Measurement of the lens accommodation in viewing stereoscopic displays

Hyungki Hong (SID Member)
Seok Hyon Kang

Abstract — In observing the stereoscopic display at the viewing distance of 1 m, the amount of the perceived depth was determined by the positions of the crossing point that the viewing direction of two eyes intersect. The positions of the crossing points of stereoscopic stimuli were controlled, and the accommodation was measured by the autorefractometer for the seven participants. Accommodation was also measured when viewing the real film chart which was placed at the same position as these crossing points. The accommodation change when viewing the stereoscopic display was measured to be noticeable only when the crossing point was quite near the participant, but this change was still much smaller compared with the accommodation change when viewing the real film chart. This change in accommodation implies the possible occurrence of fatigue related to the accommodation–convergence conflict, while the constant accommodation within the range of DOF implies no conflict between the accommodation and convergence. This measurement scheme may be used to define the range of DOF where the accommodation remains little changed, and thus define the depth of the 3D object at which no accommodation–convergence conflict occurs, for a given stereoscopic display.

Keywords *— 3D display, stereoscopic display, display human factors, accommodation.*

DOI # 10.1002/jsid.303

1 Introduction

3D technology had been expected to enhance the experience of the viewers. Stereoscopic display is one of 3D technologies which cause the perception of the depth by the generation of the slightly different images for the left and the right eye. Stereoscopic displays using the special eyeglass had nowadays become very popular for 3D movie and 3D TV.[1,2] However, the fatigue caused by stereoscopic displays had become one of the main issues against the wide use of the stereoscopic displays. And the accommodation–convergence conflict had been considered to relate to the fatigue, though the relation is still controversial. [3–6]

Optometric instrument called the autorefractometer had been used to measure the accommodation which was the optical power of the eye when watching the objects at the various viewing distances.[7,8] The accommodations had been known to depend not only on the viewing distance but also on the various factors such as the characteristics of the spatial frequency of the displayed image and the brightness of the environment.[9]

Recently, the autorefractometer with the open binocular field of view had been developed which used the half mirror and did not block the view of the users. And this measuring instrument had been reported to measure the accommodation of the viewers when viewing the 3D displays.[10–15] Yet, these reports did not cover the accommodations for the wide range of 3D technologies and the various 3D images. As the accommodation is affected by the various factors, the accommodation needs to be measured for the diverse conditions for the better understanding of the accommodative response in 3D displays.

In this paper, the accommodation when viewing the film chart and 3D chart on the stereoscopic display was investigated. The positions of the film chart and the crossing points in 3D chart were matched to be equal. The optical power of the user's eye watching 3D or the film chart was measured by the autorefractometer at these similar conditions. The measured results were compared to investigate the accommodative response when viewing the stereoscopic display.

2 Theory

When people see the objects, people can only see the clear focused object at the limited distance range as illustrated in Fig. 1. The finite range of the distance that the eye can observe the objects sharply had been defined as Depth of Field (DOF). [16] If the objects are located outside DOF, these are observed to be unfocused. For example, when the eye gazes at the far distance, DOF is located at the far distance. When the eye shifts the gaze to the near distance, the objects at the near distance initially looks defocused. Hence, this causes the increase of the optical power of the crystalline lens

Received 10/17/14; accepted 05/13/15.
Hyungki Hong is with the Department of Optometry, Seoul National University of Science and Technology, Gongneung gil, Nowon-gu, 139-743 Seoul, South Korea; e-mail: hyungki.hong@snut.ac.kr.
Seok Hyon Kang is with the Seoul National University of Science and Technology Seoul, South Korea

