Experimental determination of the range of binocular disparity for which stereoscopic fusion occurs at a viewing distance of 2.5 m for a stereoscopic TV

Hyungoo Kang
Hyungki Hong (SID Member)

Abstract — The threshold for binocular disparity for which a participant can observe a clear stereoscopic image on a 3D TV using Patterned Retarder technology and polarizing eyeglasses is determined for a viewing distance of 2.5 m. An optotype, the letter "m" with a line thickness of 1.08 mm in the upward or downward direction, was used as the stereoscopic stimulus. Under the measurement conditions of the increase and decrease of binocular disparity of the stereoscopic stimulus, the binocular disparity thresholds for 40 participants were measured for the horizontal direction. Most of the participants were in their twenties. The thresholds were measured to be slightly larger for the condition of increasing binocular disparity compared with the condition of decreasing binocular disparity. Personal differences were measured to be noticeable.

Keywords — *three-dimensional display, stereoscopic fusion, double vision, Panum's area.*

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1 Introduction

The principles of 3D displays have been known for a while. Nowadays, 3D technologies are becoming widely used for applications such as 3D theater and 3D TV. Some of these 3D technologies use horizontal binocular disparity to induce 3D depth perception. Such 3D perception has been known to happen in a limited range of the binocular disparity values. The range of the binocular disparity can be divided roughly into three zones as illustrated in Fig. 1. With respect to the crossing point between the two viewing directions of the left and right eyes, zone X in the figure represents the zone in which stereoscopic fusion occurs with the correct depth perception. This is generally called Panum's fusional area. Zone Y represents the zone in which the user observes a double image but can still roughly perceive depth. When the crossing point is located in zone Z, the user observes a double image and in general cannot determine the depth location.[1]

For stereoscopic display applications, it is important to know the range of the binocular disparity for zone X. To determine this range, Panum's fusional area experiments have been studied. However, the conditions of these experiments had been mostly limited to distances of about 25–100 cm and viewing directions of ±15°.[2–4] One of the currently popular 3D applications is 3D TV.

The viewing distance between the user and the TV are recommended to be longer for the larger size TV or the large size of pixel pitch. However, when TVs become bigger in the living room of the fixed size, the viewing distance would be limited by the size of the living room, which is smaller than the recommended viewing distance. The viewing conditions of the 3D TV are somewhat different from the reported experimental conditions. Therefore, the characteristics of binocular disparity of zone X for this range may not be the same as the reported range.

In this paper, the range of binocular disparity for stereoscopic fusion was determined for the viewing conditions of 3D TV. A stimulus with zero disparity and a stereoscopic stimulus are shown simultaneously on a 3D sample, and the binocular disparity of the stereoscopic stimulus is varied. In consideration of the living room environment, the distance from the screen to the participants was fixed to be 2.5 m. The directional characteristic of this range was measured in consideration of the angle of the field of view that the TV occupies.

2 Experiment

Stereoscopic images with different amounts of the binocular disparity were displayed on a stereoscopic 3D TV, and the threshold for which the participant observes double image or stereoscopically fused image was determined. A commercial 3D TV based on Patterned Retarder (PR) 3D technology with a diagonal length of 47 in., horizontal width of 1040 mm, resolution of 1920 × 1080 pixels, and a pixel pitch of 0.540 mm was used as the 3D display sample.[5] The performance of the PR 3D technology is reported to have a uniform crosstalk of less than 1% over a horizontal directional range

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The authors are with the Department of Optometry, Seoul National University of Science and Technology, Gongneung gil, Nowon-gu, Seoul 139-743, South Korea; e-mail: hyungki.hong@snut.ac.kr.

