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PERCEIVED DEPTH FROM MOTION PARALLAX : EFFECTS OF THE RELATIVE MOVEMENT OF AN OBSERVER'S HEAD WITH RESPECT TO A STIMULUS DISPLAY

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Abstract: Two experiments examined the effects of relative movements of the head with respect to a stimulus display on the magnitude and direction of the perceived depth from motion parallax. In Experiment 1, a velocity gradient of random-dots moving in opposite directions was presented in three viewing conditions: (a) stationary head-and-display, (b) display-movement, and (c) head-movement. The observer's task was to report the direction and magnitude of the perceived depth. The results with 10 observers showed that the magnitude of the perceived depth in condition (b) was lower than those in conditions (a) and (c), while the direction was unambiguous in (b) and (c), but ambiguous in (a). In Experiment 2, the direction of the perceived depth was examined in six conditions including the three of Experiment 1; in the other three conditions both head and display were moving in the same direction but with different ratios of the display velocity to the head one: (d) 0.5, (e) 1.0, and (f) 2.0. The results with 11 observers showed that unambiguous depth perception was obtained in conditions (b), (c), and (f) but not in conditions (a), (d), and (e). Furthermore, the depth order perceptions in (b) and (a) were identical to those in (f), and (e), respectively. The experimental results suggest that relative movement of the head with respect to the display irrespective of either movement is processed to determine the perceived depth order and that the velocity gradient within the display is processed to determine the magnitude of the perceived depth.

Keywords: *motion parallax, depth perception, depth order, relative movement of head and display*

1. INTRODUCTION

Three different methods have been used to simulate optical effects of an observer's lateral head movements in recent studies on motion parallax. First, a velocity gradient of moving random-dots produced on a stationary display is presented to a stationary observer (e.g., Ono and Steibach [1]). See Figure 1a. This is referred to as the stationary head-and-display condition, in which depth perception has traditionally been called the kinetic depth effect (Wallach and O'Connell [2]). In this condition, the relative position of the observer's head with respect to the display is always unchanged while the velocity gradient is presented. Second, the velocity gradient yoked to the lateral display movement is presented to the stationary observer (e.g., Braunstein and Tittle [3] Rogers and Graham [4]). See Figure 1b. This is referred to as the display-movement condition. Third, the velocity gradient yoked to the observer's lateral head movements is presented to her/him (e.g., Rogers and Graham [4]). See Figure 1c. This is referred to as the head-movement condition. In the last two conditions, the relative position of the observer's head with respect to the display is continuously changing while the head or display moves.

Rogers and Graham [4], who pioneered the technique to present moving random-dots yoked to head or display movements, found that both the display-movement and head-movement conditions¹ yield an effective, consistent, and unambiguous depth order as well as an extent of apparent depth. They found that the depth effects were ambiguous in the stationary head-and-display condition; and further, that the magnitude of perceived depth obtained in the head-movement condition was greater than that obtained in the display-movement condition. Whereas, Ono and Steinbach [1] compared the magnitudes of perceived depth and perceived motion between the head-movement condition and the stationary head-and-display condition² and found stable but different apparent depth and motion between the two conditions. However, they did not examine the direction of the perceived depth. Braunstein and Tittle [3] and Braunstein and Anderson [5], using the stationary head-and-display condition, and showed that the perceived

¹In their terminology; the externally produced parallax condition and the self-produced parallax condition, respectively.

²In their terminology; the no head movement condition

Figure 1: A schematic representation of the stimulus and the conditions used in the experiments. The left panel indicates the six conditions. (a): the stationary head-and-display condition, (b): the display-movement condition, (c): the head-movement condition, (d): 0.5 velocity ratio of display-to-head movement, (e): 1.0 ratio, and (f): 2.0 ratio. In the right panel, the top drawing shows random-dots moving side-to-side modulated sinusoidally and the middle and bottom drawings show percepts of 'convex' and 'concave', respectively. In the figure, only rightward arrows showing movements rightward are depicted.

depth order was unambiguous when the velocity field contained a pattern of dots moving in the same direction with different velocities, and when the maximum to minimum velocity ratio was small. When the velocity field contained dots moving in opposite directions with different velocities, however, the perceived depth order was theoretically predicted as ambiguous. In effect, their studies confirmed that the perceived depth order was ambiguous in the stationary head-and-display condition when the velocity field contained dots moving in opposite directions (Braunstein and Tittle [3] Rogers and Graham [6]).

