Importance of Visual Information at Change in Motion Direction on Depth Perception from Monocular Motion Parallax

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***Abstract*: This paper demonstrates the importance of visual information on depth perception from monocular motion parallax presented at the time of change in the motion direction of head and stimulus movements. In head-tracking systems, a longer delay time between the head and stimulus movements degrades the depth perception from monocular motion parallax. Because this delay is noticeable at this time, we hypothesized that the visual information given at the time of the direction change plays a critical role in the depth perception from motion parallax. We evaluated depth perception from monocular motion parallax with and without a visual stimulus at the time of the motion direction change to confirm our hypothesis, and clarified that stable and unambiguous depth can be perceived by presenting the change of the stimulus motion direction. We also demonstrated that it is the change in motion direction itself that is important rather than the temporal stop between deceleration and acceleration of the stimulus motion.**

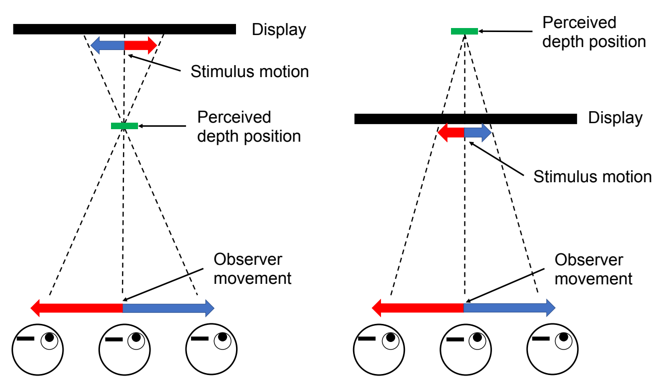
***Index Terms*: 3D, motion parallax, monocular viewing, depth perception, head movement, head-tracking, delay time, changing motion direction**

I. Introduction

Commercially available conventional 3D displays utilize binocular disparity and vergence to provide a 3D sensation. However, stereoblind people cannot perceive depth with binocular disparity. Motion parallax is a promising choice to provide a 3D sensation to everyone, including stereoblind people. Motion parallax refers to the relative motion of the retinal images of objects positioned at different depths when the observer's position changes. The direction and magnitude of the retinal motion are determined geometrically by the relationship between the movements of the positions of the observer and the objects. Motion parallax, which is one independent, monocular depth cue, provides consistent depth perception without other depth cues [1]. This means that motion parallax has sufficient information of relative depth positions of the objects even with one eye.

Monocular motion parallax can be implemented on typical 2D displays. As shown in Fig. 1, the depth by motion parallax in front of or behind the display can be perceived when the stimulus moves in the opposite or same direction as the observer's head movement, respectively. The depth magnitude depends on the magnitude of the stimulus movement. Thus, synchronizing the stimulus movement with the observer's head movement is necessary.

Motion parallax is often utilized in interactive and virtual reality (VR) systems. As mentioned above, simulated motion parallax must be synchronized with the observer's head movement. However, in principle, head-tracking systems cannot eliminate the delay between the head movement and changes in the displayed information because it takes time to detect the head movement, calculate the new position of the stimulus, and draw it at a new position on the display. Previous studies reported the negative effects of delay in VR and augmented reality (AR) environments. Increasing the delay time affects an object's localization in AR systems [2] and degrades the depth perception from monocular motion parallax [3], [4].



(a) In front of display (b) At rear of display

Fig. 1. Principle of monocular motion parallax and perceived depth

In this study, we improved our conventional motion parallax system based on a head-tracking technique by reducing the delay time and evaluated the influence of the stimulus latency relative to head movements in Experiment 1. Based on the results of Experiment 1, we focused on the visual information given when changing motion direction because the delay is especially noticeable at this time in such situations. We hypothesized that the visual information at the time of stimulus motion direction change plays a critical role in depth perception from monocular motion parallax. We therefore evaluated its importance by measuring the perceived depth with and without change of motion direction in Experiment 2. In Experiment 3, we demonstrated the importance of changing the motion direction itself, not the temporal stop between deceleration and acceleration of the stimulus and head movements, on the depth perception from monocular motion parallax. In Experiment 4, we clarified that the head movement cycle does not affect the perceived depth difference with and without changing motion direction. These results support our hypothesis of the importance of visual information at the time of changing the motion direction of the head and stimulus movements.

II. Experiment 1: Effect of Delay Time Between Head and Stimulus Movements on Depth Perception From Monocular Motion Parallax

In Experiment 1, we evaluated the effect of the delay time between the head and stimulus movements on perceived depths from monocular motion parallax with a low-latency head-tracking system.

