position and, thus, provided feedback for the observers while they practised following the guide precisely and accurately.

The magnitude of the ratio of relative image velocity to head velocity was controlled by a rotary knob attached to a potentiometer. The ratio was zero (no stimulus motion) at the middle position of the knob and increased symmetrically in proportion to the angular position of the knob from its middle position while the direction of stimulus motion relative to head motion was opposite at the two sides. With the knob turned far enough in the counter-clockwise direction, the first and third gratings appeared less distant than the second and fourth gratings. (Fig. 1A illustrates this stimulus situation). Conversely, with the knob turned far enough in the clockwise direction, the first and third gratings appeared more distant than the second and fourth gratings.

2.1.3. Experimental conditions

In all conditions, the rod guided the observers' head movements sinusoidally and the stimulus was presented throughout the entire head movement (see Fig. 1B). There were nine frequencies (0.083, 0.125, 0.167, 0.25, 0.33, 0.50, 0.67, 1.00 and 1.30 Hz) and four amplitudes (5, 10, 20 and 30 cm) of the sinusoidal movements, for a total of 36 possible conditions. Data were not collected in all of the possible conditions, however, for the following two reasons. First, even with practice, observers could not follow the guide precisely and accurately in the conditions in which the guide moved with a large amplitude and a high frequency. Therefore, the conditions of the 20 cm amplitude combined with the 1.30 Hz frequency, and the 30 cm amplitude combined with the 1.00 and 1.30 Hz frequencies, were not used. Second, observers reported seeing motion whenever they saw depth in some of the conditions in which the guide moved with small amplitudes.[1] Therefore, two conditions for observer MU (the 5 cm amplitude combined with the 0.083 Hz and 0.125 Hz frequencies) and 10 conditions for HU (the 5 cm amplitude combined with all nine frequencies and the 10 cm amplitude combined with the 0.083 Hz frequency) were abandoned. Thus, MU performed in 31 conditions and HU in 23 conditions.

2.1.4. Procedure

The day before the first experimental session, each observer attended a 2 h session in which they practised following the guide with their head in the 36 possible conditions. At the end of the session, we videotaped observers' head movements and analyzed their amplitudes and frequencies. The analyses were done by manually measuring the observers' horizontal eye positions in each NTSC frame on a 20 inch CRT monitor, and by plotting those positions as a function of time. In most of the conditions, the analyses showed that the frequencies and the amplitudes of the observers' head movements deviated by less than 10% of those required. In some conditions, however, the deviations exceeded 10% even after practice, and thus, we judged that the observers were unable to follow the guide precisely and accurately; these conditions were eliminated as experimental conditions.

Parallactic depth thresholds were obtained in eight experimental sessions for MU and six for HU using the method of adjustment. In each session, seven or eight blocks (each consisting of 10 trials of a given condition) were presented in random order. Each condition was presented in two sessions, for a total of 20 trials per condition. At the beginning of each trial, the setting of the knob was such that the observers perceived depth between the adjacent gratings, and their task was to adjust the ratio, by turning the knob, until no depth was seen. In each trial, observers tended to make the adjustment when their head reached one of the extreme positions and they then checked the outcome in the following excursion during a reciprocating head movement. Observers performed the task monocularly while maintaining fixation on the point located at the center of the display.

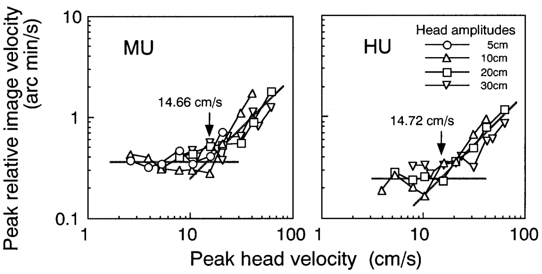

Fig. 2. Lower parallactic depth thresholds for each observer plotted as a function of peak velocity of sinusoidal head movement. The thresholds are expressed in terms of peak relative image velocity. The two straight lines in each graph were fitted to the threshold data using the least-squares method and fixing the values of their slopes as follows: zero with lower head velocities and one with higher head velocities. The value of the peak head velocity at the intersection of the two lines is shown in each of the two graphs.

