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Comparison of Stereoscopic Fusional Area between People with Good and Poor Stereo Acuity

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Purpose: This study investigated differences in stereoscopic fusional area between those with good and poor stereo acuity in viewing stereoscopic displays. **Methods:** Stereo acuity of 39 participants (18 males and 21 females, 23.6±3.15 years) was measured with the random dot stereo butterfly method. Participants with stereo-blindness were not included. Stereoscopic fusional area was measured using stereoscopic stimulus by varying the amount of horizontal disparity in a stereoscopic 3D TV. Participants were divided into two groups of good and poor stereo acuity. Criterion for good stereo acuity was determined as less than 60 arc seconds. Measurements arising from the participants were statistically analyzed. **Results:** 26 participants were measured to have good stereo acuity and 13 participants poor stereo acuity. In case of the stereoscopic stimulus farther than the fixation point, threshold of horizontal disparity for those with poor stereo acuity were measured to be smaller than the threshold for those with good stereo acuity, with a statistically significant difference. On the other hand, there was no statistically significant difference between the two groups, in case of the stereoscopic stimulus nearer to the fixation point. **Conclusions:** In viewing stereoscopic displays, the boundary of stereoscopic fusional area for the poor stereo acuity group was smaller than the boundary of good stereo acuity group only for the range behind the display. Hence, in viewing stereoscopic displays, participants with poor stereo acuity would have more difficulty perceiving the fused image at farther distances compared to participants with good stereo acuity.

Key words: Stereo acuity, Stereoscopic fusional area, Stereoscopic display

Introduction

Stereo acuity is determined by the minimum amount of the discriminable depth. Many studies have reported the abnormal functions of the binocular vision due to ametropia, anisometropia, horizontal-vertical phoria, fixation disparity and age related ocular dysfunctions.[1-10] These factors affect stereo acuity and differences in stereo acuity exist acuity among the people who are not stereo-blind.

As human eyes are separated by interpupillary distance, slightly different images are formed on the retina of the viewer's each eye and these cause the stereopsis under some conditions. In stereoscopic displays, the various techniques have been used to form the slightly different images on the retina of the viewer's each eye to make the viewer perceive the stereoscopic depth. In this paper, the area that these slightly different images of the stereoscopic display are fused was called stereoscopic fusional area, and represented an area where viewers can perceive 3D depth in viewing stereoscopic display.[11,12]

In viewing stereoscopic display, fatigue prevention was important issue.[13] People with poor stereo acuity could still perceive the depth if a 3D object was inside the stereoscopic fusional area in viewing stereoscopic display. But if stereoscopic fusional area of people with poor stereo acuity was smaller than that of people with good stereo acuity, people with poor stereo acuity would be more venerable to fatigue. Therefore, this study investigated whether there were differences in stereoscopic fusional area between the people with the good and poor stereo acuity.

Methods

39 participants with the stereo acuity of the good range

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본 논문의 일부내용은 2015년도 한국안광학회 하계학술대회에서 구연으로 발표되었음.

and the poor range were divided into two groups. The average participant age was 23.7±3.14 years. 18 participants were males and 21 participants were females. Stereoscopic fusional area of these two groups was measured for these two groups using the stereoscopic display and the control of the horizontal disparity size of the stereoscopic stimulus. Participants with monocular visual acuity lower than 0.8 and binocular visual acuity lower than 1.0 were excluded. Corrective eyeglasses are known to cause the effects such as prism effect and aniseikonia[14] To prevent these effects on the experiment, only people who did not wear corrective eyeglass or wore the contact lens were selected as the participants.

Interpupillary distances (IPD) of each participant were measured by PD meter (PD-82, Shin Nippon).[15] Stereo acuity of the participants was measured at the observation distance of 40cm using random dot stereo butterfly test (Stereo Optical Co.) as illustrated in Fig. 1.[16]

Among the four circles inside each of the nine diamond-shaped patterns, participants wearing polarized eyeglasses were asked to select the one of the four circles which was perceived to be in front or behind the test pattern. The stereo acuity of the participants could be measured into nine levels as illustrated in Fig. 1.