A. Experimental apparatus and visual stimulus

Figure 2 shows the experimental apparatus for displaying a motion parallax stimulus synchronized with a subject's head movement. We used a position sensitive device (PSD, Thorlabs PDP90A), which is an optoelectronic sensor that detects the position of a light source, and an analog to digital converter (ADC, CONTEC AI-1616L-LPE) for tracking the position of an LED light source attached to the subject's head. In our previously used head-tracking system, the PSD detected the centroid position of LED light sources with longer latency because of a proportional-integral-derivative (PID) controller's smoothing processing. In this study, we disabled this smoothing process to reduce its latency. In addition, we adopted a high-speed ADC and a high-speed program for speeding up the detection of the position of the light source attached to the subject's head. A personal computer (CPU: Core i7-6700K, GPU: GeForce GTX 1060) received head position signals from the PSD via the ADC, calculated the position of the visual stimulus on the next display frame, and depicted it on a 24-inch LCD display (ASUS VG248QE, 1920 x 1080, 144 Hz) depending on the subject's head position. The delay time between the stimulus movement and the subject's head movement was less than 33 ms [5]. The shortest delay time of the conventional head-tracking systems used in previous studies was 100 ms [3], [4]. The delay time of our new system is shorter than those conventional systems and resembles such state-of-the-art systems as Oculus Rift [6]-[8].

The visual stimulus consisted of three green squares arranged vertically (Fig. 2). The center square changed its horizontal position for synchronization with the subject's lateral and reciprocated head movements, and the positions of the top and bottom squares were fixed as depth references.

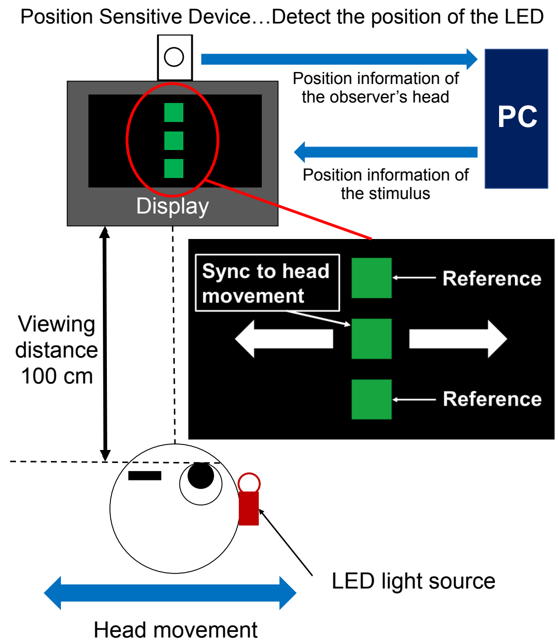


Fig. 2. Head-tracking system for displaying motion parallax stimulus synchronized with head movement and its stimulus configuration

B. Procedure

The subjects sat in front of the LCD monitor at a viewing distance of 100 cm. They observed the stimulus with their preferred eye with the other eye occluded during reciprocating and horizontal head movements in a 2-s cycle. The head movement's amplitude was 12 cm. The time for viewing the stimulus was not restricted. After observing the stimulus, the subjects verbally responded the direction of the perceived depth (in front of or behind the references) and indicated the magnitude of the perceived depth using the interval between their thumb and index finger measured by an electronic caliper, as shown in Fig. 3. Prior to the experiment, the subjects were trained to precisely and accurately calibrate the indications of their fingers based on their perceived depth between real objects.

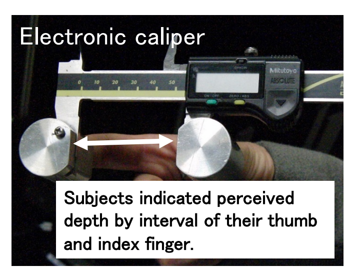


Fig. 3. Evaluating perceived depth by interval of thumb and index finger

The designed depths of the center square simulated by the motion parallax ranged from -50 mm to +50 mm from the references in 10-mm steps. The negative and positive depth values indicate the depths behind and in front of the references, respectively. The delay times were 33, 95, and 150 ms. The delay times of 95 and 150 ms were generated by the program. For comparison, we also evaluated the perceived depth of real objects (i.e., no delay). Each stimulus condition was tested three times in random order. Two subjects participated in this experiment. The experiment was conducted in a dark room.

C. *Results and discussion*

Figure 4 shows the perceived depth with various delay times for two subjects. The horizontal and vertical axes indicate the designed depth by motion parallax and the perceived depth, respectively. Differences in the symbol correspond to differences in the delay time. The diagonal line indicates the designed depth value. As shown in Fig. 4, the perceived depth of the real objects almost coincides with the designed value. On the other hand, the perceived depths degrade when the delay time increases, especially at designed depths larger than ±20 mm. Almost the same depth as the designed depth can be perceived within a range of -30 mm to +30 mm at the shortest delay time of 33 ms. By comparing the results between the 33- and 150-ms delay times, the perceived depth at 150 ms is much more degraded than that at the 33-ms delay. The two subjects showed very similar results.

These results demonstrate that the delay time between the head and stimulus movements degrades depth perception in monocular motion parallax, especially in large designed depths [5]. This also means that we can successfully improve the depth perception from monocular motion parallax by decreasing the display delay time in head-tracking systems.