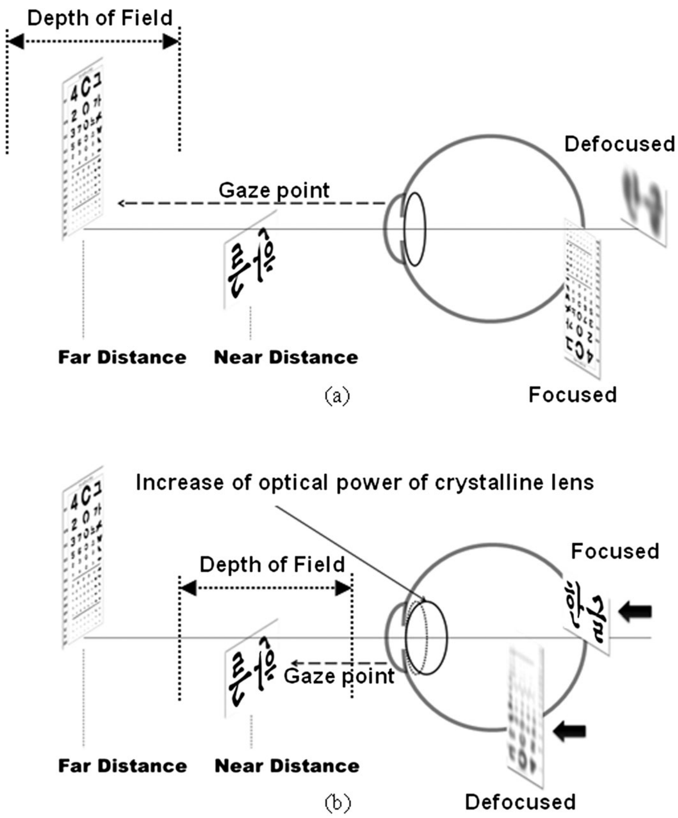


FIGURE 1 — Phenomenon of accommodation where the optical power of the eye changes depending on the gaze of (a) Far and (b) Near distance.

and the shift of DOF toward the near distance. By this change, the eye can observe the objects at the near distance to be focused. And this phenomenon of the change of the optical power of the eye had been defined as accommodation. [16]

Among the various 3D technologies, the stereoscopic display is generally defined as one of 3D technologies which provide the depth cue by the image difference observed by the left and right eyes. In this paper, the stereoscopic display was investigated among the various 3D technologies. When viewing the stereoscopic display, the viewing directions of the left and right eyes were slight different because of the horizontal difference between the left and the right images of the stereoscopic stimuli. The viewing direction of the left and right eyes intersected at the crossing point in front of or behind the display surface and the viewers would perceive the object located at the crossing point as illustrated in Fig. 2. The crossing point was determined by the horizontal difference between the left and the right images, B.

While the eyes of the viewer would try to focus on the perceived 3D objects on the crossing point, the perceived 3D object was not actually located at the crossing point. Hence, focusing on the perceived 3D objects by the change of the optical power of the eye would cause the defocus if the distance between the perceived 3D object and the stereoscopic display was larger than DOF. This was known to cause the accommodation–convergence conflict. As this

