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Effect of inter-lens distance on fusional limit in stereoscopic vision using a simple smartphone head-mounted display

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Abstract

In this study investigated the effect of the frame design of a simple smartphone HMD on the stereoscopic vision and considered the design requirements for comfortable viewing environment. We mainly focused on the lens spacing used in screen enlargement and extension of the focal length. To investigate the differences in the fusional limit attributable to lens spacing, three HMDs with left/right eye-lens spacing of 57.5, 60, and 62.5 mm were utilized. When the three types of HMD and display were compared, the positive and negative direction fusional limits were closer than the display for all HMDs. In particular, that of 62.5 mm condition was shifted to significantly close in comparison with the control condition. The results showed a trend that the fusional range becomes narrow in a simple HMD.

Introduction

A Simple frame Head Mounted displays (HMDs) is attracting attention with the spread of 360-degree panoramic images as new video content. These images capture the entirety of the surrounding scenery and allow viewing from any point during replay. Simple HMDs can be used to view these full dome images. These HMDs consist of a simple housing for a smartphone made from corrugated cardboard. With these simple HMDs, the built-in accelerometer in the smartphone can control the point of view of the 360-degree image such that it corresponds to head movements. Because such HMDs can display images for the left and right eyes separately, their application as a viewing environment for stereoscopic vision is anticipated.

The housing for these HMDs can be made from various designs (see Figure 1). One of the most famous examples is Google Cardboard [1]. Furthermore, they can be manufactured at a low price. The design differs for each product, and it is unclear whether they provide a comfortable viewing environment. Regarding binocular vision, differences in the audiovisual environment have been suggested to mitigate eye fatigue and visually induced motion sickness. Therefore, its design must be examined from the point of view of safety.

Among the many factors considered when designing the housing for a simple HMD, the design of the lens used to magnify the display of the smartphone and to extend the focal length are considered important. "Aberration" refers to the phenomenon whereby the image and color of the periphery are distorted. Aberration is one of the optical effects of the lens under consideration; the distance between the left and right lenses (hereafter, the "inter-lens distance") also affects image safety significantly. The inter-lens distance is fixed in many simple HMDs, and this distance is difficult to adjust. When the inter-lens distance changes, the center point of the image magnification displayed in the smartphone display also changes. This, in turn, changes the amount of stereoscopic image disparity, even when the same image is shown on the same display. Furthermore, the optimal inter-lens distance is expected to differ according to the viewer's interpupillary distance (IPD). Whether the image can be fused depends on the appropriate relation between the IPD and the inter-lens distance.

This study is an experimental analysis of the housing design of a simple HMD for a comfortable viewing experience with a particular focus on the effect of different inter-lens distances on the fusional vergence limit (hereafter, the "fusional limit").

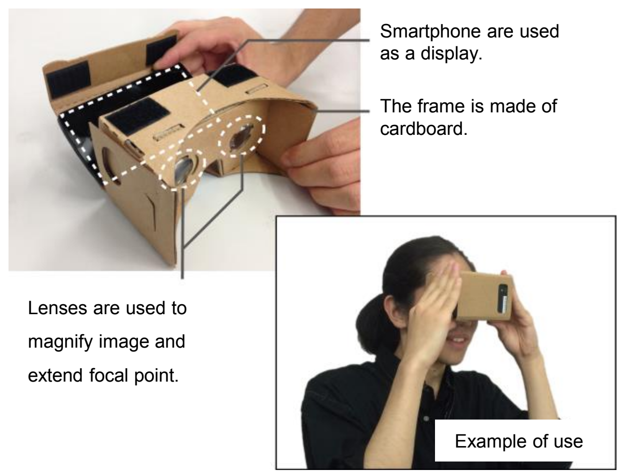

Figure 1. Simple frame HMD

Background

There are a large number of studies about the safety of the stereoscopic vision have been reported [2][3]. A lot of report has been focused on the range of parallax for comfortable observation. Shibata et al. [2] reported the zone of comfort in view of vergence-accommodation conflict and described the zone of comfort depending on the viewing distance from mobile to cinema environment. However, HMD as the environment of stereoscopic viewing is different from these general environments because it uses lenses for magnifying screen and shows separate images to each left and right eye.