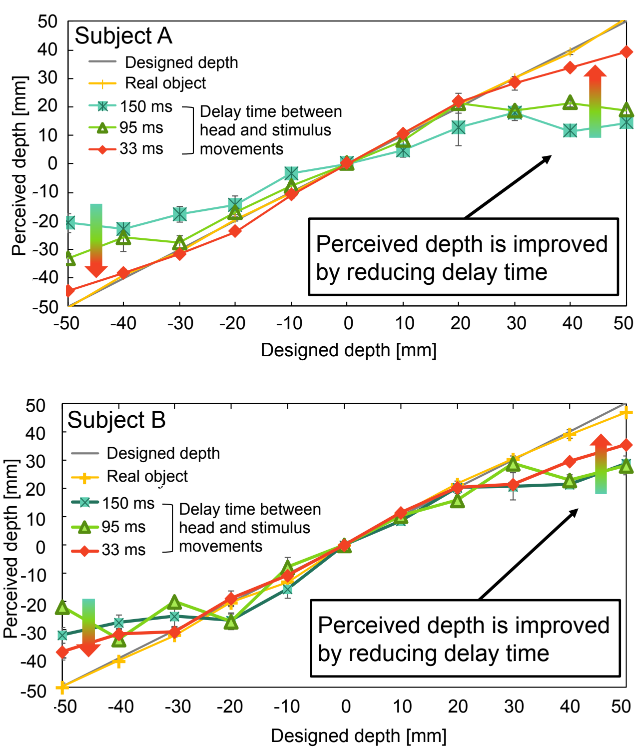


Fig. 4. Perceived depth from monocular motion parallax with various delay times between head and stimulus movements

III. Experiment 2: Effect of Displaying Motion Direction Change on Depth Perception From Monocular Motion Parallax

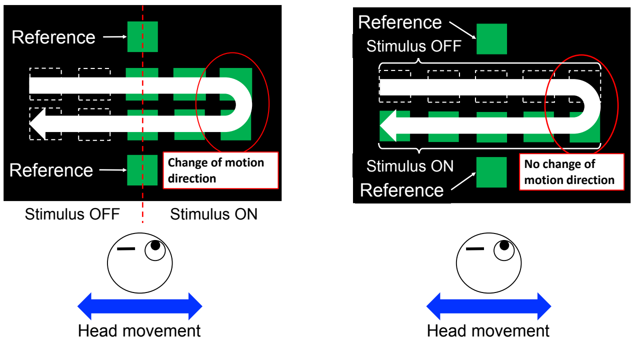
In Experiment 1, we demonstrated that the delay of the stimulus movement relative to the head movement degrades the depth perception from monocular motion parallax. Because the delay is more noticeable when the motion direction changes than during the head movements, we hypothesized that visual information given at the time of the change in motion direction is important. Experiment 2 demonstrates the importance of displaying direction change of the stimulus motion on depth perception from monocular motion parallax by comparing the perceived depths with and without visual information given at the time of changing the stimulus motion direction.

A. *Methods*

The experimental apparatus was identical to that used in Experiment 1 (Fig. 2). In Experiment 2, the delay time between the head movement and the stimulus change was also less than 33 ms, as in Experiment 1.

The stimulus configuration was also identical to that in Experiment 1 (Fig. 2). The center square was presented for 50% of the total trial time to control the stimulus presentation at the time of the stimulus motion's direction change. Figure 5 (a) shows the stimulus condition with the display of the change of the motion direction by presenting the center square only when the head position is on either the right or left side of the center of the head movement range. Figure 5 (b) shows the stimulus condition without displaying the change of the motion direction by presenting the center square only during either the rightward or leftward movements of the subject's head. The stimulus durations in both conditions were set equally by checking the recorded image of a high-speed camera. The head movements were identical in both conditions. The designed depths of the center square simulated by motion parallax were -70 mm, -50 mm, -30 mm, ±0 mm, +30 mm, +50 mm, and +70 mm from the references, where the positive and negative values indicate in front of and behind the references, respectively. In addition to these two conditions, we also evaluated the perceived depth when the stimulus was continuously presented throughout the trial.

The subjects observed the stimulus with one eye during the reciprocating, lateral head movement with a 2-s cycle. The head movement's amplitude was 10 cm. We evaluated the perceived depth of the center square relative to the references using the interval between the subject's thumb and index finger, as in Experiment 1. Each stimulus condition was run three times in random order. Three subjects participated in Experiment 2 and the experiment was conducted in a dark room.



(a) With change of motion direction (b) Without change of motion direction

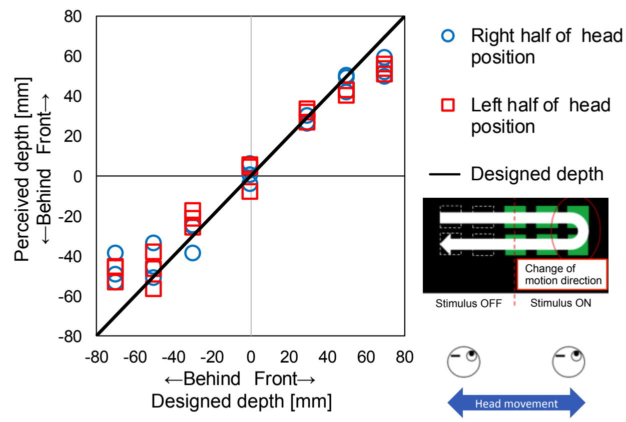
Fig. 5. Experimental conditions of moving stimulus in Experiment 2: (a) with change of motion direction, (b) without change of motion direction