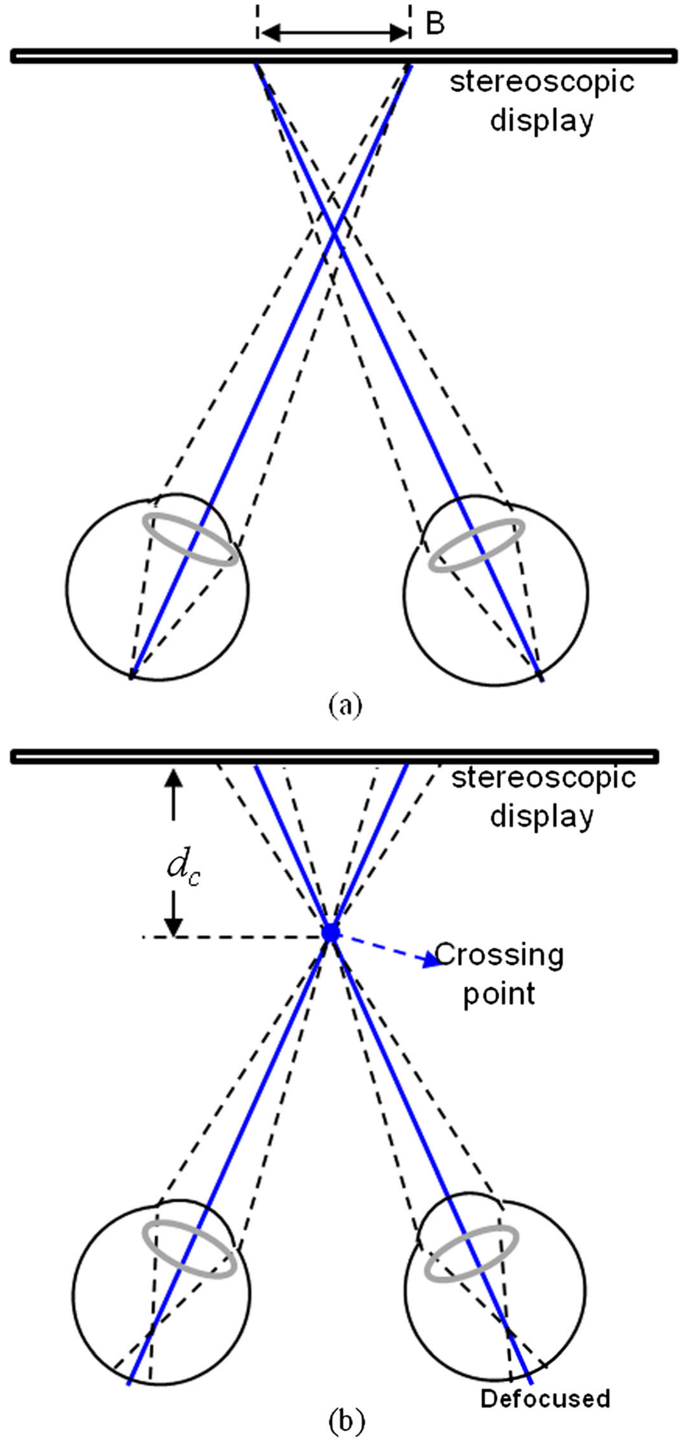


FIGURE 2 — Accommodation–convergence conflict in the stereoscopic display. (a) Focus at the display surface does not accord with the perceived depth. (b) Focus at the crossing point causes the defocus. Crossing point is the point where the viewing direction of the left and right eyes intersects. B represents the horizontal difference between the left and the right images of the surface. d_c represents the distance from the display to the position of the crossing point.

conflict would induce the incorrect focal distance or the need to accommodate more frequently compared with the observation of the actual object, this conflict was generally considered to relate to the fatigue in watching stereoscopic displays.[3–6]

Yet, the accommodation–convergence conflict should occur only when distance between the perceived 3D object and the stereoscopic display is larger than DOF.[5] According to Patterson (ref. 5), the logic underlying the concept of accommodation–convergence conflict is centered on oculomotor responding.[5] It is commonly believed that converging or diverging to a depth plane different from the display surface will draw the accommodative response to that plane, thereby causing images on the display surface to become blurred. And blurred images would then draw the accommodative response back to the display surface, thus causing an accommodation–convergence conflict. However, Patterson argued that such a conflict should occur only for viewing distances outside DOF because converging or diverging within the depth of field would mean that the images on the display surface would still be in focus.

Observation and stimulus for the accommodation in the stereoscopic displays are different from those of the actual object. The accommodations when viewing the stereoscopic displays and the actual object would need to be compared to understand the behavior of the optical power of the eye in observing the stereoscopic displays.

FIGURE 3 — Autorefractometer with the open binocular field of view: Shin-Nippon Nvision—K 5001. Through the open window, the participant can observe the stereoscopic display.

3 Method

Measurement device of the optical power of the eye should not block the view of the participants when viewing the stereoscopic display. Autorefractometer with open binocular field of view (Shin-Nippon Nvision—K 5001) illustrated in Fig. 3 was used as the measurement device for the accommodation. While the participant was observing stereoscopic display through the open window of this autorefractometer, the optical power of each eye of the participant was measured. Commercial 3D TV using the patterned retarder and the polarized glass was used as the stereoscopic sample display.[17] The diagonal size of the sample was 47 inch, the pixel resolution was 1920 by 1080 and the pixel size was 0.54 mm. The pixel of the display sample occupied the angle of 1.8 arc min at the viewing distance of 1 m. Optic axes of the patterned retarder in front of the sample display were different for the horizontal even and odd lines of the sample display. Hence, each eye of the participant wearing the polarized eyeglass can only see the lights coming from either horizontal even or odd lines of the sample display.

3D chart for the measurement was designed in consideration of the resolution and the size of stereoscopic sample display. 3D chart for the left and the right eye was placed at the opposite side from the center of the sample display as illustrated in Fig. 4(a). Other area on the sample display was kept on the white level whose luminance was measured to be 91 cd/m^2 at the center of the sample display. Luminance was measured with the polarized eyeglass in front of the luminance meter (UA-10, TOPCON). Figure 4(b) illustrates the layout of the Optotypes. Generally, 10 letters of C, D, H, K, N, O, R, S, V and Z had been used as the Optotypes for the measurement of visual acuity.[18] Among these letters, nine letters were selected for 3D chart. In the designed 3D chart, three lines with three letters were used. Sizes of the characters between two adjacent lines were represented as a, b, c in Fig. 4 (b). The values of a/b and b/c were selected to be approximately 5:4. The intervals between these lines were represented as d and e in Fig. 4(b). The value of d/e was also selected to be approximately 5:4. This ratio of 5:4 for the character size and the line interval was selected in consideration of logarithmic size progression of the optotype.[18] The sizes of c and d were 17 times the pixel size. The actual film chart was made by printing the optotype on the sheet.