Circles	Angle of stereopsis at the distance of 40cm (arc sec)
1	800
2	400
3	200
4	140
5	100
6	80
7	60
8	50
9	40

Fig. 1. Random dot stereo butterfly test (Stereo Optical Co.) and the angle of stereopsis measured by this test.

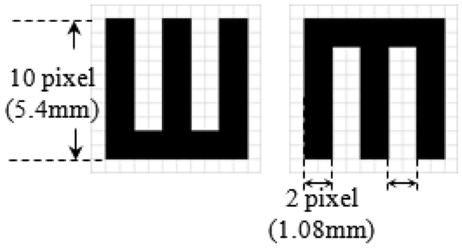

Fig. 2. Optotype ‘m’ of UP and DOWN directions.

Stereoscopic fusional area along the horizontal direction was measured using the stereoscopic display and the control of the amount of the horizontal disparity that two eyes observed.[17] The selected sample display was the stereoscopic display based on the Patterned Retarder technology with the resolution of 1920×1080 and the pixel pitch 0.54 mm (LG, 47LW4000).[18] To measure stereo acuity, the participants wore the polarized eyeglasses to perceive the stereoscopic image. Fig. 2 illustrated the optotype ‘m’ of UP and DOWN directions used for the experiment. For the sample display of 0.54 mm pixel pitch, the height and the width of the optotype on the display were 5.4 mm. The line thickness and the interval between lines were 1.08 mm.

Fig. 3 illustrated the experimental setup for the measurement of the threshold of stereoscopic fusional area where the stereoscopic stimulus was nearer than the fixation point. A crossing point between the viewing directions of two eyes of the participant was in front of display. Illuminance of the experiment room was kept at 300 lux and the distance between the participant and the display sample was selected as 2.5 m. The eye position of the participant was along a line perpendicular to the display sample and through the point **A**. The point **A** was located at the same distance from the upper and lower boundaries of the sample display. In addition, point **A** was 100 pixels apart horizontally from the boundary of the sample display. Optotypes of Fig. 2 with up or down directions were used as the stereoscopic stimulus. If a person could discern this optotype at the observation distance of 2.5 m, this corresponded to the visual acuity of 0.7. Visual acuity of 0.7 had been generally used for measuring binocular vision such strabismus and vergence.[19]

For the left eye observation, optotype of up or down directions was located on the position which was horizon-

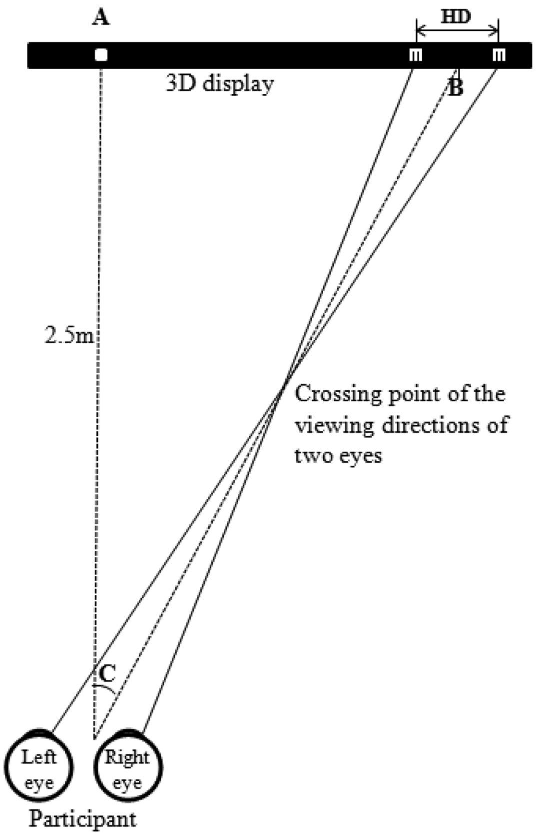

Fig. 3. Top view of schematic diagram of the experiment setup to measure stereoscopic fusional area boundary. Stereoscopic stimulus was located around the point **B**. **HD** represented the horizontal disparity of the optotype for the left and right eyes on 3D sample display. Angle from the participant to the point **A** and **B** on the display was represented as angle **C**.