B. Results and discussion

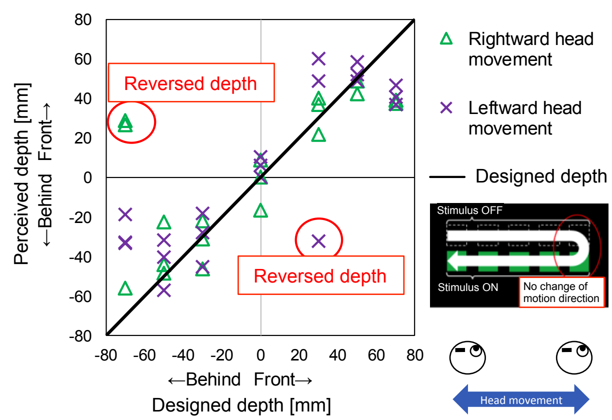
Figure 6 shows the perceived depths for one subject in three stimulus conditions: (a) with motion direction change, (b) without motion direction change, and (c) continuous display throughout the trial. The horizontal and vertical axes indicate the designed depth by motion parallax and the perceived depth of the subject, respectively. In Fig. 6 (a), the blue circles and red squares indicate the perceived depths of the stimulus shown only when the subject's head is located in the right and left halves of the head movement range, respectively. In Fig. 6 (b), the green triangles and purple crosses indicate the perceived depths of the stimulus shown only during the rightward and leftward movement of the subject's head, respectively. A diagonal line indicates the designed depth, as in Fig. 4.

As shown in Fig. 6 (a), the perceived depths of the stimulus displaying the motion direction change are close to the designed depth except for the closest (+70 mm) and the farthest (-70 mm), with small variations. These closely resemble the perceived depths when the stimulus is always displayed throughout the trial (Fig. 6 (c)). This result indicates that stable depth perception is maintained by presenting visual information at the time of changing the stimulus motion direction despite a decrease in the display time ratio to 50% of the total trial time. On the other hand, the perceived depths of the stimulus not displaying the motion direction change deviated significantly from the designed depth with large variations (Fig. 6 (b)). In addition, the perceived depth order (in front or behind) is sometimes reversed without displaying a change in direction (Fig. 6 (b)). These results show that the depth perception for the stimulus without presenting a motion direction change is ambiguous and unstable. The other subjects showed similar results.

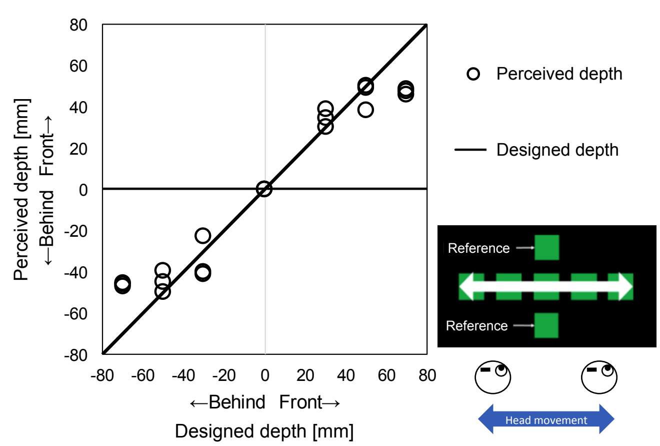
Because of the equal stimulus durations (50% of total trial time) in both conditions, the difference in perceived depth depends on whether or not the center square is presented when the stimulus is changing motion direction.



(a) With change of motion direction



(b) Without change of motion direction



(c) Stimulus continuously displayed throughout trial

Fig. 6. Perceived depth from monocular motion parallax for three stimulus conditions in Experiment 2: (a) with change of motion direction, (b) without change of motion direction, and (c) continuously displayed throughout the trial

These results suggest that visual information that indicates a direction change of the stimulus motion contributes to stable and unambiguous depth perception in monocular motion parallax [9]. A previous study reported that decreasing the display time of the motion parallax stimulus without changing the motion direction degrades the depth perception [10]. On the other hand, in our experiment, the depth perception did not degrade when the display time ratio was decreased to 50% of the total trial time if the motion direction change was displayed at the time of changing head motion direction. However, emphasizing the importance of visual information at the time of the motion direction change might be premature because changing the stimulus motion direction involves two factors: the change of direction itself and the temporal stop of the stimulus movement between deceleration and acceleration of the stimulus motion.

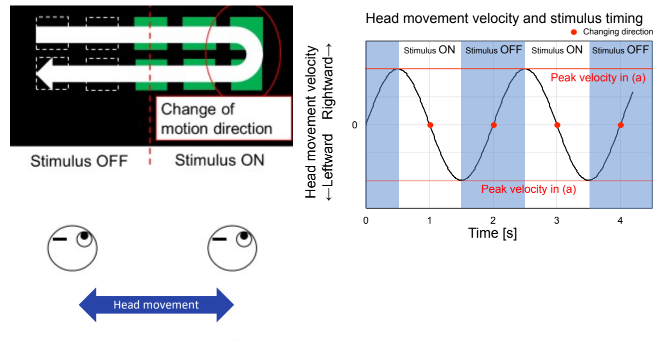
IV. Experiment 3: Effect of Temporal Stopping and Deceleration and Acceleration of Stimulus and Head Movements on Depth Perception from Monocular Motion Parallax

In Experiment 3, we clarified which is more important, changing the motion direction itself or a combination of temporal stop, deceleration, and acceleration of the stimulus and head movements for stable and unambiguous depth perception from monocular motion parallax.