Figure 5 illustrated the schematic setup of the accommodation measurement when seeing the actual film chart and 3D chart on the stereoscopic sample display. The optical power of the lens was inversely proportional to the focal distance in the unit of meter. For example, the difference of optical power between the lenses of the focal distance of the 2.5 m and 1 m would be 0.6 Diopter. That means that the difference of the accommodation for the object located at 2.5 m and the 1 m would not be larger than 0.6 Diopter. In the pre-test to determine the suitable positions of the film chart, the sample display and the crossing point of 3D chart, the measured change of the optical power was around or smaller than 0.25Diopter, when the film chart and 3D chart were located at the distance larger than 1 m. In the field of

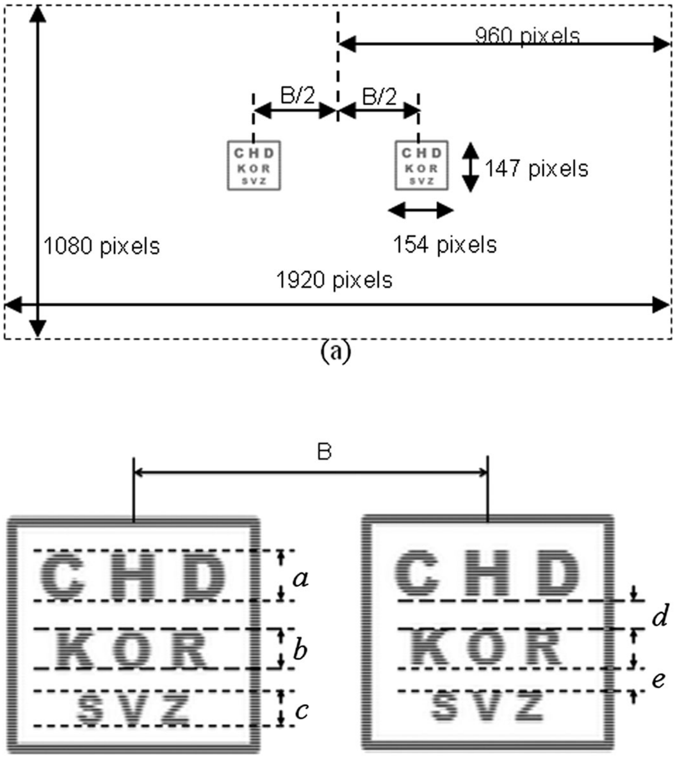


FIGURE 4 — Example of 3D stereoscopic chart where the optotypes for the left and the right eyes are separated by the distance B. (a) Layout of 3D chart and (b) configuration of optotypes. The ratio of *a*:*b*, *b*:*c* and *d*:*e* are approximately 5:4. The sizes of *c* and *d* are 17 times the pixel size. The pixel size of the stereoscopic display sample is 0.54 mm. B represents the horizontal difference between the left and the right images of the display.