There are also many of previous studies about stereoscopic vision of HMD [4] [5]. The evaluation of safety of HMD tends to be focused on not only a visual fatigue but also a simulator sickness, long term observation, usability as a wearable device. For example, Pölönen et al. [4] reported a user experience of film viewing using consumer HMD products. Kawai et al. [5] reported characteristics of monocular HMD for a ubiquitous computing. These reports also mentioned an effect of frame design of HMD at the viewpoint of a fitting for easy viewing of image. On the other

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hand, these studies were used consumer product. Thus, the optical design such as inter-lens distance was adjustable. Therefore, we considered of the influence of the design of low-cost HMD that has a possibility of uncomfortable viewing. Especially, the inappropriate inter-lens distance could be cause an interference with a stereoscopic vision depends on viewer's IPD. Accordingly, we measure the fusional limit for an evaluation of the effect for a stereoscopic viewing using the simple HMD.

Method

Purpose

Of the many factors that affect image viewing when designing a simple HMD, this study first focuses on the distance between the lenses used to magnify the screen and on the effect of a longer focal length. The inter-lens distance is fixed in many simple HMDs. When the inter-lens distance changes, the convergence point of the image also changes, and this affects stereoscopic vision. Because images are separately presented to left and right eyes, it is important that the respective images are fused and viewed stereoscopically in an HMD. Accordingly, an experiment was conducted to measure the change in the range required to fuse images as the inter-lens distance changes.

Equipment

The HMD used for the experiment was prepared using the Google Cardboard template available from Google. The lens mount was adjusted, and 3 HMDs were prepared with inter-lens distances of 57.5 mm, 60.0 mm, and 62.5 mm, respectively (see Figure 2). The experimental conditions are referred to as the 57.5 mm condition, 60.0 mm condition and 62.5 mm condition, respectively. Moreover, plastic lenses with a diameter of 30 mm and a focal length of 45 mm were used.

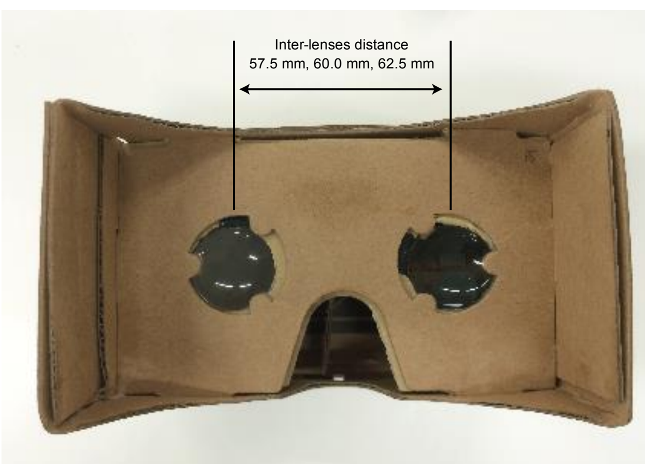

Figure 2. Inter-lens distance

A Nexus 5 (LG Electronics) smartphone was used as the display. The display resolution was 1920×1080 pixels, and the screen size was 110×62 mm. The distance between the lenses and the display was 40 mm.

The position of the virtual image formed by the lenses is obtained using Eq. (1), where A is the distance to the viewing object from the lens center, F is the focal length of the lens, and B is the position of the virtual image:

$$\frac{1}{A} - \frac{1}{B} = \frac{1}{F} \tag{1}$$

When viewing the display at the distance of 40 mm through the lens with a 45 mm focal length, a virtual image is formed at 360 mm in front of the viewer's eyes. The rate of magnification is obtained by dividing the value of B by the value of A. Thus, 360/40 mm results in a 9× magnification. Because the display is divided into halves, and each half is viewed by the left and right eye, respectively, one eye sees a display of (110 mm / 2) × 9 = 495 mm in width. The horizontal angle of view from the lens' center is approximately 69°.