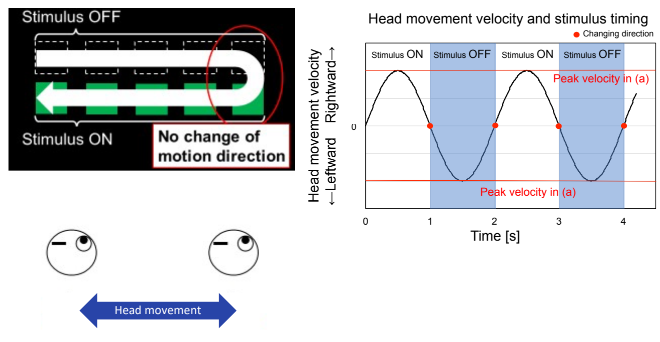
A. Methods

Figure 7 shows the experimental conditions of the moving stimulus. The velocity profile of the head movement with the timing of the stimulus presentation is shown on the right side of each condition in Fig. 7. Figures 7 (a) and (b) show the stimulus condition examined in Experiment 2 with and without a change in motion direction. As shown in the velocity profile, the head movement in these conditions is the same; only the timing of the stimulus presentation is different.

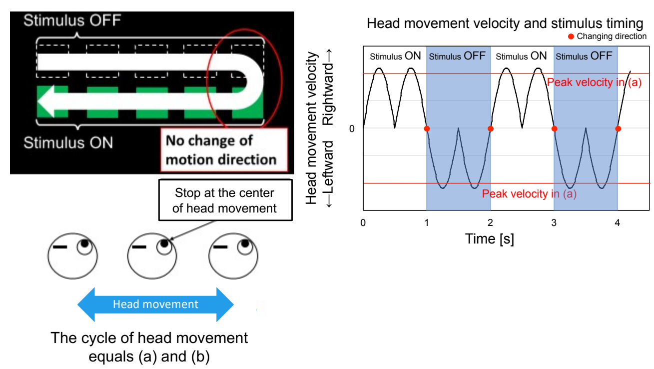
To separate the effects of changing the direction of the stimulus motion and the temporal stop, the subjects temporally stopped their head movement midway during the movement path without changing direction. Figures 7 (c) and (d) show the conditions without changing the movement direction by only presenting the stimulus during one head movement direction with a temporal stop at the middle point of the head movement. The head movement cycle in Fig. 7 (c) was the same (2 s) as those in Figs. 7 (a) and (b) (equal cycle condition). The peak velocity of the head movement in Fig. 7 (d) was the same as those in Figs. 7 (a) and (b) (equal velocity condition). The perceived depths in the (c) equal cycle and (d) equal velocity conditions were measured to evaluate the effect of the temporal stop between the deceleration and acceleration of the stimulus and head movements without changing motion direction. Table 1 summarizes these four experimental conditions.



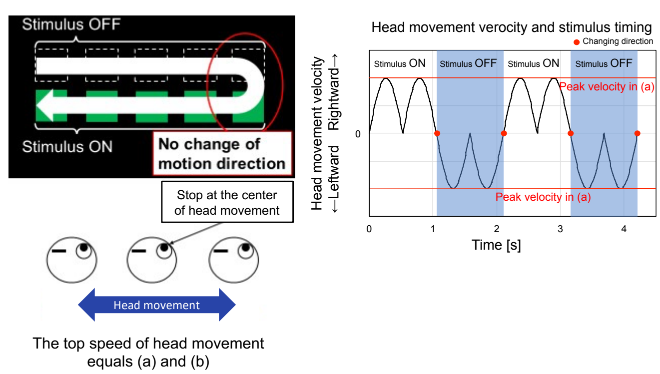
(a) With changing direction (repeated from Experiment 2)



(b) Without changing direction (repeated from Experiment 2)



(c) Stopping without changing direction (equal cycle condition)



(d) Stopping without changing direction (equal velocity condition)

Fig. 7. Experimental conditions in Experiment 3: (a) with changing direction (repeated from Experiment 2), (b) without changing direction (repeated from Experiment 2), (c) stopping without changing direction (equal cycle condition), and (d) stopping without changing direction (equal velocity condition)