The studies cited above suggest that when a velocity field contains random-dots moving in opposite directions with different velocities, the visual system utilizes visual and/or non-visual information to disambiguate the depth of a surface. Proprioceptive and vestibular signals as non-visual information are produced when the observer's head moves. Or, additional visual information is available when the display or head moves. It seems likely that this information is used for the visual system to disambiguate the depth of the surface. Rogers and Rogers [7] confirmed such predictions to be valid.

When both the observer's head and the display move with the same or different velocities, what would happen? Figure 1 illustrates six types of head and/or display movement conditions employed in the present study. In (a) both the

head and the display are stationary, while either the display (b) or the head (c) moves at a certain velocity. In the remaining conditions (d-f), the head moves at the same velocity as in (c), while the display velocity is changed such that the display to head velocity ratio is 0.5 (d), 1.0 (e) or 2.0 (f). Relative movement between the display and the head, defined here as display velocity minus head velocity, is the same for (a) and (e) and for (b) and (f). The basic question here is whether or not depth perception is identical when the relative movement of the head with respect to the display is the same.

The primary aim of this study was to answer to this question. That is, we examined effects of the relative movement of the observer's head with respect to the display on the perceived depth order of a velocity field containing random-dots moving in opposite directions and with different velocities. In particular, we focused on perception of the depth order in the conditions in which the relative movements were unchanged. If the relative movement of the head with respect to the display determines unequivocally the perceived depth order, the perceived depth order should be unchanged when the relative movement is identical even though both head and display move with different velocities. The secondary aim of the study was to compare the extent of the perceived depth among three conditions, the head-movement, the display-movement, and the stationary

head-and-display conditions, in making the velocity gradients within the display constant. This is because, as far as we know, there is no study comparing these three conditions where the velocity gradients presented are identical.

2. EXPERIMENT 1

The experiment essentially replicated Rogers and Graham [4] and Ono and Steinbach [1]. The former examined depth perception in just head-movement and display-movement conditions, while the latter examined depth perception in just head-movement and stationary head-and-display conditions. The present experiment, however, examined the direction and extent of perceived depth in the three conditions with the same extent of velocity gradient consisting of the random dots pattern: the stationary head-and-display, the display-movement, and the head-movement conditions.

2.1 Method

2.1.1 Stimulus and Apparatus.

Random dot techniques were used to simulate a sinusoidally corrugated three-dimensional surface similar to those of Rogers and Graham [4]. The stimulus was a square-shaped random-dot pattern, as shown in Figure 1, projected on a rear screen. The size of the stimulus was $24.4\text{ cm} \times 24.4\text{ cm}$, $13.7^\circ \times 13.7^\circ$ in visual angle. The dot size was 10 min of arc with a density of 6.5 dots/cm^2 . The dot motion modulated sinusoidally was yoked to the observer's head or the display movement.

Figure 2 shows schematically the apparatus used in our experiment. The TV camera 1 (Hamamatsu Photonics, C1700) displayed black and white randomly distributed cells providing the random-dot pattern on the X-Y monitor (Tektronics, 604). The TV camera 2 displayed the random-dot pattern on the X-Y monitor on a liquid crystal TV monitor. The pattern was projected to a translucent projection rear screen by a slide projector (Fuji Model E1). The liquid crystal TV monitor and the slide projector were mounted on the joined Y-bars of two X-Y recorders (Graphtec Model 4401) so that the TV monitor could be moved by a signal fed into the X-Y recorders. A rectilinear potentiometer was used to yoke the lateral movement of the observer's head to the horizontal movements of dots within the display.