tally shifted by an amount of **HD**/2 from the point **B. HD** represented the horizontal disparity between the left and the right images located around the point **B**. For the right eye observation, optotype of the same direction was located on the position which was horizontal shifted by the amount of **-HD**/2 from the point **B**. The point **B** was located either on the left or right side of the position **A**. For the larger amount of horizontal disparity **HD,** a crossing point between the viewing directions of two eyes of the participant would be more distant from the display and the participant would perceive the larger depth inside stereoscopic fusional area. During the experiment, the amount of the horizontal disparity was changed with step of 2.7 mm on the sample display. At different amounts of horizontal disparity, each participant was asked to answer whether the optotype was perceived to be fused, blurred or double within 1 second.[17] The participant was also asked to answer the direction of optotype. If the participant could perceive the clear fused stimulus, the participant would answer the correct direction of the optotype.

In the experiment, the horizontal disparity first increased from zero to the amount that the optotype was perceived by the participant to be blurred or double, which was called the threshold of **HD** increase. Then the procedure was repeated in the direction of the decreasing disparity from the initial horizontal disparity which was 8.1 mm larger than the threshold of **HD** increase. The participants should see the double image at the initial horizontal disparity. The horizontal disparity decreased until the participants perceived the fused image instead of the double image and this value was called the threshold of **HD** decrease.

The distance between **A** and **B** on the display was horizontally changed by a step of 162 mm. The thresholds of **HD** increase and decrease were measured at the 10 positions of **B**, respectively. The horizontal angle **C** was defined as the angle between **A** and **B** from the position of the participant as illustrated in Fig. 3. The change of each step of 162 mm between **A** and **B** approximately corresponded to the change of 3.72 degrees of the angle **C**. The range of 10 positions of point **B** corresponded to the range of ±18.6 degrees of the angle **C**.

The thresholds of **HD** increase and decrease were also measured in case of the stereoscopic stimulus farther than the fixation point. In this condition, a crossing point between the viewing directions of two eyes of the participant would be located behind the display.

Various values had been reported as the boundary of the normal stereo acuity range.[20-26] Saladin[20] reported that forty to fifty arc seconds was an acceptable score for Randot stereo-test. Cho et al.[22] found the criterion for the normal subjects were less than 50 arc seconds and stereo acuity of the abnormal subjects was ranged from 60 to 400 arc seconds. Westheimer[23] noted that a normal observer should manifest a reading of better than 1 arc min on the first test. McIntire et al.[25] reported that clinically normal stereoscopic acuity was usually considered to be on the order of 30-40 arc seconds or better. From these reports, the boundary of the good stereo acuity was selected as 50 arc seconds or better, and the poor range was selected as 60 arc seconds or worse in this paper. By this criterion, participants were divided into two groups of the good and poor stereo acuity.

Stereoscopic fusional area was statistically compared between these two groups. PSAW statistics 18 program (SPSS for windows, IBM) was used to statistically analyze the result. P-value of 0.05 was used to check whether two groups of good and poor stereo acuity had the different stereoscopic fusional area.[27]

Results and Discussion

The measured IPD of 39 participants were in the range of 57~67 mm and the average was 63.00±2.45 mm. The measured stereo acuity of the participants was listed in Table 1. With 50 arc seconds of stereo acuity as a criterion, participants were divided into two groups of the good and poor stereo acuity. Among the 39 participants, 26 participants (12 males, 14 females) were measured to have the good stereo acuity. The stereo acuity of 13 participants (6 males, 7 females) was measured to be 60 arc seconds or worse.

In the measurement setup of stereoscopic fusional area using the stereoscopic display, the crossing point of the viewing direction of two eyes was generally considered to be the position of the observed stereoscopic stimulus. From the measured threshold value of the horizontal disparity and measured IPD of each participant, the location of the crossing points was calculated.[28] The crossing points for the nearer and farther stereoscopic stimuli of the horizontal disparity of 2.7 mm corresponded to the positions of 84 mm in front of the display and 135 mm behind the display. For the same stereo acuity, the depth perceived by the participants was also affected by IPD. For example, if a person with IPD of 63 mm was located at a distance of 2.5 m, the stereo acuity of 40, 60 and 140 arc seconds corresponded to the depth of 19 mm, 28 mm and 65 mm, respectively. Hence, even the participants with the worst stereo acuity of 140 arc seconds could perceive the depth of the stereoscopic stimulus 2.7 mm horizontal disparity of on the stereoscopic display.