TABLE I
EXPERIMENTAL CONDITIONS OF STIMULUS AND HEAD MOVEMENT

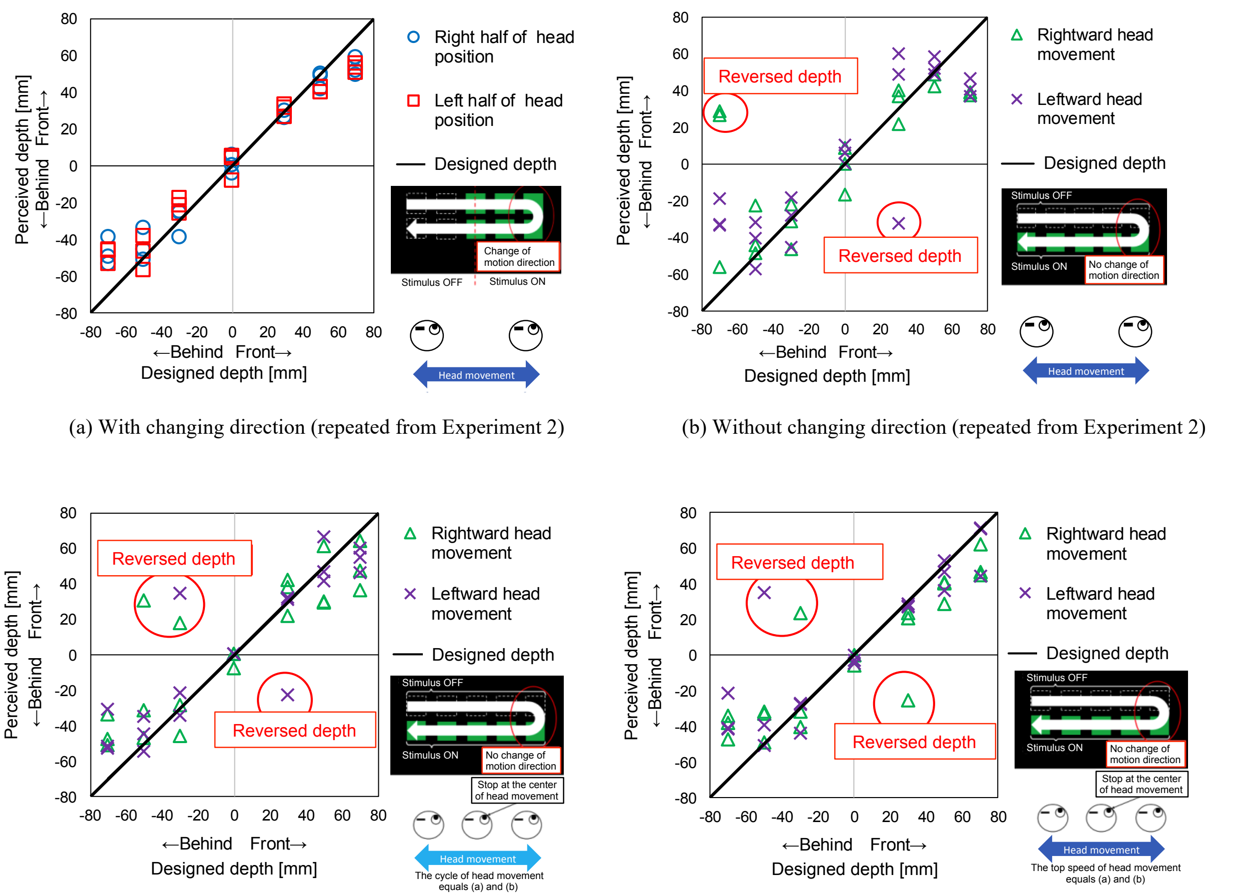
Condition	Description		
	Change in direction of stimulus motion	Head movement cycle	Peak velocity of head movement
(a) Changing direction	Included	2 s	–
(b) No change in direction	Not included	2 s	same as (a)
(c) Stopping without changing direction (equal cycle)	Not included	2 s	faster than (a)
(d) Stopping without changing direction (equal velocity)	Not included	> 2 s	same as (a)

The designed depth was changed from -70 mm (behind) to +70 mm (in front) relative to the references, as in Experiment 2. The subjects observed the stimulus with one eye while moving their head laterally within a range of 10 cm. The subjects responded their perceived depth of the center square relative to the top and bottom reference squares using the intervals between their thumb and index finger, as in Experiments 1 and 2. We ran three trials at each randomly selected designed depth. The same three subjects from Experiment 2 participated in this experiment.

B. *Results and discussion*

Figure 8 shows the perceived depth of one subject in each condition. Figures 8 (a) (with changing direction) and (b) (without changing direction) are repeated from Experiment 2. Figures 8 (c), stopping without changing direction (equal cycle), and (d), stopping without changing direction (equal velocity), are newly obtained data in Experiment 3. The perceived depths with the temporal stop of the head and stimulus movements deviate significantly from the designed depths with large variations. In addition, the perceived depth order (in front or behind) is sometimes reversed. These results are very similar to Fig. 8 (b), without changing direction, especially as compared to Fig. 8 (a), with changing direction. The other two subjects showed similar results.

These results indicate that the temporal stop between deceleration and acceleration of the head and stimulus movements did not contribute to stable and unambiguous depth perception. In other words, changing the motion direction itself is necessary for stabilizing and eliminating the ambiguity of the depth perception produced by monocular motion parallax [11], [12].