2.2. Results and discussion

The analyses were performed in the following steps. First, the magnitude of the ratio of relative image velocity to head velocity as set by the observers' positioning of the knob was noted for each trial. Second, the standard deviations of the 20 obtained ratios (arc min/cm) for each condition were computed. Third, each standard deviation was multiplied by 0.6745 to estimate the just-noticeable difference (see, for example, Wood-

[1] The parallactic depth threshold may be higher when relative motion is perceived than when it is not, because there is a trade-off between parallactic depth perception and relative motion perception (Ono & Steinbach, 1990). We controlled for this effect by eliminating the conditions in which observers saw motion whenever they saw depth. The percept of relative motion described here is different from the percept of relative alignment change. When one sees two stationary planes in depth relative to exocentric coordinates, the relative alignment appears to change, but no relative motion is perceived, during head movements. When one sees two planes moving relative to exocentric coordinates, relative motion is seen.

worth & Schlosberg, 1954; Graham, 1965; Ono, 1993). Henceforth, the value computed in these steps is referred to as the 'threshold'. To convert this threshold into peak relative image velocity (arc min/s), it was multiplied by peak head velocity (cm/s). (If the reader wishes to examine the values in terms of equivalent disparity in arc min, use the conversion factor of 6.2/constant head velocity in cm/s.) Fig. 2 shows the values of peak relative image velocity as a function of peak head velocity.

The figure indicates that parallactic depth is not limited by a single determinant because the data points at high peak head velocities clustered around a slope of one and the data points at low peak head velocities clustered around a constant value. These data indicate that the lower parallactic depth threshold is determined by the ratio of peak relative image velocity to head velocity when the peak head velocities are high, and by peak relative image velocity alone when the peak head velocities are low.

To estimate the slope of the line(s) around which the data points clustered, best-fitted lines were determined for three sets of lines by the least-squares method. To quantify the extent of the clusters, η^2s (correlation ratios) were computed and used as indices of goodness of fit. Set A consisted of the best-fitting straight line for which the slope was free to vary. The other two sets consisted of the following two best-fitting straight lines. In set B, the slopes of the two lines were fixed, and in set C, the slopes of the two lines were free to vary. The fixed values of the slopes for set B were zero at the lower end of the tested head velocities and one at the higher end of the tested head velocities. The method used to fit two lines to the data points in sets B and C was the same as that described by Bogarts (1968), except that the slopes of the fitted lines were fixed in set B. The obtained η^2 and the values of the slopes of the fitted lines are presented in Table 1.

The results shown in Table 1 are congruous with our interpretation of Fig. 2 in that they show that the determinant of the lower parallactic depth threshold is head velocity-dependent. The fitted line with a slope of zero indicates that relative image velocity is the determinant of the lower parallactic depth threshold when the head moves slowly. The fitted line with a slope of one indicates that the ratio (equivalent disparity) is the determinant of the lower parallactic depth threshold when the head moves quickly. Our conclusion that two determinants of the lower parallactic depth threshold are operative over the range of tested head velocities is corroborated further by the following analyses. First, the least-squares fits for the data from both observers were appreciably better with two lines than with a single straight line, as shown by the larger η^2 in set B (0.79 for MU, and 0.82 for HU) and set C (0.80 for MU, and 0.83 for HU) as compared to set A (0.63 for MU and 0.74 for HU). Second, the goodness of fits with two different sets of two straight lines was almost the same. Set B, the one with more constraints (two fixed and two free parameters), yielded almost the same η^2 value as did Set D (four free parameters).