2.1.2 Procedure

The observer's head was supported on a chin-and-forehead holder that could move 10 cm along a

track parallel to the projection screen. The location of the holder was adjusted so that the center of the stimulus was in the median plane of the observer's head at eye level. The screen was viewed in a room dimly illuminated by a room light. The observers viewed the screen monocularly with their left eye at a distance of 100 cm from the screen. The equivalent disparity and the simulated depth given by motion parallax were 14.4 min of arc and 7.5 cm, respectively.

In the head-movement condition (Fig. 1c), the observer was required to move her/his head 10 cm from side-to-side at a preferred speed.³ In the display-movement condition (Fig. 1b), the observer was required to hold her/his head still on the stationary chin-and-forehead holder and the relative motion of dots within the display was yoked to the overall translation of the display. The display was arranged to move externally 10 cm by the signal at 0.4 Hz from a function generator (FM-Model 122). In the stationary head-and-display condition (Fig. 1a), the observer was required to hold her/his head still on the stationary chin-and-forehead holder and the relative motion of dots

Figure 2. A schematic representation of the apparatus used in the experiments. (See text in detail)

³A pilot study showed that the observer's preferred frequency of head movement was approximately 0.4 Hz on average. Accordingly, one cycle of head movement took 2.5 sec. Since distance of the head movement of a half cycle was 10 cm, the average velocity of head movement was approximately 8 cm/sec.

within the display was driven externally by a signal at 0.4 Hz from the function generator.

Two opposite phases of dot movements within the display were used so that the observer's spatial interpretation of the surface was not always associated with the same direction of the motion of dots. In phase A, each movement of the observer's head to the right (the head-movement condition) or each movement of the display to the right (the display-movement condition) caused a horizontal portion of dots nearest to the horizontal midline of the display to move to the left, as shown in the right panel of Figure 1. In phase B, each movement of the observer's head to the left or each movement of the display to the left caused a horizontal portion of dots nearest to the horizontal midline of the display to move to the left. This transfer from phase A to phase B was done by making the phase of the sinusoidal signal from the function generator reverse. In the stationary head-and-display condition, the two phases of the dot motion were identical.

There were three tasks required of the observers. The first was to indicate verbally whether the random-dots surface appeared to be a rigid three-dimensional corrugated surface or a two-dimensional flat surface. The second was that if the 3-D surface was perceived the observers had to report 'convex' when the central horizontal portion of the display appeared convex and 'concave' when it appeared concave. These responses were a measure for the perceived depth order. The third was to adjust the length of a tape so that it appeared equal to the extent of the perceived depth, namely a separation between the peak and trough of the corrugation perceived in the central portion of the display. These adjustments were a measure for the extent of the perceived depth. Twelve trials were run for each observer and each condition. Half the trials were for phase A and the other half for phase B. The order of the presentation of the two phases was randomized, and the order of the conditions was changed for the observer.

2.1.3 Observers

Ten observers, volunteers from the National Institute of Advanced Industrial Science and Technology, participated in the experiment. All had self-reported normal or corrected-to-normal visual acuity. Eight observers were naive concerning the purpose of the experiment. The two authors also participated as observers.

2.2 Results and Discussion

All observers reported a rigid 3-D surface of the display; that is, the central portion of the display appeared either

convex or concave in all trials.⁴ This was true even for the stationary head-and-display condition.

Two sets of analyses were performed: one for the depth order and the other for the magnitude of the perceived depth. The rate of the 'convex' response for 6 trials in each stimulus phase was calculated for each observer and was used as a basic unit for further analyses. (One minus the rate of the convex response is the rate of concave response.)

2.2.1 Perceived depth order

A one way (3 viewing conditions) repeated measure analysis of variance was performed using the mean rate of the convex response averaged over the six trials for each subcondition and each observer as a basic unit of analyses, which was transformed to arcsine, separately for each phase. The main effect of the condition was significant for both phases [phase A: $F(2, 18) = 65.301, p < .001$; phase B: $F(2, 18) = 49.865, p < .001$]. These significant main effects of the condition are illustrated in the bar graph shown in Figure 3, in which the mean rate of the convex response as a function of the conditions; separately for phases A and B.