Table 1. Stereo acuity of 39 participants

Stereo acuity (arc sec)	Number of participants
40	16
50	10
60	4
80	3
100	1
140	5

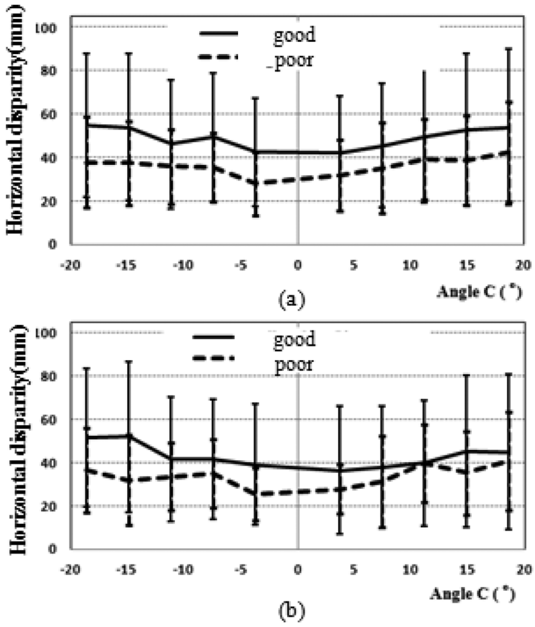

Fig. 4. Average of the measured threshold of horizontal disparity **HD** at the condition of the stereoscopic stimulus farther to the participants with the good and poor stereo acuity for the condition of (a) **HD** increase and (b) **HD** decrease. Horizontal axis represented the angle **C** of Fig. 3. Vertical axis represented the threshold of **HD** beyond which the binocular fusion did not occur.

Fig. 4 and 5 illustrated the threshold of the horizontal disparity measured on the farther and nearer stereoscopic stimuli for the participants with the good and the poor stereo acuity. Table 2 represented the analysis result of t-test between the two groups of the good and the poor stereo acuity. In case of the stereoscopic farther stimulus, the threshold for the participants with the poor stereo acuity was measured to be smaller than the threshold for the participants with the good stereo acuity. And the results of two groups were statistically significantly different (p=0.000). In case of the nearer stereoscopic stimulus, the threshold for the participants with the good stereo acuity was slightly smaller than the threshold for the participants with the poor stereo acuity, but the difference of thresholds was not statistically significant as shown in Table 2. In Fig. 4 and 5, threshold at the condition of **HD** increase was measured to be larger than threshold at the condition of **HD** decrease. This result accorded with the fact that fusional range of the object moving away from the screen was known to be larger than the object moving toward the

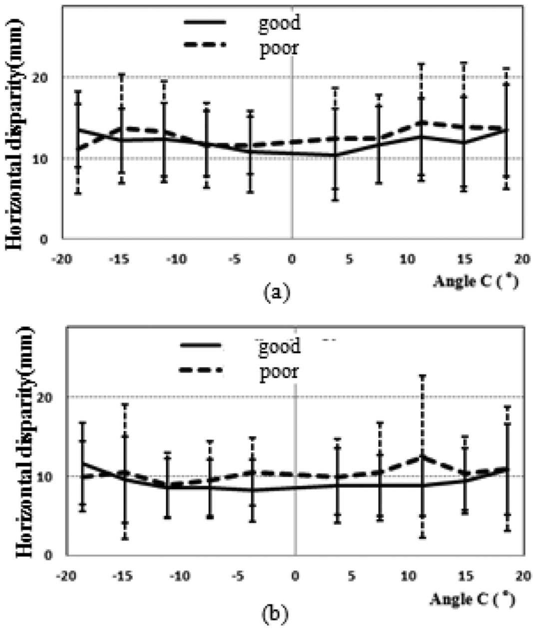

Fig. 5. Average of the measured threshold of horizontal disparity **HD** at the condition of the stereoscopic stimulus nearer to the participants with the good and poor stereo acuity for the condition of (a) **HD** increase and (b) **HD** decrease. Horizontal axis represented the angle **C** of Fig. 3. Vertical axis represented the threshold of **HD** beyond which the binocular fusion did not occur.