3. Experiment 2

Depth thresholds were measured with five different constant-head velocities instead of the sinusoidal head velocities used in Experiment 1. The aim was to determine whether our finding in Experiment 1 was dependent upon the acceleration and deceleration portion of the stimulus and head movements. Therefore, in Experiment 2, the stimulus for parallactic depth was not presented during the acceleration or deceleration portion of the head movement. Also, the motion threshold without head movement was measured to determine whether it is responsible for the depth threshold obtained with low velocity head movements.

3.1. Method

3.1.1. Observers

Four observers, one female (MU) and three males (HU, MO, QY) from the York University community participated. Observer, MU, had normal acuity, and

Table 1
Correlation ratio and slope of the line(s) fitted to the data shown in Fig. 2

	Fitted line	Observer	Correlation ratio η^2	Slope of fitted line	
				Slower HM[a]	Faster HM
Set A	One free straight line	MU	0.63		0.45
		HU	0.74		0.56
Set B	Two straight lines with 0 and 1[b]	MU	0.79	0.00	1.00
		HU	0.82	0.00	1.00
Set C	Two free straight lines	MU	0.80	0.04	0.90
		HU	0.83	0.18	0.95

[a] HM represents head movement.
[b] 0 and 1 indicates a slope of zero for lower head velocities and positive unity for higher head velocities.

observers HU, MO and QY wore glasses to correct for myopia. All four observers were experienced in psychophysical experiments, and all but one (HU) were naïve as to the purpose of the experiment.

3.1.2. Apparatus and stimulus

The apparatus and the stimulus were the same as those in Experiment 1. The movement of the head guide and the stimulus presentation differed, however. Unlike in Experiment 1, the head movement guide moved through a fixed distance of 30 cm. During the middle 20 cm portion of its excursion, it moved with a constant velocity, whereas, during its initial and final 5 cm excursions, it accelerated and decelerated, respectively. The stimulus was presented only when the guide moved with a constant velocity; when the guide accelerated or decelerated, a homogeneous gray (23.8 cd/m^2) field replaced the stimulus. As in Experiment 1, the ratio of relative image velocity to head velocity was adjusted with a rotary knob attached to a potentiometer.

During motion threshold trials, a rotary knob attached to a potentiometer controlled the relative velocity of the stimulus. The relative velocity was zero (no stimulus motion) at the middle position of the knob and increased up to 16.8 arc min/s symmetrically in proportion to the angular position of the knob from its middle position while the direction of motion was opposite at the two sides. The head movement guide was fixed at its middle position during the measurements.

3.1.3. Experimental conditions

In all conditions in which the depth thresholds were measured, the stimulus was presented only during the constant-velocity phase of the observers' head movements. There were five constant head velocities (3.92, 7.89, 15.8, 31.6 and 60.0 cm/s) and five stimulus durations (5.10, 2.53, 1.27, 0.63 and 0.33 s). These velocities and durations were combined to form nine experimental conditions. Five conditions were formed by combining each constant head velocity with the stimulus duration representing the time required for the observers to move their head 20 cm (3.92 cm/s with 5.10 s, 7.89 cm/s with 2.53 s, 15.8 cm/s with 1.27 s, 31.6 cm/s with 0.63 s, and 60.0 cm/s with 0.33 s). In addition, four conditions were formed by combining the four slowest constant head velocities with the shortest stimulus duration required for observers to report depth with confidence (3.92 cm/s with 0.63 s, 7.89 cm/s with 0.63 s, 15.8 cm/s with 0.63 s, and 31.6 cm/s with 0.33 s). For the 60.0 cm/s head velocity, the shortest stimulus duration required to report depth was the same as the time required to complete the head movement (i.e. 0.33 s). The purpose of the last four conditions described above was to ensure that any increases, expected from the results of Experiment 1, in the depth threshold at the higher head velocities were not due to the decrease in stimulus duration at the higher head velocities.