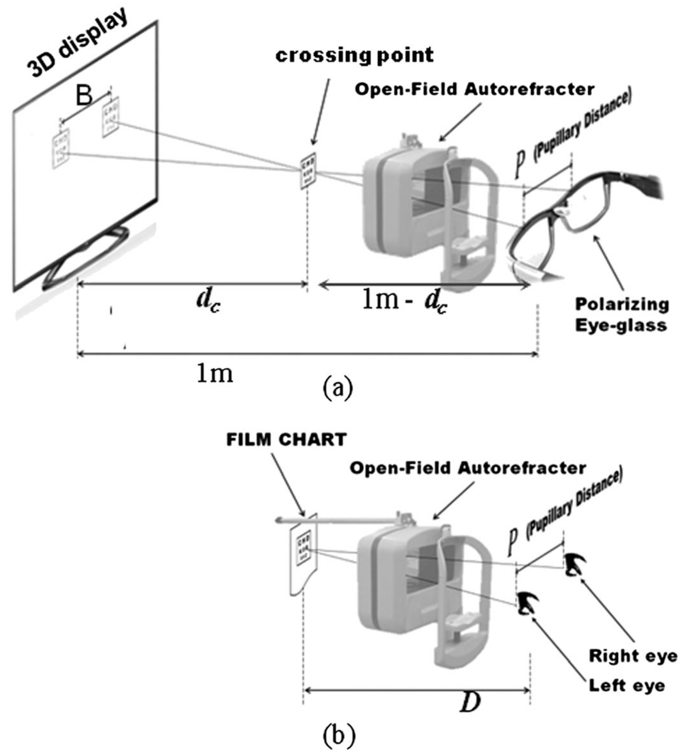


FIGURE 5 — Schematic setup of the accommodation measurement for (a) 3D chart shown on the stereoscopic display sample and (b) the actual film chart. d_c represents the distance from the display to the position of the crossing point. Distance from the participant to stereoscopic display was 1 m. *D* represents the distance from the participant to the film chart which was 1 m, 0.5 m, 0.4 m. 0.3 m or 0.2 m.

the optometry, 0.25 Diopter was considered to be the minimum size of the optical power to affect the visual acuity. As the change of the optical power larger than 0.25 Diopter needs to occur in the experiment, the distance of stereoscopic sample display from the participant was selected as 1 m. And the distance between the participant and the crossing points was selected to be smaller than 1 m. In case of the accommodation measurement when viewing the film chart, the distance between film chart and the participant was selected to be the same as that between the participant and the crossing point.

Participants consisted of eight persons. Seven persons had the normal stereoscopic vision and the visual acuity of better than 0.8 in the decimal representation. One person had the amblyopia for the left eye and was stereo-blind. Ages of the participants were 23.3 ± 1.7 years.

The crossing point could be determined by Inter Pupillary Distance (IPD) and the horizontal difference between the left and the right images, B. [19–21] If IPD of the participants were the different, the positions of the crossing point would be different for the same amount of B. Hence, IPD of each participant was measured by PD meter (PD-82, Shin-Nippon). And the size of B for the image data of the 3D chart was specifically adjusted for each participant in consideration of the different IPD of each participant such that the crossing point was located at the same position. And the 3D chart specifically modified for each participant was used for the accommodation measurement.

Before the experiment, the purpose and the procedure was explained to each participant. Illuminance of the room was kept as 450 lux during the experiment.

First, the accommodation when viewing 3D chart was measured using autorefractometer. Stereoscopic sample display was located at the distance of 1 m from the participant and each participant wearing the polarized eyeglass was asked to watch 3D chart on the stereoscopic sample display. To maintain the stereoscopic fusion of the participant, the position of the crossing point was consecutively changed by step of 5 cm toward the participant. And the participant was instructed to notify the authors if the stereoscopic fusion was broken and the double vision occurred. Optical power was measured at the condition that the distances from the participant to the crossing point were 100 cm, 50 cm, 40 cm, 30 cm and 20 cm. The optical power of each eye of the participant was measured three times by the autorefractometer for each condition.

Second, the film chart was placed at the distance of 100 cm, 50 cm, 40 cm, 30 cm and 20 cm from the participant. And the optical power was measured, while the participants were observing the film chart. This corresponded to the accommodative response when viewing the real object at the different distances.

4 Result and discussion

Seven individuals with normal stereoscopic vision were selected as the participants. The ranges of the crossing points that stereoscopic fusion was maintained when viewing the stereoscopic display were measured to be different for the participants.[21,22] The optical power was measured only in the range that stereoscopic fusion was maintained. Table 1 shows the minimum distance from each participant that the stereoscopic fusions were maintained when reading the 3D chart.

The measured results of the accommodation for seven participants were illustrated in Fig. 6(a). Horizontal axis represents the distances from the participant to the position of the film chart or to the estimated crossing point of 3D chart. Theoretical accommodative stimulus in the unit of Diopter was typically defined as the inverse of the distance from the participant to the actual object. And conventionally (-) sign was used to represent the object located in front of the eye.[16] Hence, the distance of 1 m, 0.5 m, 0.4 m, 0.3 m and 0.2 m from the participants corresponded to the theoretical accommodative stimulus of −1.00, −2.00, −2.50, −3.33 and −5.00 Diopter. In Fig. 6(a), the measured accommodations for the film chart were different from the theoretical accommodative stimulus. The difference between the theoretical accommodative stimulus and the measured accommodation when viewing the real object had been known to be caused by Depth of Field (DOF). [12] The range of DOF that the eye could observe the objects sharply was generally finite. If the film chart was located outside DOF, the film chart would look unfocused. Then, the optical power of the eye would change and the position of DOF would shift toward the position of the film chart. If the film chart was located within the range of DOF, the eye could see film chart sharply even though the focus was not exactly on film chart. Hence, the optical power of eye would not change no more, and the accommodation response of the eye could be different from the given theoretical accommodative stimulus because of the finite size of DOF.