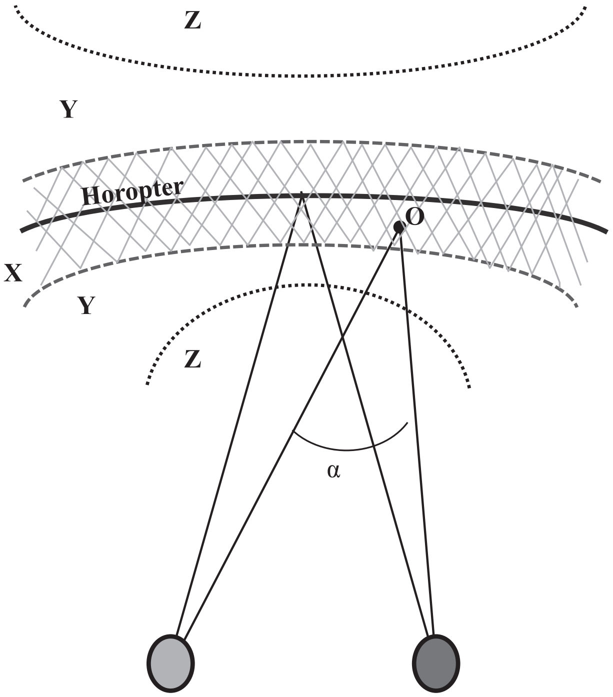
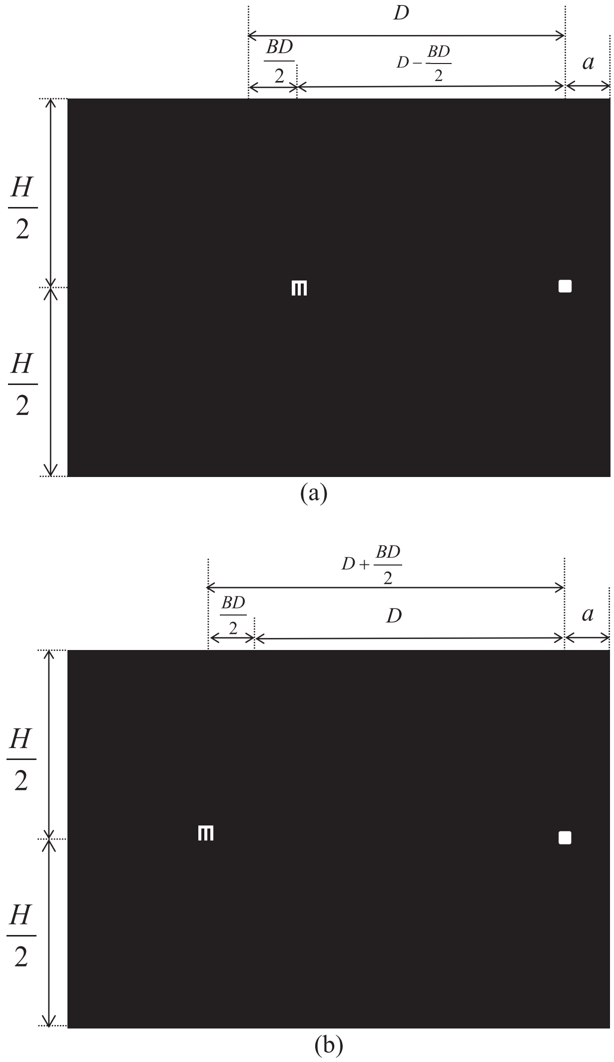


FIGURE 1 — Diagram representing the zones in which the stereoscopic fusion or double vision occurs. The curved soled line represents the horopter. When an object O is located near the horopter, the perceived vision is different for zones X, Y, and Z. X, Y, and Z represent the zones of stereoscopic fusion (i.e., Panum's fusional area), double vision with limited depth perception, and double vision with no depth perception, respectively. Angle α represents the angle between the two viewing directions of the left and right eyes.

of ±30°.[6] To perceive the 3D images in this 3D sample, users were required to wear polarizing eyeglasses, which are compatible to the chosen 3D sample.