The motion thresholds were measured under two conditions. In one condition, the stimulus was presented intermittently with duration of 0.63 s and a duty ratio of 0.5. This duration was chosen from the set of durations used for the depth threshold measurements and was the shortest duration required for observers to report motion with confidence. In the other condition, the stimulus was presented intermittently with duration of 5.1 s and a duty ratio of 0.5. This duration was the longest duration used for the depth threshold measurements. When the stimulus was off, a homogeneous gray (23.8 cd/m^2) field replaced the gratings.

3.1.4. Procedure

The day before the first depth threshold session, each observer attended a 2 h session in which they practised following the guide with their head. At the end of the session, we videotaped the observers' head movements and analyzed their velocity profiles in the same manner as in Experiment 1. The analyses showed that all four observers followed the guide precisely and accurately in all of the nine experimental conditions. For each observer, the depth thresholds and the motion thresholds were measured on different days.

The depth thresholds were obtained in two experimental sessions using the method of adjustment. In each session, nine blocks (each consisting of 10 trials of a given condition) were presented in random order. Each condition was presented in both sessions, for a total of 20 trials per condition. At the beginning of each trial, the setting of the knob was such that the observers perceived depth among the gratings, and their task was to adjust the ratio, by turning the knob, until no depth was seen. In each trial, observers tended to make the adjustment after the homogeneous gray field replaced the stimulus and they then checked the outcome in the following stimulus presentation during a reciprocating head movement. Observers performed the task monocularly, while maintaining fixation on the point located at the center of the display.

The motion thresholds were obtained in six experimental sessions using the method of adjustment. In each session, two blocks (each consisting of 10 trials of a given condition) were presented in random order. Each condition was presented in all six sessions, for a total of 60 trials per condition. At the beginning of each trial, the setting of the knob was such that the observers perceived relative motion among the gratings, and their task was to adjust the velocity, by turning the knob, until no motion was seen. Observers performed the task monocularly and with a stationary head, while maintaining fixation on the point located at the center of the display.

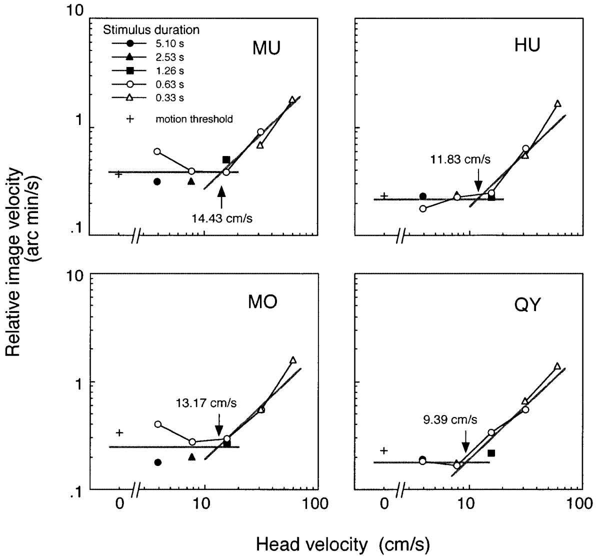

Fig. 3. Lower parallactic depth thresholds for each observer plotted in terms of relative image velocity as a function of head velocity. The two straight lines in each panel were fitted to the threshold data using the least-squares method and fixing the values of their slopes as follows: zero for lower head velocities and one for higher head velocities. The value of the peak head velocity at the intersection of the two lines is shown in each panel.

3.2. Results and discussion

The thresholds were analyzed in the same manner as in Experiment 1, and the results are shown in Fig. 3. The motion thresholds were computed in the same way as the depth thresholds, with the exception that all of the obtained relative image velocities (arc min/s) from both duration conditions were combined prior to calculating the standard deviation ($n = 120$). This was done because our preliminary calculations indicated that the motion thresholds were independent of stimulus duration for all but one observer. (For observer QY, the 5.1 s stimulus duration yielded a smaller threshold than did the 0.63 s duration.) The estimated motion threshold is plotted as a cross in Fig. 3.