(a) With changing direction (repeated from Experiment 2)

(b) Without changing direction (repeated from Experiment 2)

(c) Stopping without changing direction (equal cycle)

(d) Stopping without changing direction (equal velocity)

Fig. 8. Perceived depth produced by monocular motion parallax for each condition in Experiment 3: (a) with changing motion direction (repeated from Experiment 2), (b) without changing motion direction (repeated from Experiment 2), (c) stopping without changing motion direction (equal cycle), and (d) stopping without changing motion direction (equal velocity)

V. Experiment 4: Effect of Head Movement cycle on Depth Perception from Monocular Motion Parallax

In our previous three experiments, the subjects moved their heads laterally in a 2-s cycle. If changing motion direction is critical for stable and unambiguous depth perception from monocular motion parallax, the head movement cycle should not affect the perceived depth. In Experiment 4, we evaluated the effect of the head movement cycle on depth perception from monocular motion parallax with and without changing motion direction.

A. Methods

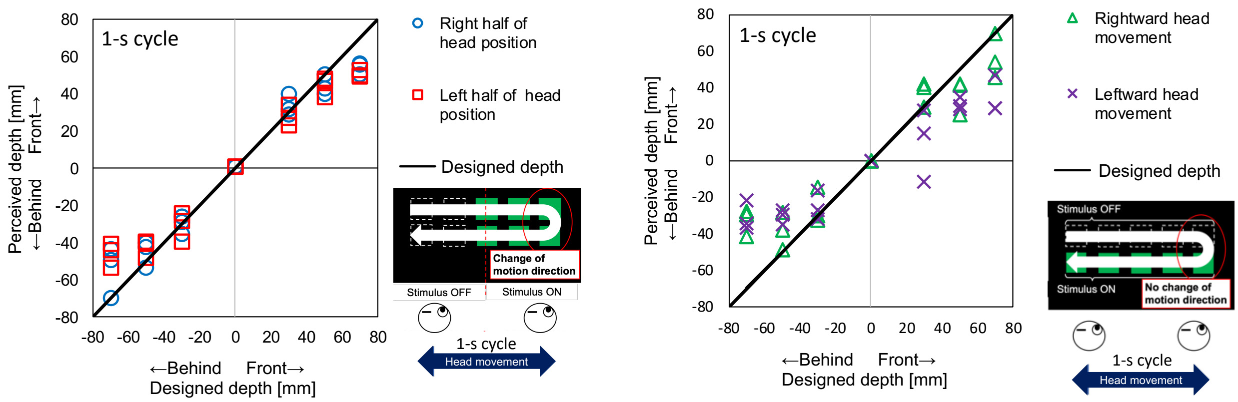
The experimental apparatus, stimulus configuration, and experimental conditions were identical to that in Experiment 2 except for the head movement cycle. In this experiment, we compared perceived depths with 1-s, 2-s, and 4-s cycles to clarify the effect of the head movement cycle.

The display time ratio of the center square was 50% of the total trial time for both with and without changing motion direction. The designed depths by motion parallax were -70 mm, -50 mm, -30 mm, ±0 mm, +30 mm, +50 mm, and +70 mm from the references, where the positive and negative values indicate in front of and behind the references.

The subjects observed the stimulus with one eye during the lateral, reciprocal head movement with 1-s, 2-s, or 4-s cycles. We used a metronome to control the head movement cycle. The amplitude of the head movement was 10 cm. We evaluated the perceived depth of the center square relative to the references by using the interval between the subject's thumb and index finger, as in our previous experiments. Each stimulus condition was tested three times in random order. Three subjects participated in Experiment 4 and the experiment was conducted in a dark room.