When an identical image is projected in the divided display, the images are 55 mm apart. When the inter-lens distance is 55 mm, the distance between the virtual images would be identical to their distance were they viewed without lenses. If the inter-lens distance is different, however, the distance between the virtual images changes. This is because the magnification center of the virtual image is on the optical axis. For example, when the inter-lens distance is 57.5 mm and the identical image is projected onto both sides of the display, the image is formed at a visual range of 920 mm, appearing to the viewer as though it is being pushed into the display.

The disparity of a stereoscopic image is often expressed in terms of the angle of disparity. The angle is indicated by θd–θs, where the convergence angle of a point on the display is θd and that of the stereoscopic image is θs. In the example above, the disparity angle is approximately 5.6°. Similarly, the disparity angle is approximately 2.0° when the inter-lens distance is 60.0 mm, and approximately -1.6° when the inter-lens distance is 62.5 mm. A negative disparity value indicates that the image is formed closer to the viewer than on the display.

A liquid crystal display was used as the control condition. The display used was a 23-inch passive 3D display (D2342p-PN by LG Electronics). Polarized glasses were used to view the stereoscopic image with this display. To equalize the angle of view, the viewing distance was set to 370 mm.

Stimulus

A random-dot stereogram was used as a stimulus for measuring the fusional limit (see Figure 3). The stimulus image consisted of a background and a target. The background image consisted of white dots of 3×3 pixels distributed in equal density on a black background. The dot density was about 80 dots per 100 square degrees. Identical background images were shown next to each other on the left and right sides of the display. The vergence distance of the background therefore varied according to conditions.

The target was a black circle with dots of the same density as those in the background. The circle had a viewing angle of about 9.1°. When viewing stereoscopic images through an HMD, the left and right images are viewed separately. Consequently, it is difficult to determine whether they are fused. To determine this, a circle without an outline was designed such that it could only be perceived when the target images were fused.

When the smartphone is crookedly fixed to the HMD, the left and right images will be misaligned. To avoid this misalignment, white horizontal lines were placed at the top and bottom of the target. These heights were trisection of the screen height.

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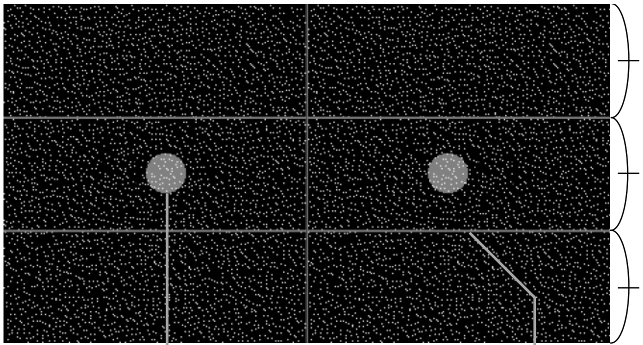

Figure 3 Visual stimuli

Evaluation

The fusional limit was measured with the so-called up-and-down method using the following procedure. The participants viewed a target with continuously changing disparity. The participants indicated when they deemed that the images were fused and when the images were not. They first viewed a stimulus with increasing disparity. Upon indicating that the images were fused, the disparity was then decreased until they indicated that the images were no longer fused. The disparity was increased and decreased alternately a few times, and the average of the reported disparity in each trial was deemed the fusional limit.

The far and near fusional limits were measured independently. The far fusional limit represents the limit of image fusion expressed as positive parallax, and the near fusional limit indicates the limit of image fusion expressed as negative parallax. In what follows, the far fusional limit shall be referred to as "F-FL," and the near point of fusional limit as "N-FL."