As in Experiment 1, the results from this experiment show that there are two determinants of the lower parallactic depth threshold. From Fig. 3, it is clear that for slow head movements, the threshold is determined by relative image velocity alone, and for fast head movements, the threshold is determined by the ratio of relative image velocity to head velocity. In addition, the results confirm that the increase in the depth threshold at the higher head velocities is not due to a decrease in stimulus duration. Only two of the 16 comparisons (four observers × four head velocities) revealed a significant effect of stimulus duration, ($F(19,19) = 3.64$, $P < 0.01$ for observer MU, and $F(19,19) = 4.93$, $P < 0.01$ for observer MO; both at the 3.92 cm/s head velocity). Although these two comparisons showed that for observers MU and MO, the depth threshold was higher for the short stimulus duration (0.63 s) than for the long stimulus duration (5.10 s), at the 3.92 cm/s head velocity, this increase in the depth threshold was well below the increase as a function of head velocity (see Fig. 3). Accordingly, we conclude that the higher depth thresholds observed at the higher head velocities were not due to the short stimulus durations associated with those head velocities.

To quantify the extent to which the two determinants account for the results, we fitted two sets of lines to the plotted values and determined η^2s (correlation ratios) for the fitted line(s). Set A consisted of the best-fitting straight line for which the slope was free to vary. Set B consisted of the two best-fitting straight lines whose slopes were fixed to zero at the lower end of the tested head velocities and to one at the higher end of the tested head velocities. The obtained correlation ratios are presented in Table 2.

The results shown in Table 2 are congruous with our interpretation of Fig. 3, in that they show that the determinant of the lower parallactic depth threshold is head velocity-dependent as in Experiment 1. That is, the correlation ratios with two fitted lines (Set B) are larger than those with a single fitted line (Set A). Moreover, the horizontal position of the transition point between these two determinants derived with the two fitted lines, as indicated by the arrow in each panel of Fig. 3, is almost identical to that shown in Fig. 2 of Experiment 1. In this experiment, the mean value is 12.21 cm/s, while in Experiment 1, the mean value was 14.69 cm/s.

In addition to confirming our finding that the determinant of the lower parallactic depth threshold, when the head moves slowly, is relative image velocity, our

Table 2
Correlation ratio of the line(s) fitted to the data shown in Fig. 3

	Fitted line		Correlation ratio η^2			
		Observer	MU	HU	MO	QY
Set A	One free straight line		0.60	0.76	0.62	0.83
Set B	Two straight lines with 0 and 1[a]		0.85	0.92	0.85	0.96

[a] 0 and 1 indicates a slope of zero for lower head velocities and positive unity for higher head velocities.

statistical analyses show that the value of this determinant equals the value of the motion threshold. For the two highest head velocities (31.6 and 60.0 cm/s), all eight comparisons showed that the depth threshold was significantly higher than the motion threshold ($P < 0.05$); the range of F values was $F(39,119) = 3.19$ to $F(19,119) = 49.0$. For the three lowest head velocities (3.92, 7.89 and 15.8 cm/s), nine out of 12 comparisons showed that the depth threshold did not differ significantly from the motion threshold ($P > 0.05$); the range of F values was $F(39, 119) = 0.73$–1.60. Of the remaining three comparisons, one showed that the depth threshold was marginally higher than the motion threshold ($F(39,119) = 1.71$ for MU at the 3.92 cm/s head velocity), and two showed that it was marginally lower than the motion threshold ($P < 0.05$; F values were, $F(39,119) = 0.55$ for QY and $F(39,119) = 0.57$ for MO, both at the 7.89 cm/s head velocity). When the slow head velocity results were analyzed by combining each observer's depth thresholds from the three lowest head velocities, however, no significant differences between these combined depth thresholds and the motion threshold were observed; ($F(119,119) = 1.37$, $P > 0.05$ for MU; $F(119,119) = 0.94$, $P > 0.05$ for HU; $F(119,119) = 0.73$, $P > 0.05$ for MO; $F(119,119) = 0.97$, $P > 0.05$ for QY). Therefore, we tentatively conclude that when the head moves slowly, the motion threshold determines the lower parallactic depth threshold. The statistical analyses described above consisted of a series of F-tests, rather than a within-subject ANOVA, because for a given observer, there was no within-condition variability associated with the thresholds (i.e. the within-condition variability was the threshold).