The stereoscopic image used as the input signal is illustrated in Fig. 2. The stereoscopic image consists of a black background, a white box pattern of zero binocular disparity, and a stereoscopic stimulus of non-zero binocular disparity. An optotype, the letter of "m" with a size of 10 × 10 pixels as illustrated in Fig. 3, is used as the stereoscopic stimulus. In the test for the visual acuity, a 20/30 optotype chart is generally used for the binocular vision test such as for phoria and vergence.[7] At a distance of 2.5 m, people with the visual acuity larger than 20/30 can discern the optotype m and the inverted m of Fig. 3 when this optotype is shown in a 3D display sample with a pixel pitch of 0.540 mm. For each input signal, the m and the vertically inverted m are randomly interchanged to verify that the participant observed the clear stereoscopic image.

Figure 4(a) represents the experimental setup for which the stereoscopic image of Fig. 2 is used as the input signal. In Fig. 4(a), position "A" corresponds to the position of the white box of Fig. 2, and position "B" corresponds to the center position between the optotypes of the left and right images of Fig. 2. Position A of the input signal is located to the right side of the screen, and the stereoscopic stimulus is located to the left side of the participants. A participant wearing the polarizing eyeglasses is located at a distance of



(a)

(b)

FIGURE 2 — Stereoscopic image with a resolution of 1920 × 1080 pixels, used as the input signal. (a) Image for the left eye and (b) image for the right eye. Regarding the reference position, a small white box with a size of 10 × 10 pixels and zero binocular disparity was located on the right side of each image. The optotype m represents the stereoscopic stimulus with a non-zero binocular disparity. *BD* and *H* represent the size of the binocular disparity and the height of the screen, respectively. *D* represents the distance from the white box to the stereoscopic stimulus. The size of "*a*", which is the distance from the right boundary of the screen to the white box, is 100 pixels.

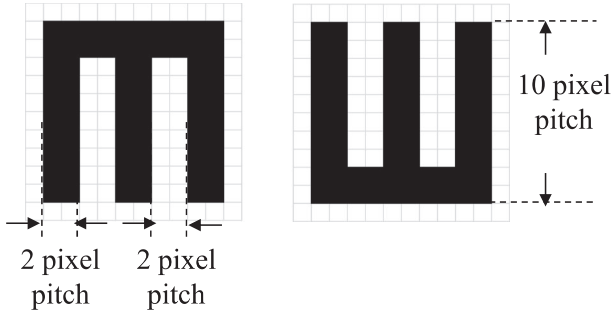


FIGURE 3 — Two types of optotype of the letter "m" consisting of 10 × 10 pixels are used as the stereoscopic stimuli of Fig. 2. The line thickness and the interval between the vertical lines are 2 pixels thick. The pixel pitch of the selected 3D sample is 0.54 mm.

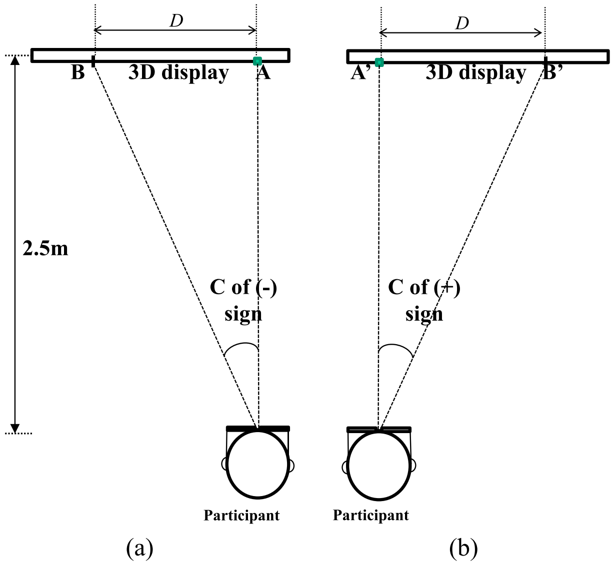


FIGURE 4 — Top view of a schematic diagram of the experimental setup where the participant is located perpendicular to position A and the stereoscopic stimulus is displayed in position B. (a) A stereoscopic image of Fig. 2 is used as the input signal, and position A is located at the right side of the display. (b) The horizontally inverted image of Fig. 2 is used as the input signal, and position A is located at the left side of the display. Angle C represents the angle between positions A and B with respect to the participant. The sign of C is defined as (−) when position A is located at the right side of the display and as (+) when position A is at the left side of the display.