The disparity was increased and decreased by shifting the target to the left and right. Because the dot size was 3×3 pixels, the target was shifted in increments of three pixels. Because the target shifted simultaneously to the left and right sides, the disparity increased or decreased by increments of six pixels. The disparity was increased and decreased in three-second intervals.

Procedure

The participants provided informed consent to participate in the experiment. Subsequently, their stereoscopic vision function was tested and confirmed to be normal. Each participant's IPD was also measured.

The participants practiced the measurements using the up-and-down method prior to the experiment, and the concept of fusion was explained to each of them. Following the measurements under the control condition using the liquid crystal display, the far and near fusional limits were measured under three HMD conditions. The increasing and decreasing series were tested six times for far and near points, respectively. Combining these 6 trials, 2 fusional limits, and 4 conditions, the experiment was repeated 48 times in total. The HMD conditions and the type of fusional limit were presented in random order.

When the participants viewed the images through the HMD, their chins were fixed on a chin rest, and they were not allowed to move the HMD. The position of the head was also fixed for the control condition using the same chin rest. To prevent the HMD from tilting, its housing was secured by the participants with both hands. The stimulus image was presented by sending the image to the smartphone wirelessly from a PC. The experimenter controlled the disparity. The distance of the target when the participants indicated that the images were fused was recorded in pixels. Figure 4 shows the experimental environment. There were 19 participants (average age: 21.6 years).

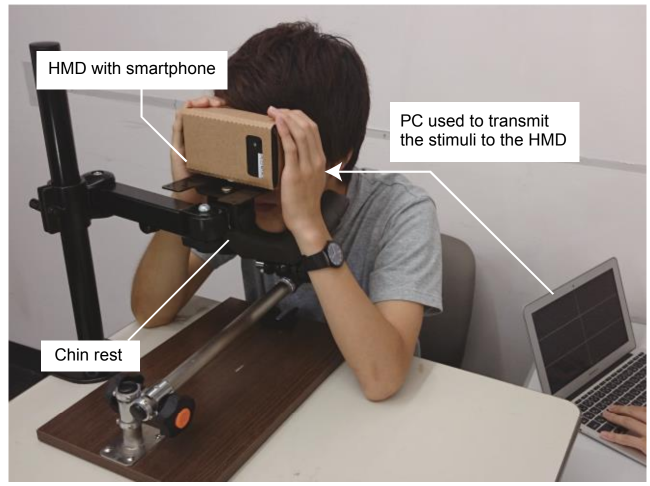

Figure 4. Experimental environment

Result

Of the 19 participants, those whose results varied more than twice the standard deviation and those who did not indicate image fusion were excluded. Thus, the results from 17 participants were collected. The results were evaluated with Welch's test using the Bonferroni correction to adjust the p value of the comparisons.

The measurements comprised the distance of the target image measured in pixels. The disparity angle was calculated from this disparity in pixels. When calculating the disparity angle, it was assumed that the distance of the screen plane was 360 mm, which is the focal point extended by the lens, and that the viewing point was the center of the lens.

Figure 5 shows a histogram of number of participants for IPD. The class intervals are 2 mm. Average of IPD was 62.4 mm, and SD was 2.40.

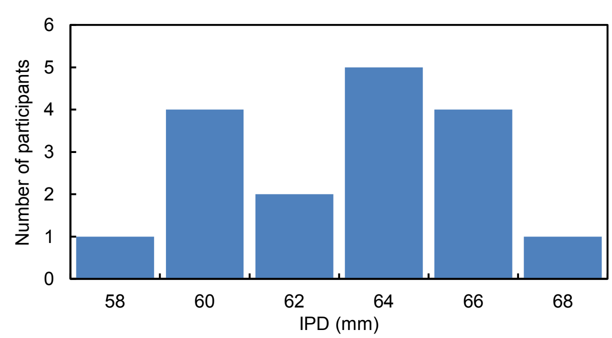

Figure 5. Number of participants for IPD

The average values of the F-FN and N-FL under the control condition the three HMD conditions are shown in Figure 6. The

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fusional limit is expressed as a disparity angle and the negative parallax as a negative value. The error bar indicates standard errors. The results from the multiple comparisons show that the values shifted significantly toward a narrow fusional limit under the 62.5 mm condition (F-FL: $t(16) = 3.56$, $p < 0.05$, N-FL: $t(16) = 4.91$, $p < 0.01$) compared to the control condition. Regarding the other HMD conditions, the fusional limit was generally narrow, although this difference was not significant.