4. General discussion

The results of the experiments show that both relative image velocity alone and the ratio of relative image velocity to head velocity determine the lower parallactic depth threshold. Which of the two is operative is dependent on head velocity (or peak head velocity when head velocity is sinusoidal). When the head moves slower than approximately 13 cm/s, relative image velocity alone, or more precisely the motion threshold (approximately 0.26 arc min/s) determines the depth threshold. Conversely, when the head moves faster than approximately 13 cm/s, the ratio of relative image velocity to head velocity (approximately 0.021 arc min/cm) determines the depth threshold. These two determinants account for the results provided by both sinusoidal and constant-velocity head movements in Experiments 1 and 2, respectively.

An alternative explanation of our results is that the motion threshold increases when the head velocities are above 13 cm/s, and thus the motion threshold, in fact, determines the lower parallactic depth threshold over the entire range of head velocities. A possible cause for the increase of the motion threshold that we found is the increasing instability of fixation with higher head velocities (Ferman, Collewijn, Jansen, & Van den Berg, 1987). This instability of eye fixation adds common motion to the relative image motion (Ferman et al., 1987), which in turn increases the parallatic depth threshold by increasing the differential motion threshold (Nakayama, 1981; McKee & Nakayama, 1984).

We tentatively reject this alternative explanation for the following reason. When one moves his/her head with stationary stimuli visible in the wide visual field, the vestibulo-ocular reflex and the optokinetic reflex stabilize eye fixation quite well (Schweigart, Mergner, Evdokimidis, Morand, & Becker, 1997). Specifically, the gain of eye-in-head rotation was one when head movement frequencies ranged from 0.05 to 1.6 Hz. Instability of fixation with high head velocities reported by Ferman et al. (1987) was measured with small visual stimuli (12 min of arc diameter) and does not apply to our stimulus situation, since the frame of our screen display and the dimly illuminated room were clearly visible. To evaluate this alternative explanation, however, we need to measure fixation errors during a lateral head movements, since Schweigart et al.'s (1997) data were obtained with a head rotation.

Assuming that there are two determinants of the lower parallactic depth threshold, we propose the following ratio-coding system to explain how they operate. We propose that the perception of parallactic depth is based on the coded ratio of relative image velocity to head velocity, and that the relative image velocity used by the parallactic depth system is the same as that used by the motion perception system, as claimed by Ono and Ujike (1994) and Ono et al. (1998). Presented in Fig. 4 is a schematic illustration of how this ratio–coding system operates. In the figure, the vertical position of the line with the slope of zero represents the motion threshold, and the position of the line with the slope of one represents the critical ratio. The system can code the ratio only when the relative image velocity is above this motion threshold and can produce a percept of depth only when this coded ratio exceeds its critical value. Neither of the following two situations yields a percept of depth: neither (a) a relative image velocity above the motion threshold with a ratio below the critical value (hatched area A in Fig. 4), nor (b) a ratio above the critical value with a relative image velocity below the motion threshold (hatched area B in Fig. 4). Depth is seen when relative image velocity is at or above the motion threshold and when the ratio is at or above the critical value. The line above area A represents the depth threshold as determined by the critical ratio when the head moves quickly. The line above area