2.5 m in front of the 3D sample, perpendicular to position A of the screen. The viewing distance of 2.5 m is selected in consideration of the viewing conditions of a typical living room, and specifically that the viewers and the TV are generally located on opposite sides of the living room, irrespective of the TV size. The illuminance of the experiment room was measured to be 300 lx. The head movements of the participants were restricted to prevent effects due to head movement.[4] When the stereoscopic image of Fig. 2 is horizontally inverted, position A is placed to the left side of the screen, and the stereoscopic stimulus is located to the right side of the participants. Figure 4(b) represents the experimental setup when this horizontally inverted stereoscopic image is used as the input signal. In this case, the positions of the participant should be changed as illustrated in Fig. 4(a, b). Angle C represents the angle between positions A and B with respect to the participant for a viewing distance of 2.5 m. The measurement conditions of the distances between A and B as well as angle C of Fig. 4 are shown in Table 1. The (−) and (+) signs of angle C correspond to Fig. 4(a, b), respectively. Combining these two setups, the result for the horizontal viewing directions corresponding to twice the size of the 3D sample of diagonal length of 47 in. can be obtained. With respect to the position of the participant, the stereoscopic stimulus is horizontally located in the range of −810–810 mm in the 47-in. sample for the setup of Fig. 4 (a, b). For comparison, the horizontal widths of a flat panel display of diagonal length of 65 and 72 in. are about 1439 and 1593 mm, respectively. Therefore, horizontal directional characteristics of the binocular disparity range of stereoscopic fusion for a flat panel display of a diagonal length of 60–70 in. at a viewing distance of 2.5 m can be estimated by the setup of Fig. 4.

Regarding the participants, 40 people (19 men and 21 women) were selected who have normal stereopsis and a visual acuity larger than 20/25 for monocular vision and 20/20 for binocular vision. Thirty-eight of the participants were in their twenties (23.6 ±3.15 years). Among the remaining two participants, one person was 31 years old and the other person was 34 years old.

Stereoscopic acuity was measured by the random dot stereo test (random dot Stereo Butterfly, Stereo Optical).[8] Thirty participants had a stereoscopic acuity better than 60 arc sec, while 10 people had a stereoscopic acuity worse than 70 arc sec. The stereoscopic acuities of all participants were in the range of 40–200 arc sec. Stereoscopic acuities of two persons in their thirties were 40 and 50 arc sec.

The interpupillary distance (IPD) of each participants was measured by a PD meter (PD-82, Shin-Nippon, Tokyo, Japan). The average IPD was measured to be 63 mm. The measured value of the IPD of each participant was used in calculating the angle α between the viewing directions of the left and right eyes.

Test procedure sequences are illustrated in Fig. 5. Each sequence consists of the four procedures, S1–S4, described in the upper part of Fig. 5. To prevent any unwanted effects caused by the order of these four procedures, four sequences are designed where four procedures, S1–S4, are uniformly distributed. The 40 participants were separated into four groups of 10 participants. Each sequence was applied separately for each group of 10 participants. Stereoscopic images with different amounts of binocular disparity were shown to the participant for 1 s. Each participant was then asked to answer whether the participant observed the double image or the stereoscopically fused image, and the direction of the optotype, that is, the letter m. When the participant cannot answer with certainty within 1 s, this disparity range is treated as outside the zone of stereoscopic

TABLE 1 — The relation between the angle C and the distance *D* of Fig. 4, where the participant is located at a distance of 2.5 m.