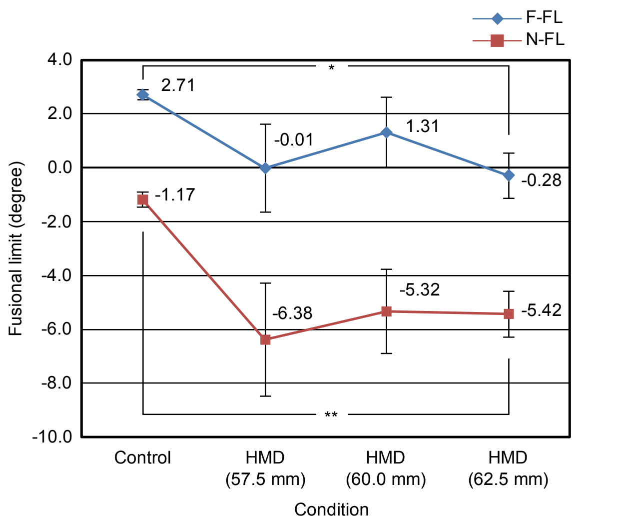

Figure 6. Average F-FL and N-FL values under different conditions (: p < 0.05, **: p < 0.01)*

No correlation was found between the IPD and the fusional limit under the tested conditions. However, a high correlation between the F-FL and N-FL values was found in all three HMD conditions (see Table 1). This indicates that the disparity range of fusion was consistently narrow, and that the F-FL and N-FL values did not change independently.

Figure 7 is scatter diagrams that show dispersion of fusional limit in each participant's IPD. The dispersion of fusional limit tends to become small according to the difference between the IPD and the inter-lens distance was small.

Table 1 Correlation coefficient between the far and near points of the fusional limit

Condition	Correlation coefficient	
Control	-0.124	n.s.
HMD (57.5 mm)	0.884	p<.01
HMD (60.0 mm)	0.744	p<.01
HMD (62.5 mm)	0.709	p<.01