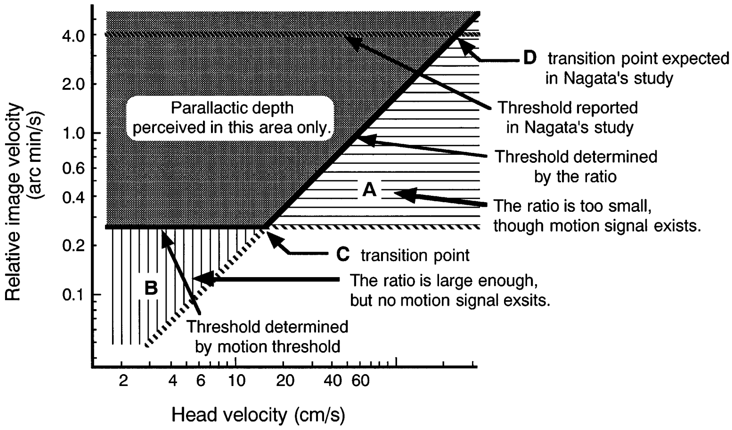

Fig. 4. Schematic illustration of the conditions required to perceive parallactic depth. Parallactic depth can be perceived when relative image velocity is above the motion threshold and the ratio is above its critical value (gray area). Parallactic depth cannot be perceived when the relative image velocity is above the motion threshold and the ratio is below its critical value (area A), or when relative image velocity is below the motion threshold and the ratio is above its critical value (area B).

B represents the depth threshold as determined by the motion threshold when the head moves slowly.

In the ratio-coding system, the denominator of the ratio is head velocity. There are several sources from which a head velocity signal can be produced. For example, Rogers and Rogers (1992) found that both non-visual (i.e. vestibular and proprioceptive information) and visual information (i.e. retinal image transformation produced by head movement) can effectively disambiguate parallactic depth direction, by providing sufficient information about head movement (Rogers & Graham, 1979; Hayashibe, 1993). In addition to the sources examined by Rogers and Rogers, the oculomotor system may be another possible source. In our experiments, for example, eye movements covaried with head movements and, thus, the visual system could potentially use the eye movement signal as a head movement signal (Nawrot, 1997, 1998).

The ratio-coding system explains Nagata's (1984) results, which show that the depth threshold is independent of head velocity for the range of velocities he examined. Given that Nagata's stimulus was much simpler and smaller (two rods, 20 arc min width $\times$ 40 arc min height) than ours, it is likely that the motion threshold in his study was much higher than that for our stimulus. (For a study showing that the motion threshold increases with a decrease in stimulus size (width $\times$ length), see Anderson & Burr, 1991, for example.) The two likely consequences of the higher motion threshold in Nagata's stimulus situation are: (a) an increase in the depth threshold for the head velocities in which the depth threshold is determined by the motion threshold and (b) an increase in the range of head velocities over which the depth threshold is determined by the motion threshold. In terms of our Fig. 4, the transition point between the two determinants of the lower parallactic depth threshold would shift to a much higher head velocity in Nagata's study. In fact, the depth threshold reported by Nagata was approximately 16 times higher than the value we obtained (approximately 4 arc min/s across different head velocities compared to our 0.26 arc min/s). Thus, for his stimulus situation, the transition point C for the vertical position of 4 arc min/s in Fig. 4 would shift to a higher head velocity value along the line of the depth threshold determined by the ratio; the transition point for his stimulus situation would be at point D of our Fig. 4.

Although the ratio-coding system proposed here explains the results of our experiments, the question of why this system does not make use of low-velocity signals when the head moves fast is not addressed (area A in Fig. 4). A possible answer to this question, from an engineering point of view, is that the signal-to-noise ratio for the coded ratio of relative image velocity to head velocity below its critical value is too small for the system to recover the parallactic depth. Another possible answer, from a biological point of view, is that the motion parallax system is rarely required to detect such small extents of depth; the value near the threshold, for example, is about 0.34 mm at 50 cm away. When such fine resolution is required, the binocular stereopsis system, which has a sensitivity of about twice that of the motion parallax system (Rogers & Graham, 1982), can provide the depth information.

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