Distance (mm)	−810	−648	−486	−324	−162	162	324	486	648	810
Angle C (°)	−18.6	−14.9	−11.2	−7.44	−3.72	3.72	7.44	11.2	14.9	18.6

The distance *D* changes with the intervals of 300 pixels, which is equal to 162 mm for the selected 3D sample.

S1	(-) direction of angle C, *D* increase
S2	(-) direction of angle C, *D* decrease
S3	(+) direction of angle C, *D* increase
S4	(+) direction of angle C, *D* decrease

S1 → **S2** → **S3** → **S4**

S2 → **S1** → **S4** → **S3**

S3 → **S4** → **S1** → **S2**

S4 → **S3** → **S2** → **S1**

FIGURE 5 — Four kinds of experimental sequences where one of these is applied for each participant. S1–S4 represent four procedures that compose each sequence. For example, procedure S1 means that the experimental setup of Fig. 4 (a) is used and that the distances between positions "A" and "B" increase.

fusion. When the participant gives the wrong answer about the direction of the optotype m, it means that the participant cannot observe the stereoscopic image clearly. Hence, this disparity range is also treated as outside the zone of stereoscopic fusion.

At the start of each experiment, the purpose of the experiment and the required verbal response during the experiment was explained to each participant. After that, one of the four sequences was used for the experiment. The positions of the participant were adjusted for the tests of Fig. 4 (a, b) during the experiment. The authors changed the input signal and recorded the response of the participant for each condition. In determining the threshold range of each procedure of S1–S4, the binocular disparity of the stereoscopic image monotonically increased from the position of zero binocular disparity until the double image was observed by the participant. During the experiment, the binocular disparity of the stereoscopic stimulus of the input signal was changed in 5 pixels steps in the image position, which corresponds to 2.7 mm for the 3D display sample. Once this threshold was found, it monotonically decreased from a value that was larger than the threshold for the binocular disparity by 15 pixels. The near depth, which is the crossing point of the two lines connecting the viewing direction of the two eyes, which is located in front of the screen, was measured first. Then the far depth, which is the crossing point of the two lines connecting the viewing direction of the two eyes, which is located behind the screen, was measured, starting from the position of zero binocular disparity.

3 Results and analysis

Figure 6(a) illustrates the measured average threshold and the standard deviation for the 40 participants of the binocular disparity for the near depth for which the participant perceives a stereoscopic stimulus in front of the display. As the performance of the 3D sample along the horizontal direction is reported to be uniform for a directional range of less than 30°,[6] it is assumed that the dependence of the measured results on the angle C is not caused by the directional performance of the 3D sample. Figure 6(b) illustrates the threshold represented by the angle α between the two viewing directions of each eye at the crossing point. The IPD measured from each person is used in calculating this angle from the binocular disparity. In the case that the binocular disparity increases from zero disparity, the threshold and the standard deviation are measured to be 12.2 and ±5.35 mm, respectively, when the results from the 10 spatial positions of B are averaged. On the other hand, when the binocular disparity decreases toward zero disparity, the spatially averaged threshold and the standard deviation are measured to be