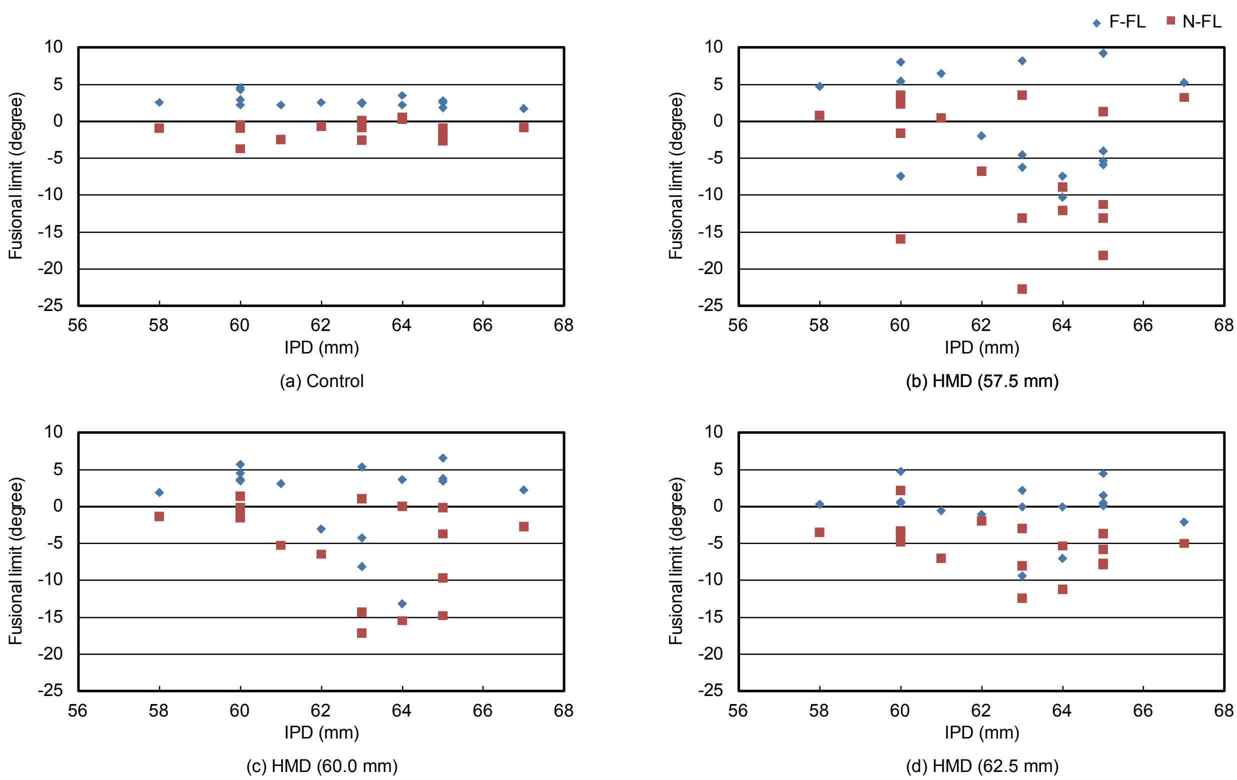

Figure 7. Dispersion of fusional limit in each IPD for each condition.

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Therefore, the difference between the IPD and the inter-lens distance was examined. Participants whose difference was 5.0 mm or less were categorized into the small differential group under the 57.5 mm condition, and those with the difference of ±2.0 mm were categorized into the small differential group under the 60.0 mm and 62.5 mm conditions. The remaining participants were categorized into the large differential group. Thus, among the participants, N = 7 for the small differential group, and N = 10 for the large differential group for all 3 HMD conditions.

Figure 8 shows the aggregated results according to each group in terms of the F-FL and N-FL regarding the change in the fusional limit compared to the control condition. The small differential group showed a smaller deviation to the fusional limit from that of the control condition. The tendency was reversed, however, under the 62.5 mm condition, where the change in the small differential group was larger. The two-way analysis of the variance of the HMD conditions and the IPD and inter-lens distance differential did not show any significant difference for the F-FL. For N-FL, however, the interaction was significant ($F(2,45) = 3.784$, $p < 0.05$), and the main effect under the HMD conditions for the small differential group was marginal ($F(2,18) = 2.738$ $p < 0.10$). The multiple comparisons showed a significant difference between the 60.0 mm and 62.5 mm conditions ($t(11.16) = 2.941$, $p < 0.05$). There was also a significant difference between the IPD and inter-lens distance differential groups under the 60 mm condition ($t(13.13) = 2.4521$, $p < 0.05$).