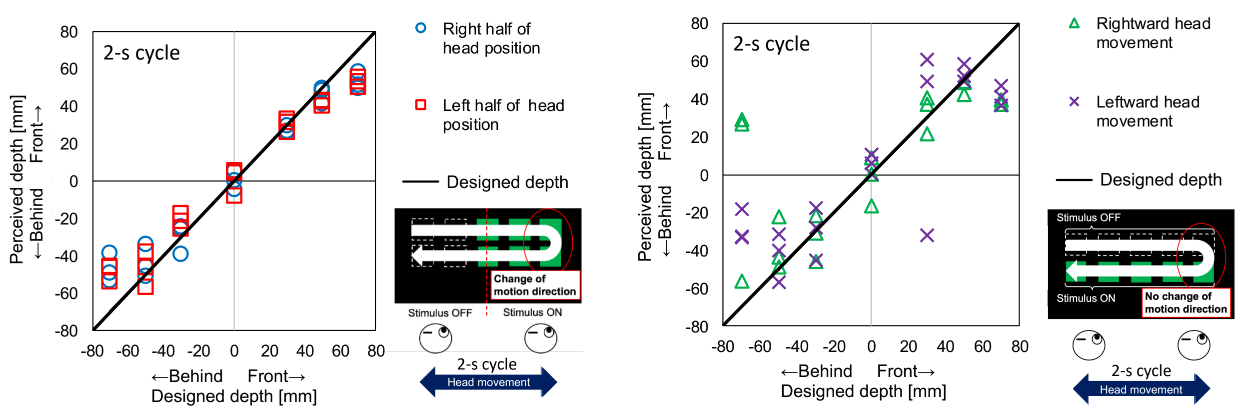
B. Results and discussion

Figures 9, 10, and 11 show the perceived depths for one subject (a) with and (b) without motion direction change with 1-s, 2-s, and 4-s head movement cycles, respectively. The perceived depths with the change of motion direction are close to the designed depth, as shown in (a) of Figs. 9, 10, and 11. On the other hand, the perceived depths without change of motion direction deviated significantly from the designed depth and sometimes reversed the order of the depth, as shown in (b) of Figs. 9, 10, and 11. The other two subjects showed similar results. These results are very similar to those in Experiment 2, in which the head moved with a 2-s cycle, and indicate the importance of visual information of motion direction change in stable and unambiguous depth perception from monocular motion parallax. No difference was found in perceived depths among these different head movement cycles, indicating that the head movement cycle is irrelevant in perceived depths from monocular motion parallax and supporting our hypothesis of the importance of visual information at the time of changing the motion direction of the head and stimulus movements.



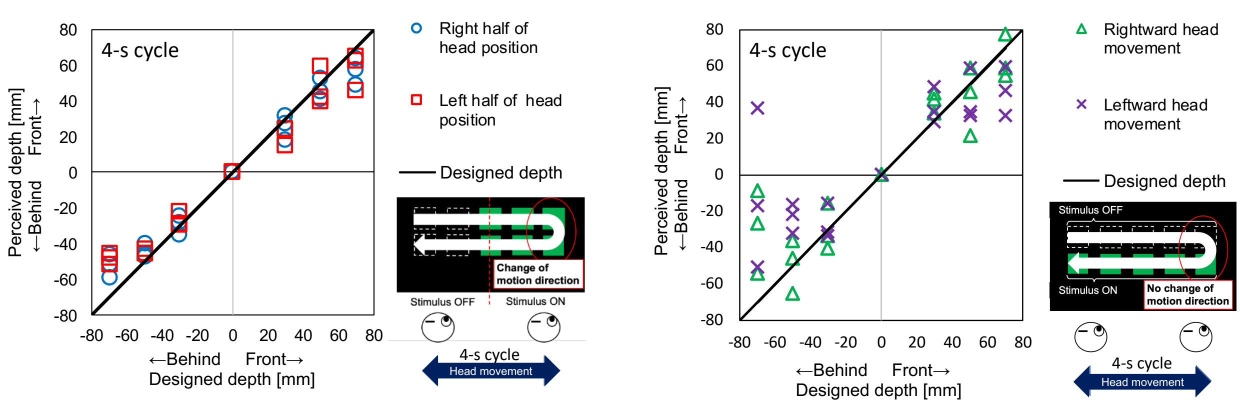
(a) With change of motion direction (b) Without change of motion direction

Fig. 9. Perceived depths produced by monocular motion parallax with 1-s cycle head movements in Experiment 4: (a) with changing direction, (b) without changing direction



(a) With change of motion direction (b) Without change of motion direction

Fig. 10. Perceived depths produced by monocular motion parallax with 2-s cycle head movements in Experiment 4: (a) with changing direction, (b) without changing direction



(a) With change of motion direction (b) Without change of motion direction

Fig. 11. Perceived depths produced by monocular motion parallax with 4-s cycle head movements in Experiment 4: (a) with changing direction, (b) without changing direction

VI. CONCLUSION

We hypothesized and demonstrated the importance of visual information at the time of changing the direction of the head and stimulus movements on depth perception produced by monocular motion parallax.

In Experiment 1, we evaluated the effects of display latency between the head movement and the stimulus change in a head-tracking system. The results indicate that increases in delay time degrade the depth perception from monocular motion parallax. This suggests that the visual information given at the time of changing the direction plays a critical role in depth perception from motion parallax because the delay is especially noticeable at the time of the direction change. These results also indicate that decreasing the delay time in newly developed systems such as head-mounted displays is a reasonable design concept. Low latency is needed not only for preventing motion sickness and dizziness, but also for accurately and precisely perceiving the designed depth.

In Experiment 2, we directly evaluated the importance of visual information when changing the direction by measuring the perceived depth from monocular motion parallax with and without displaying the moving stimulus at the time of changing the stimulus' direction. The results suggest that visual information at the time of changing direction contributes to stable and unambiguous depth perception.

In Experiment 3, we clarified which is more important, changing the motion direction itself or the temporal stop between deceleration and acceleration of the head and stimulus movements. The results indicate that changing the movement direction, not the temporal stop, plays a critical role in maintaining stable and unambiguous depth perception from monocular motion parallax. This is consistent with the conclusion of Experiment 2 and supports our hypothesis.

In Experiment 4, we evaluated the perceived depths with head movement in 1-s, 2-s, and 4-s cycles. We found no difference among perceived depths with different head movement cycles. These results also support our hypothesis that changing the motion direction of the head and stimulus movements is critical for depth perception from monocular motion parallax.

These findings deepen our understanding of the human visual mechanism of depth perception from monocular motion parallax and can be applied to VR and AR systems for more realistic representation of 3D environments. For example, developing low-latency VR/AR systems and creating visual content with motion direction change are effective for accurate and precise depth perception from motion parallax.

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