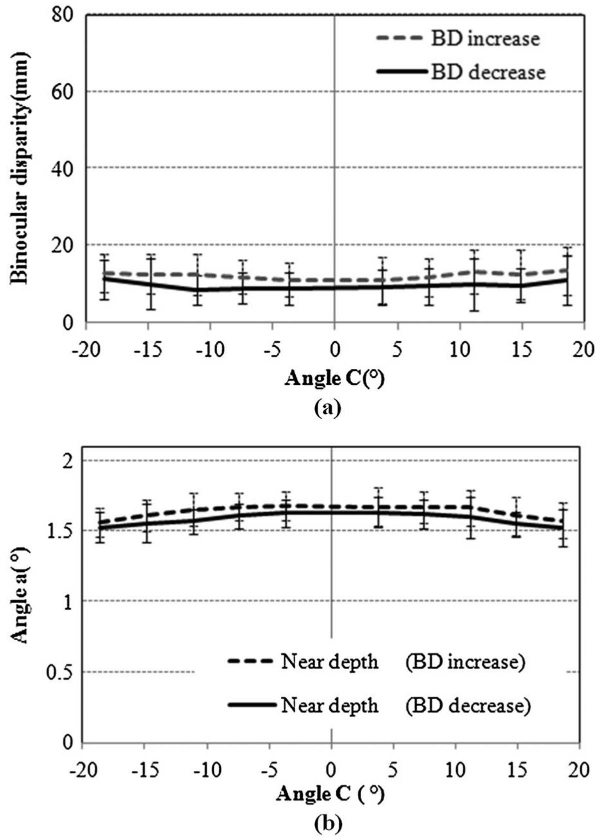


FIGURE 6 — The measured average thresholds and standard deviation for the near depth, which are represented as (a) the binocular disparity and (b) the angle α between the two viewing directions of the left and right eyes. The horizontal axis represents the angle C as defined in Fig. 4. "*BD* increase" and "*BD* decrease" represent the two conditions for which the binocular disparity increases from zero disparity, or decreases toward zero disparity, respectively.

9.71 ± 5.03 mm. The threshold is measured to be somewhat uniform irrespective of the angles between positions A and B. The threshold is measured to be larger for the condition that the binocular disparity increases from zero compared with the condition that the binocular disparity decreases toward zero. This difference is related to vergence movements, which try to keep the left and right retinal images locked once stereoscopic fusion occurs. Hence, a pair of eyes can follow the movement of a 3D object moving away from the screen more easily.[9] The measured thresholds for each participant are illustrated in Fig. 7. Some of the results are quite flat while some results show fluctuation trends. The range of stereoscopic fusion had been known to show large personal differences.[9] The large standard deviation of Fig. 6 (a) can be attributed to these personal differences.

Figure 8(a) illustrates the average threshold of the binocular disparity for the far depth in which the participant perceives the stereoscopic stimulus behind the display. Figure 8(b) illustrates the angles α between the two viewing directions of the left and right eyes at the crossing point for these thresholds of binocular disparity. In the case that the binocular disparity increases from zero disparity, the average threshold and the standard deviation are measured to be 45.4 ± 27.7 mm when the results from the 10 spatial positions of B are averaged. In the case that the binocular disparity decreases toward zero disparity, the spatially averaged threshold and the standard deviation are measured to be 40.7 ± 27.6 mm. Similar to the result for the near depth, the threshold is larger for the condition that the binocular disparity increases from zero compared with the condition that the binocular disparity decreases toward zero.[8] The threshold of the binocular disparity is measured to increase for the larger angle C, while the angle α shows a tendency to decrease for the larger angle C. As the angle α approaches 0°, the two viewing directions of the left and right eyes become parallel, and the position of the crossing point becomes infinite.

The measured thresholds of the binocular disparity of two participants in their thirties were in the range of "average ± standard deviation". As there were only two participants in their thirties, the age effect of fusional ability cannot be determined.

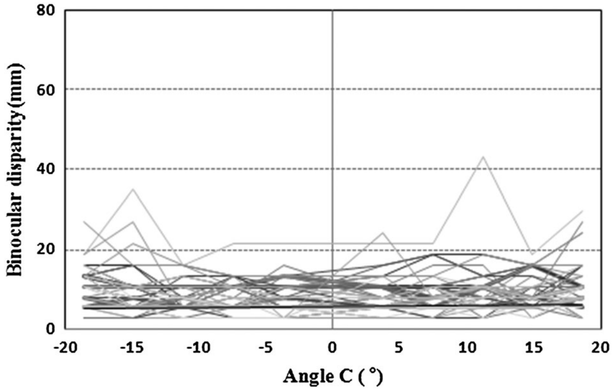


FIGURE 7 — The measured threshold for binocular disparity for the near depth on the condition that the binocular disparity increases from zero. Each line represents the threshold of one of the 40 participants. The horizontal axis represents the angle C defined in Fig. 4.