The results of multiple comparisons (by Ryan's method) showed significant differences among the means of the three conditions [Stationary head-and-display condition vs Display-movement conditions: $t(2) = 3.169, p < .05$, for phase A; $t(2) = 6.692, p < .05$, for phase B; Head-movement vs Display-movement conditions: $t(2) = 11.093, p < .05$, for phase A, $t(2) = 9.766, p < .05$, for phase B; Stationary head-and-display condition vs Head-movement conditions: $t(2) = 7.924, p < .05$, for phase A, $t(2) = 3.074, p < .05$, for phase B].

The mean rates of the convex response in the stationary head-and-display condition were .317 and .300 for phases A and B, respectively. These values were not always 0.5, i.e., the chance level. These facts may imply that the stimuli used in this experiment had somehow a bias to produce the convex response more than the concave. However, 99 % confidence intervals calculated from the mean and standard deviation obtained were 0 – .634 and 0 – .621, for phases A and B, respectively, indicating the chance level contained in the interval. These results imply that depth order perception produced in this condition is unstable and ambiguous, being consistent with the theoretical prediction that the rate of convex response is 0.5.

The depth perception obtained in the display-movement

⁴One minus the rate of the convex response represents the rate of 'concave' response.

Figure 3. Mean rate of the convex response plotted as a function of the condition; separately for phases A and B (Experiment 1). (a): the stationary head-and-display condition, (b): the display-movement condition, and (c): the head-movement condition.

and head-movement conditions is stable and unambiguous, confirming the results of previous studies (Ono and Steinbach, [1] Rogers and Graham [4] Rogers and Rogers [7]). The rate of the convex response in the head-movement condition was .983 and .017 for phases A and B, respectively. These results showed that the dots moving in the opposite direction to that of the head movement appeared nearer than those moving in the same direction for nearly 98.5 %. The rate of the convex response in the display-movement condition was .050 and .917 for phases A and B, respectively. These results showed that the dots moving in the same direction as that of display movement appeared nearer than those moving in opposite direction for nearly 93.4 %.

2.2.2 Perceived magnitude of depth

A two-way (3 viewing conditions by 2 phases) repeated measure analysis of variance was performed on the mean magnitude of the perceived depth averaged over 6 trials in each subcondition and for each observer. The main effect of the viewing condition was significant [$F(2, 18) = 9.773, p < .001$] but the main effect of the phase and the interaction effect were not significant [phase: $F(1, 9) = .035$; interaction effect: $F(2, 18) = .067$]. The significant main effect of the viewing condition is illustrated in the bar graph shown in Figure 4, in which the mean magnitude of the perceived

depth is averaged over the two phases as a function of the conditions.

Figure 4. Mean magnitude of the perceived depth averaged over the two phases plotted as a function of the condition. The small vertical lines indicate the standard deviations. The horizontal dotted line indicates the physical depth simulated by the equivalent disparity of the motion parallax. (a): the stationary head-and-display condition, (b): the display-movement condition, and (c): the head-movement condition.

The results of multiple comparisons for the main effect of the viewing conditions (by Ryan's method) showed that the mean magnitude of the perceived depth in the display-movement condition was smaller than those in the head-movement and the stationary head-and-display conditions. [Head-movement: $t(18) = 4.374, p < .05$; Stationary Head-and-Display condition: $t(18) = 2.743, p < .05$]. The larger magnitude of the perceived depth in the head-movement condition than that in the display-movement condition confirmed the findings of Rogers and Graham [4]. No significant difference was observed in the magnitude of the perceived depth between those in the head-movement condition and in the stationary head-and-display condition was inconsistent with the results of Ono and Steinbach [1], who showed that the magnitude of perceived depth in the head-movement condition was greater than that in the stationary head-and-display condition. The reason of this inconsistency between the results of the two experiments is unclear. However, the difference in the methods used

between the two studies, such as an extent of motion parallax (equivalent disparity), the viewing distance, and the distance of head movement, might have been reflected in the inconsistency.