In the observation of the film chart, the accommodative response was induced by the actual distance change of the film chart. However, the accommodative stimulus for the 3D chart was stereoscopic images on the display of the fixed distance of 1 m, though the perceived depth was in front of the display surface. In Fig. 6(a), accommodations for 3D chart were measured to be affected by the distances between the participant and the crossing point. Data for 3D chart at the distance of 30 cm in Fig. 6(a) were the average of the measured accommodation of six participants as one participant could not maintain the stereoscopic fusion for 3D chart at this distance. Similarly, data at the distance of 20 cm were the average of five participants. The difference of the accommodation between the crossing points of 100 cm and 40 cm for 3D chart was smaller than 0.25 Diopter. But the difference was quite noticeable for the crossing point of 20 cm.

In Fig. 6(b), stimulus difference was defined as the difference between the theoretical accommodative stimulus of 100 cm and the position of the film chart. As the distance from the participant to the sample display was 100 cm, this distance was used as the reference distance in the

TABLE 1 — Minimum distance of the stereoscopic fusion of 3D chart of the stereoscopic display.

Minimum distance from participant	Number of participants
Less than 20 cm	Four persons
Less than 30 cm	Two persons
Less than 40 cm	One person

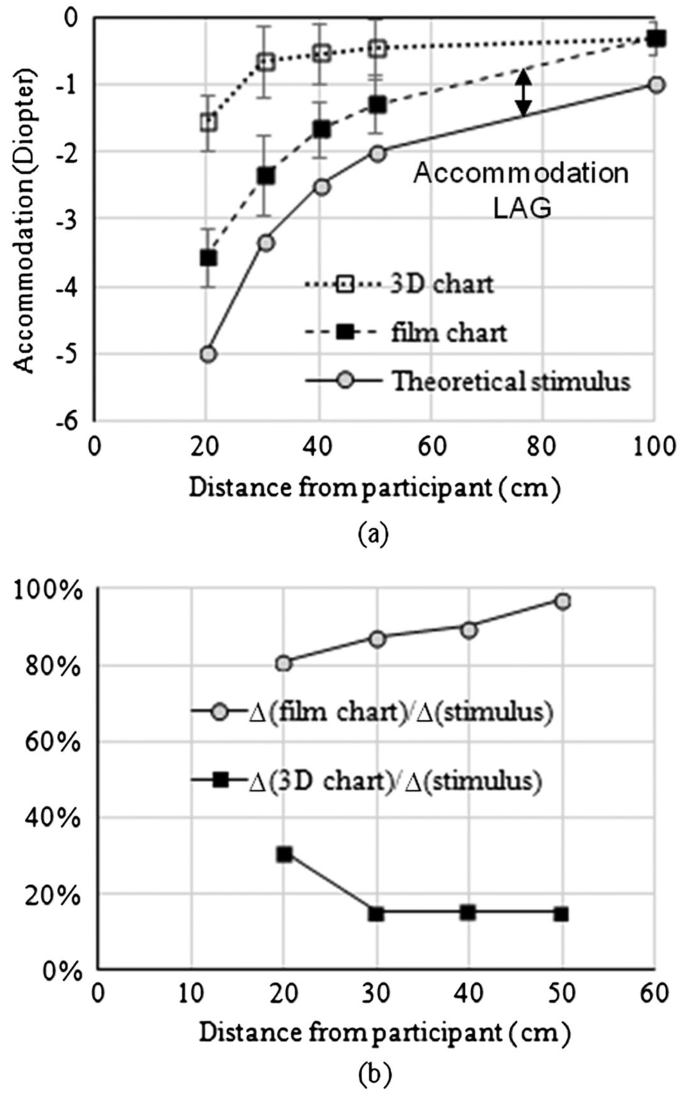


FIGURE 6 — (a) Accommodation measured in 3D chart and the film chart for 14 eyes of seven participants with the normal stereoscopic vision. Vertical axis represents the optical power. Solid line represent theoretical accommodative stimulus for film chart. (b) Ratio between the accommodation difference and the stimulus difference with respect to the distance of 100 cm. Horizontal axis represents the distance from the participant to the position of the film chart or to the estimated crossing point of 3D chart. The number of participants at the distance of 20 cm and 30 cm for 3D chart was less than seven because of the difference of the fusional range of the participants.