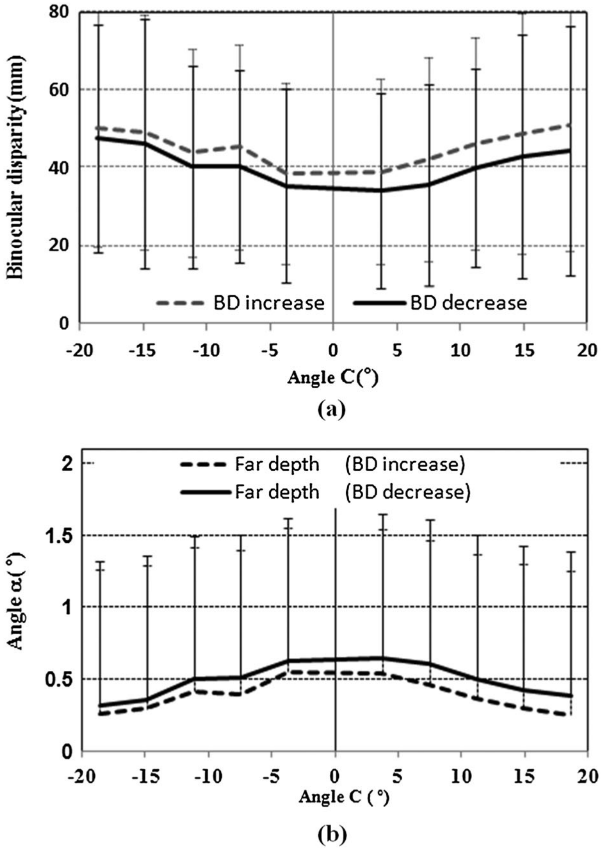


FIGURE 8 — The measured average thresholds and the standard deviation for the far depth, which is represented as (a) the binocular disparity and (b) the angle α between the two viewing directions of the left and right eyes. The horizontal axis represents the angle C defined in Fig. 4. "*BD* increase" and "*BD* decrease" represent the two conditions that the binocular disparity increases from zero disparity and decreases toward zero disparity, respectively.

The results of the thresholds for the various conditions are summarized in Table 2. Figure 9 illustrates the positions of the crossing points determined from the measured threshold of the near depth and the far depth. The crossing point at the angle α of the average ± standard deviation is illustrated as well as the crossing point at the average of the angle α. The range derived from the average angle determines the boundary that 50% of the participants can observe the stereoscopically fused images, while the range derived from the "average – standard deviation" determines the boundary for which 84.1% of the participants can observe the

TABLE 2 — The measured average thresholds of the binocular disparity for the far depth and near depth.

	Binocular disparity (mm)	
	Near depth	Far depth
BD increases	12.2 ± 5.35	45.4 ± 27.7
BD decreases	9.71 ± 5.03	40.7 ± 27.6

BD, binocular disparity.