3. EXPERIMENT 2

The aim of this experiment was to examine the effects of the relative movement of the head with respect to the display on perceived depth order from motion parallax. In particular, we were interested in the perceived depth order when both head and display moved with equal or different velocities. Six different viewing conditions were used; three conditions were the same as those in Experiment 1 and the other three were conditions in which both head and display moved with equal or different velocity ratios, as shown in Figure 1. (These were called the head-and-display movement conditions.)

If the relative movement of the head with respect to the display was to be critical in determining depth order, then the perceived depth order should be varied depending on the velocity ratios between the head and display. Furthermore, the perceived depth order in the head-and-display movement with a 1.0 velocity ratio condition (e) should be equal to that in the stationary head-and-display condition (a). Also, the perception of depth order in the head-and-display movement with a 2.0 velocity ratio (f) should be equal to that in the display-movement condition (b). These predictions were examined in the experiment.

3.1 Methods

3.1.1 Stimulus and apparatus.

The stimulus and apparatus were essentially the same as those used in Experiment 1, with the exception that in the head-and-display movement condition the display moved yoked to the head movement. The signals from the rectilinear potentiometer, which picked up the head movements, were used to move the display with its gain varied.

3.1.2 Procedure

The procedure was the same as that in Experiment 1 except for the head-and-display movement condition. The six conditions as shown in Figure 1 were used. The extent of velocity gradient of moving the random-dots within the display was held constant in all conditions. In Figure 1, the (a), (b), and (c) conditions were the same as those in Experiment 1; the (d), (e), and (f) conditions were new; in these both head and display moved with different velocity

ratios; 0.5, 1.0, and 2.0, respectively. With regard to the relative movement between the head and display, condition (a) was equal to condition (e) and (b) was equal to (f).

Two phases of dot movements were used as Experiment 1. In the three head-and-display movement conditions, each movement of the observer's head to the right caused a horizontal portion of dots nearest to the horizontal midline of the display to move to the left and right in phase A and B, respectively.

Two tasks were required of the observers. The first was to indicate verbally whether the random-dot surface appeared to be a rigid three-dimensional corrugated surface or a two-dimensional flat surface. The second task was that if the 3-D surface was perceived the observers had to report 'convex' when the central horizontal portion of the display appeared convex or 'concave' when the central horizontal portion of the display appeared concave. Twelve trials were run for each subcondition; half of the trials were for phase A and the other half were for phase B; 72 trials were run in total. The order of presentation of the two phases was randomized in each condition; and the order of the condition was changed for each observer.

3.1.3 Observers

Eleven observers (including the two authors) participated in the experiment, 9 were thus naive concerning the purpose of the experiment. All had self-reported normal or corrected-to-normal visual acuity.

3.2 Results and Discussion

All observers reported the rigid 3-D corrugation in the display in all trials as in Experiment 1. The mean rate of the convex response averaged over 6 trials for each phase of each viewing condition and for each observer was calculated, then transformed to arcsine, and used as a basic unit for further analyses.

A two-way (6 conditions by 2 phases) repeated measure analysis of variance was performed. The main effect of the condition and the interaction effect were significant [condition: $F(5, 50) = 9.133$, $p < .001$; interaction: $F(5, 59) = 126.775$, $p < .001$]. The main effect of the phase was not significant [$F(1, 10) = 1.475$]. A one-way (6 conditions) repeated measure analysis of variance was performed separately for each phase. The main effect of the condition was significant for each phase [phase A: $F(5, 50) = 56.134$, $p < .001$; phase B: $F(5, 50) = 67.294$, $p < .001$]. Figure 5 shows the mean rate of the convex response plotted as a function of the condition, separately for each phase. The main effects of the condition are illustrated in the bar graph

Figure 5. The mean ratio of the convex response plotted as a function of the condition, separately for phases A and B. (a): stationary head-and-display, (b): display-movement, (c): head-movement, (d): 0.5 velocity ratio of display-to-head movement, (e): 1.0 ratio, and (f): 2.0 ratio.

shown in Figure 5. The non-significance of the main effect of the phase was because the profiles of the mean rate of convex response obtained for phase A were opposite to those for phase B. This was because one minus a rate of the convex response indicates a rate of the concave responses.