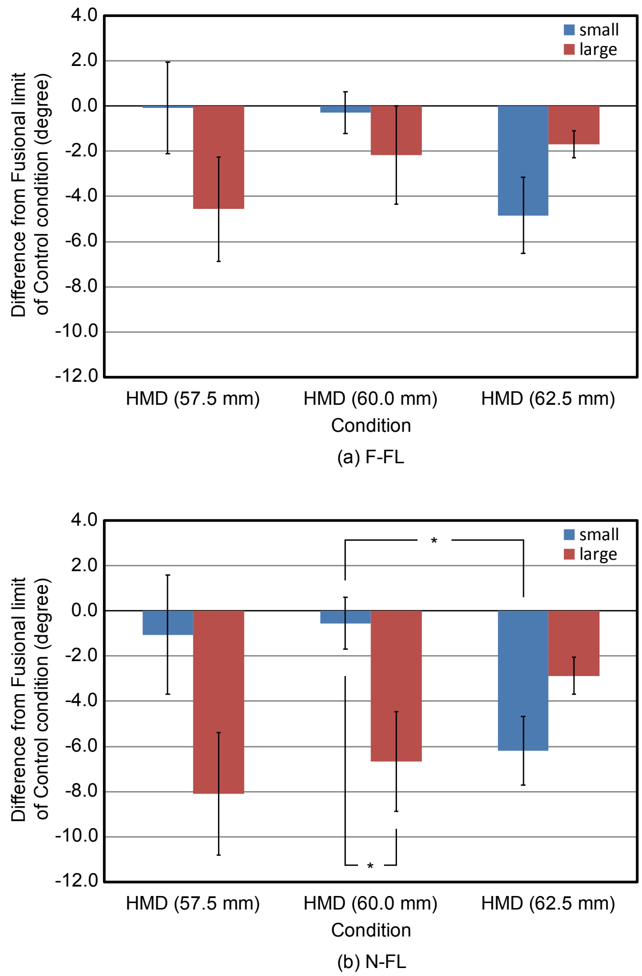

Figure. 8. Change in fusional limit by group according to the IPD and inter-lens distance differential (: p<0.05, error bars: standard error)*

Discussion

The results of the stereoscopic image viewing experiment using simple HMDs showed that the range of the fusional limit tended to be narrow. This tendency was observed in general, regardless of the inter-lens distance, but it was more prominent when the inter-lens distance was wide. The correlation analysis showed that a narrow fusional limit is found at both far and near points.

The results of the change due to the differential of the IPD and inter-lens distance showed that the smaller the inter-lens distance, the smaller the change in fusional limit was from that of the control condition in the small differential group. Conversely, when the inter-lens distance was large, the change in the fusional limit was greater in the small differential group.

Based on these results, a stereoscopic image pulled toward the viewer may be easier to view in a simple HMD than on a display, but an image pushed into the screen is expected to be difficult to view. Therefore, the closer the inter-lens distance is to the IPD, the closer the image can be viewed as it is viewed on a display. However, because the effect was not achieved at a certain inter-lens distance, the narrow fusional limit in a simple HMD may be attributed to the psychological effect of viewers trying to see an image that is close to the viewer when both the lens and the housing itself are close to the eyes. The viewer's posture while looking into such a small box may have exacerbated this effect. Because the participants viewed the display through lenses, and the images projected to the left and right eyes were separately displayed, the depth of the virtual screen was difficult to perceive. The random-dot image used as the stimulus in this experiment may have demanded that the participants spend more time finding the corresponding dots in the left and right images.

It is possible to interpret from these results that HMDs have a wider fusion range than that of a display, but this means that images containing extremely negative parallax can also be viewed. These results are not positive from the perspective of image safety. One of the criteria for safe stereoscopic images is to maintain disparity within ±1 degree in general. Under the HMD conditions used in this experiment, the 60.0 mm condition was the only condition that allowed the image to be viewed with 1° disparity in the direction of depth. Whereas this experiment measured only the fusion range, an evaluation of fatigue is also necessary.

Conclusion

This study investigated the effect of the inter-lens distance, one of the design factors, on fusing left and right images, when viewing stereoscopic images through a simple HMD using a smartphone. Our results show that the fusion range tended to be narrow when viewing a stereoscopic image through an HMD, compared to viewing them with a display. Further, whereas a smaller difference in the inter-lens distance and IPD is desirable, the results showed that changes in the fusion range increased beyond a certain inter-lens distance. The results therefore suggest

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that it is necessary to establish a reasonable inter-lens distance in order to view stereoscopic images comfortably.

Other factors when designing HMDs are thought to affect the stereoscopic view. Investigations into such factors and examinations of the techniques used to calibrate images according to the HMD housing are topics for future research.

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