screen.[29,30]

For the condition of farther stereoscopic stimulus where the threshold between two groups of the good and poor stereo acuity was significantly different, the relation between the stereo acuity and the threshold of horizontal disparity was investigated. Fig. 6 illustrated the threshold of the horizontal disparity of each participant averaged at the angle **C** of −3.72 degrees and 3.72 degrees. Statistical method of Pearson product-moment correlation was used to measure the linear association between the stereo acuity and the threshold of horizontal disparity for the stimulus behind display. Pearson correlation coefficient (Pearson's r) was −0.206, indicating the negative association which was represented as the solid line in Fig. 6. Yet, P-value was 0.209 and

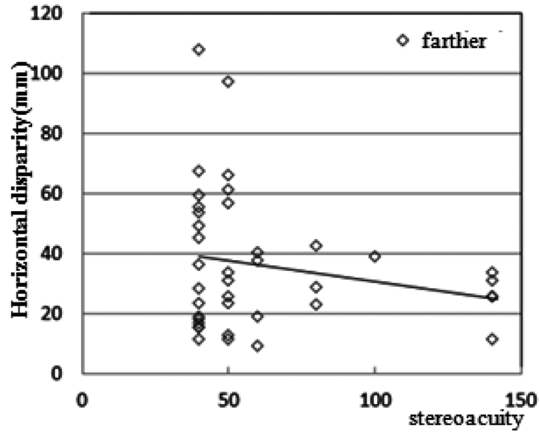

Fig. 6. Stereo acuity vs. the threshold of horizontal disparity **HD** of each participant for the stereoscopic farther stimulus. Solid line represented Pearson correlation coefficient of −0.07.

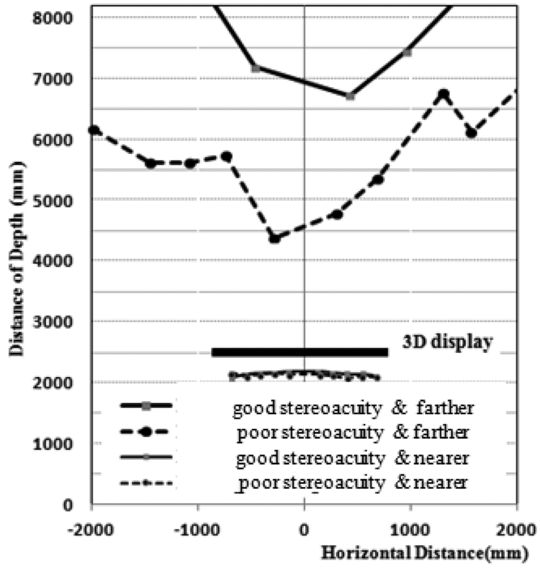

Fig. 7. Boundaries of stereoscopic fusional area which were determined from crossing points positions between the viewing directions of two eyes for the participants with the good and poor stereo acuity. Averages of the thresholds between **HD** increase and **HD** decrease were used to determine crossing points positions. Horizontal and vertical axis represented the horizontal distance and the distance to the participant from the center of the display sample.

Table 2. Statistical analysis of the measured horizontal disparity **HD** between the participants with the good and poor stereo acuity

	Groups of Stereo acuity	Nearer (mm)		Farther(mm)	
		Average ± std	p-Value	Average ± std	p-Value
Threshold of **HD** increase	good	12.14 ± 4.93	0.251	49.22 ± 30.78	0.000*
	poor	12.86 ± 6.19		36.33 ± 18.59	
Threshold of **HD** decrease	good	9.34 ± 4.55	0.082	43.09 ± 31.05	0.000*
	poor	10.41 ± 6.19		33.75 ± 18.01	

*marks means statistically significantly different result for $p<0.05$

there was no significant relation between the stereo acuity and the threshold of horizontal disparity.