The results of multiple comparisons (by Ryan's method) showed that there were no significant differences in the mean rates of the convex response between the stationary head-and-display and the head-and-display movement with 1.0 velocity ratio conditions [phase A: $t(50) = 0.398$, phase B: $t(50) = 0.006$]. There were also no significant differences between the display-movement and the head-and-display movement with 2.0 velocity ratio conditions [phase A: $t(50) = 0.043$, phase B: $t(50) = 0.941$].

When the relative movement of the head with respect to the display was identical in the two conditions, the perceived depth order was unchanged irrespective of whether the head or the display moved, or if both moved. The results of the above statistical analyses shows that the mean rate of the convex response in the stationary head-and-display condition, (a), was nearly equal to that in the 1.0 velocity ratio condition, (e). The mean rate of the convex response in the display-movement condition, (b) was nearly equal to that in the 2.0 velocity ratio condition, (f).

The results of the depth order in conditions (a), (b), and (c) confirmed those in Experiment 1 and previous studies. The

mean rates of the convex response for phase A in conditions (a), (b), and (c) of Experiment 1 were .317, .050, and .983, and those of Experiment 2 were .236, .041, and .973, respectively. The mean rates of the convex response for phase B in conditions (a), (b), and (c) of Experiment 1 were .300, .917, and .017, and those of Experiment 2 were .264, .973, and .014, respectively. The differences in the corresponding values between Experiments 1 and 2 were not significant [phase A: $t(19) = 0.629, 0.209$, and 0.437 ; phase B: $t(19) = 0.273, 1.244, 0.131$, respectively]. These results showed that the perception of depth order in Experiment 1 was almost equal to that in Experiment 2.

The results obtained in the head-and-display movement conditions showed that the perception of depth order changed in a systematic fashion when the relative movement of the head with respect to the display was varied. When the relative movement increased from -1.0 to 1.0 , the mean rate of the convex response for phase A increased gradually, while that for phase B decreased gradually. These results suggest that the visual system determines the depth order as if utilizing the relative movement of the head to the display. It is interesting to note that when the relative movement was 0.5 , the mean rate of the convex response was intermediate between 0 and 1.0 relative movements. This result suggests that the visual system monitors precisely the velocity ratio of the head movement to the display movement.

4. GENERAL DISCUSSION

The results of the experiment showed that the relative movement of the head with respect to the display determines the perceived depth order of a velocity gradient of random-dots moving in opposite directions within the display, whether the head and display move, or either move. For instance, the perceived depth order was quite ambiguous in condition (e), in which the head and display move with a 1.0 velocity ratio. This implies that depth order perception does not depend on the head movement or the display movement per se, but rather it depends on the relative movement between them.

The idea that the perception of depth order depends on the relative movement of the head with respect to the display is consistent with the 'common motion' hypothesis (Braunstein and Tittle [3] Howard and Rogers [8]), which states that head movement adds velocity vectors to relative motion within the display. This velocity vector provides independent information on the relative positional change of the head with respect to the display. The movement of the display also adds a velocity vector to the velocity gradient as the movement of the head. The visual system determines the depth order from the velocity gradient within the display by taking information on the direction of the common motion.

It has been argued that there are two sources for perception of common motion (Howard and Rogers [8]); one is an extra-retinal signal, and the other a retinal signal. Both efference and afference signals from eye and head movements are candidates for the extra-retinal signal. The former is an efference signal commanding the eye and/or head to move, while the latter is a feedback signal from the eye muscles and vestibular system. Retinal signals are visual or optical changes of perspective cues as a result of eye or display movements and the relative change of the display with respect to the background. However, based on the results of the present study we conclude that the visual system determines the depth order by utilizing information on the relative movement of the head with respect to the display, which is derived from retinal information.

In summary, the visual system processes two types of separate relative motion: one is the relative motion within a display, and the other is the relative movement between the head and display. The extent of perceived depth is based on the former information while the perceived depth order is based on the latter.

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