investigation of the accommodative change. Accommodation difference when viewing the film chart was defined as the difference of the measured optical power between the position of the film chart and 100 cm. Accommodation difference when viewing the 3D chart was defined as the difference of the measured optical power between the estimated crossing points and 100 cm. The ratio of the accommodation difference and stimulus difference when viewing the film chart and 3D chart were illustrated in Fig. 6(b). The results of Fig. 6(b) shows the relatively little change of the accommodation if the distance to the crossing point in 3D chart was larger than 30 cm. But the change at the distance of 20 cm was not negligible. The difference of the result for the film chart and 3D chart of Fig. 6 can be attributed to the fact the stimulus for driving accommodation for the real object varied with depth whereas the accommodative stimulus for the virtual object was the images on the display of the fixed distance.

Figure 7 illustrated the measured accommodation for two participants whose stereoscopic fusion was maintained up to 20 cm and 30 cm. The accommodation for 3D chart for one participant in Fig. 7(a) showed the trends similar to the averaged accommodation of Fig. 6 that the noticeable change occurred at the distance of 20 cm. The accommodations for 3D chart for another participant in Fig. 7(b) was relatively constant in the range of 40 cm and 100 cm, while the accommodation at 20 cm could not be measured because of the breakup of the stereoscopic fusion. Accommodation was measured three times at each distance. Three measured values of accommodation at each distance for 3D did not show any larger distribution compared with those of the film chart. That implies that the accommodation remains stable or approaches the stable state when viewing the 3D displays.

Compared with Fig. 6, the result for the participant who has the amblyopia of the left eye was illustrated in Fig. 8. The accommodation for the left eye of this participant was not measured. The accommodation of the right eye of this participant was measured to be barely changed up to the crossing point of 20 cm, in contrast to the results of the seven participants with the normal stereoscopic vision for 3D chart. This difference can be attributed to the stereo-blindness of this participant. This participant would perceive the optotype of 3D chart placed at the position of the sample display, regardless of the positions of the crossing point. Hence, accommodation change did not occur for 3D chart.

In Fig. 6, the difference of the measured accommodation between the 50 cm and 1 m was 0.15 Diopter while the difference of the measured accommodation between the 40 cm and 1 m was 0.23 Diopter. The trend of the measured accommodation in Fig. 6 may be explained by the range of DOF (Depth of Field) that the accommodation changes noticeable only when the crossing point was outside DOF. If the range of DOF was estimated to be around 50 cm in front of the display sample at the distance of 1 m, average Depth of Focus would be around 2.0 Diopter. Though Depth of Focus