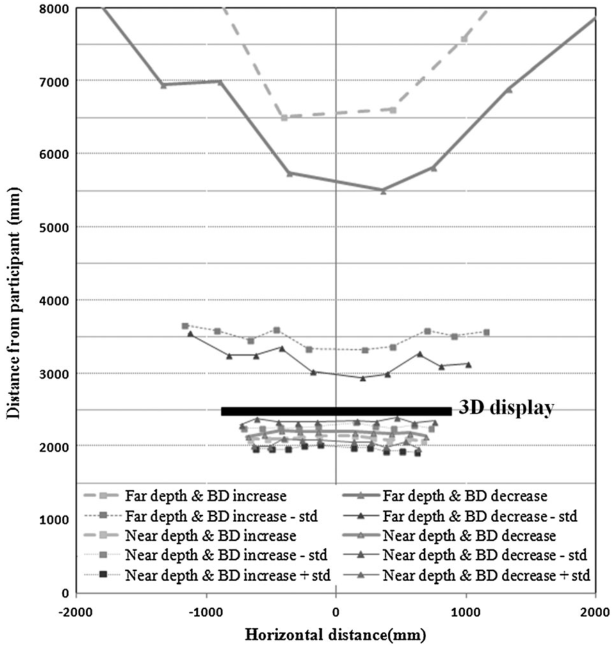


FIGURE 9 — The positions of the crossing points between the two viewing directions of the left and right eyes derived from the average threshold of the near depth and the far depth. Lines notated by "±std" represent the crossing points derived from the average binocular disparity ± the standard deviation. The participant is located at position (0, 0), and the 3D display is located at 2.5 m along the direction of the vertical axis.

stereoscopically fused images. As the angle α approaches zero, the crossing point changes greatly even for small changes of the angle α. Therefore, the average + standard deviation of the angle α is not illustrated in Fig. 8(b), and the crossing point for these angles is not illustrated in Fig. 9 as well.

It is known the participant becomes uncomfortable as the binocular disparity increases toward the threshold.[10–12] However, a binocular disparity that is too small cannot provide the 3D experience of depth. By selecting a suitable amount of binocular disparity for the 3D content in consideration of the viewing conditions of the 3D display and the threshold for the given viewing condition, it is expected that the user can perceive a good 3D image. Personal differences of the threshold are measured to be quite large, as illustrated in the aforementioned results. Statistically, the average − standard deviation defines a boundary of the probability of 84.1%. Therefore, limiting the binocular disparity to values smaller than the value of the average − standard deviation is expected to provide 84.1% of the viewers with a clear stereoscopic image.

4 Conclusion

The range of the binocular disparity for which a participant can observe a clear stereoscopic image is measured at a viewing distance of 2.5 m using a stereoscopic 3D TV based on PR technology and polarizing eyeglasses. Most of the participants for the experiments were in their twenties. Regarding the input signal, a stimulus of zero disparity and a stereoscopic stimulus of variable binocular disparity were shown in a 3D sample for the horizontal direction.

The measured ranges of the binocular disparity showed large personal differences. The threshold at the increase of the binocular disparity was measured to be larger than the threshold at the decrease of the binocular disparity, as shown in Table 2. These trends are similar to previous experimental results, although the conditions of the measurement distance and the directional range are different.[8]

One of the major factors for the eyestrain caused by the stereoscopic display is the difficulty in fusing the left and right images with large binocular disparity. Hence, visual fatigue and the thresholds of the binocular disparity are closely related.[10–12] In order for the user to observe a good stereoscopic image comfortably, 3D content with a suitable amount of binocular disparity is needed. For this to be achieved, the threshold of the binocular disparity should be determined for the specific environment in which the viewers watch the stereoscopic display. The result of our study determines the threshold for the binocular disparity for 3D TV at a viewing distance of 2.5 m and where the field of view that the 3D TV occupies is less than ±20°. We expect that these results will be useful to help provide 3D content with a suitable amount of binocular disparity under such viewing conditions.

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Hyungoo Kang received his BS degree from the Seoul National University of Science and Technology in 2009 and is currently taking his master's degree.

Hyungki Hong is an assistant Professor at the Department of Visual Optics, Seoul National University of Science and Technology, since 2010 and is a member of SID. He received his BS in Physics from Seoul National University and PhD in Physics from Korea Institute of Science and Technology (KAIST). After receiving his PhD in 1998, he joined LG Display (at that time LCD division of LG Electronics) and worked for the performance improvement and the performance characterization of LCD and 3D display until 2010.