The positions of the crossing points between the viewing directions of two eyes in viewing 3D display were determined from the measured thresholds of the horizontal disparity.[28] These positions for the farther and nearer stereoscopic stimuli were the boundary of stereoscopic fusional area around the stereoscopic display in viewing the stereoscopic display. Fig. 7 illustrated the boundaries of stereoscopic fusional area obtained from the threshold of horizontal disparity for the participants with the good and the poor stereo acuity. Due to the difference of the horizontal disparity threshold of the two groups at the farther stereoscopic stimulus, stereoscopic fusional area for the group of the poor stereo acuity was measured to smaller than the area for the group of the good stereo acuity behind the stereoscopic display.

In case of the stereoscopic farther stimulus, the angular change became smaller as the crossing point moved farther from the participant. If a participant with the poor stereo acuity had difficulty distinguishing the angular change and aligning two eyes within the angles smaller the stereo acuity, the participant would have more difficulty accurately controling the minute alignment of two eyes for the stereoscopic vision at the far distance. And this difficulty might cause the reduction of stereoscopic fusional area at the side of the farther distance. In case of the stereoscopic nearer stimulus, the larger angular change occurred as the crossing points moved toward the participant. So even a participant with the poor stereo acuity might distinguish this large angular change at a close distance. This might result in the difference of boundaries of stereoscopic fusional area behind the display for both the good and poor stereo acuity groups.

Conclusions

Stereoscopic fusional areas were measured and compared between the two groups of participants with the good and the poor stereo acuity. Stereoscopic fusional areas between these two groups were measured to be statistically significantly different in case of farther stereoscopic stimulus while the differences between two groups were not significant for nearer stereoscopic stimulus. Hence, the participant with the poor stereo acuity would have more difficulty perceiving the stereoscopically fused image at the larger range compared with the participants with the good stereo acuity in viewing stereoscopic display, though there was no difference between these two groups for the nearer range.

In viewing 3D images or movies, the stereoscopic fusional range of the viewer is an important factor affecting their comfort. Hence, the difference of stereoscopic fusional range between people with the good and poor stereo acuity needs to be considered in production of 3D images or 3D movies.

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입체 시력이 양호한 사람과 불량인 사람간의 입체시 융합 가능 영역 비교

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목적: 이 연구는 입체 영상 장비를 시청시 입체 시력이 양호한 사람과 불량인 사람 간에 입체시 융합 가능 영역의 차이가 있는지 알아 보기 위함이다. **방법:** 입체시가 가능한 39명(남 18명 여 21명, 23.6±3.15세)을 대상으로 random dot stereo butterfly 측정법을 사용하여 입체 시력을 검사하였다. 입체맹인 피검자는 포함되지 않았다. 입체시 융합 가능 영역은 안경방식 3D TV를 이용하여 수평 시차를 다르게 하여 측정하였다. 입체시력이 60 arc sec 미만을 입체 시력 양호의 기준으로 하여, 입체시력 양호군과 입체시력 불량 군으로 나누었다. 측정 결과를 통계적으로 비교 분석 하였다. **결과:** 입체 시력 측정 결과에서, 피검자 중 26명을 입체시력 양호군, 13명을 입체시력 불량 군으로 나누었다. 주시점 보다 원거리 입체시 자극이 있는 경우, 입체 시력이 불량인 군의 수평 시차의 경계는 입체 시력이 양호한 군에 비해 통계적으로 유의한 수준에서 작은 것으로 측정되었다. 주시점 보다 근거리 입체시 자극이 있는 경우, 두 군 사이에 통계적으로 유의한 차이는 없었다. **결론:** 입체 영상 장비를 시청시 입체 시력이 불량인 군의 입체시 융합 가능 영역은 양호한 군과 비교하여 입체 영상 장비 뒤쪽 방향에서 좁았다. 그러므로 입체 영상 장비를 시청시할 때 입체 시력이 불량한 피검자는 양호한 피검자에 비교하여, 원거리에서 융합된 영상을 인지하기 힘들 것이다.

주제어: 입체 시력, 입체시 융합 가능 영역, 입체영상 표시장치