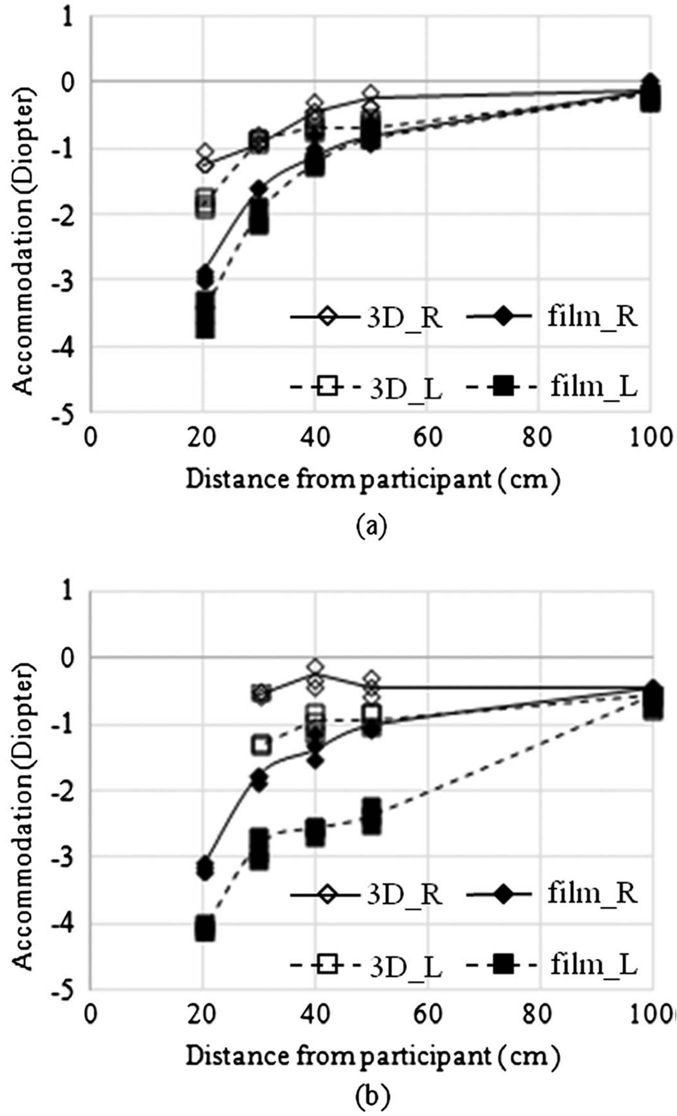


FIGURE 7 — Examples of the measured accommodations for two participants whose stereoscopic visions were maintained to (a) 20 cm and (b) 30 cm. Horizontal and vertical axes represent the distance from the participants and the optical power. R and L represent the right and left eye of the participants.

was known to be affected by many factors, the value from 0.67 Diopter to 2.00 Diopter had been reported.[5] For the viewing distance of 1 m, the accommodation–convergence conflict would occur if the crossing points were quite close to the participant. However, a conflict between accommodative and vergence responses should not occur if the virtual stimuli and the display are within the depth of field in accordance with the theory by Patterson. [5]

In the previous reports about the accommodation in 3D displays, various types of 3D displays were used.[10–15] HMD (Head Mounted Display) and II (Integral Imaging) were based on 3D technologies different from the technology of the sample display of this paper. Hence, only the previous reports using the stereoscopic displays with special eyeglass were compared. In a report by Ohzu (Ref. 10), the stereoscopic display with the shutter glass was placed at the

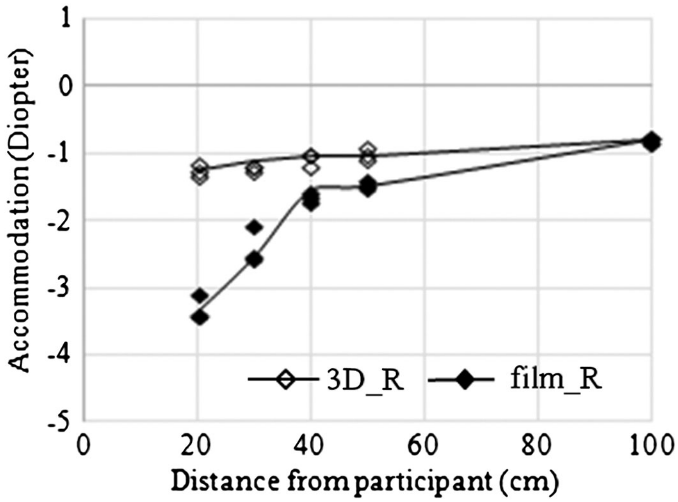


FIGURE 8 — Accommodation measured for a participant with the amblyopia of the left eye. Horizontal axis represents the distances from the participant to the position of the film chart or to the estimated crossing point of 3D chart. Vertical axis represents the optical power. R represents the right eye of the participant. Notations of 3D and film represent the results for 3D chart and the film chart.

distance of 1 m from the participant and the static 3D image was used. The accommodative responses for 3D images were measured to change steadily while these accommodative responses were smaller than those for the real target. However, the luminance of the 3D images used for that experiment was only 8.8 cd/m^2 while the experiment of this paper was performed with the sample display of 91 cd/m^2 at the illuminance of 450 lux. As the lower luminance was known to cause the larger pupil size and the narrower range of the DOF, this may cause the different trend of the accommodative responses compared with the result of this paper. In another reports by Shiomi (Ref.15), the stereoscopic display with the shutter glass was located at the distance of 1 m from the participant. The dynamic stimulation was used and the perceived depth as well as the size of the moving 3D object was changed. The accommodation was reported to change in accord with the moving 3D object. The discrepancy from the previous report may be because of the difference of the dynamic and static stimulus as the motion was known to be one of the strong cues to induce the depth perception.[23] Or it may be attributed to the size change of 3D object in accord with the perceived depth.

Figure 9 illustrates two cases where the accommodation varies in accord with the crossing point (that is, 3D object) or does not vary. In case of Fig. 9(a) corresponding to the previous reports of the changing accommodative responses, the range of DOF will also move accordingly and the center of DOF will be near the crossing point. In case of Fig. 9(b) that the accommodation is almost constant, the center of DOF will remain near the stereoscopic display. As long as the crossing point and stereoscopic display are within the range of DOF, any of these two cases may be possible and the 3D object will not look blurred.

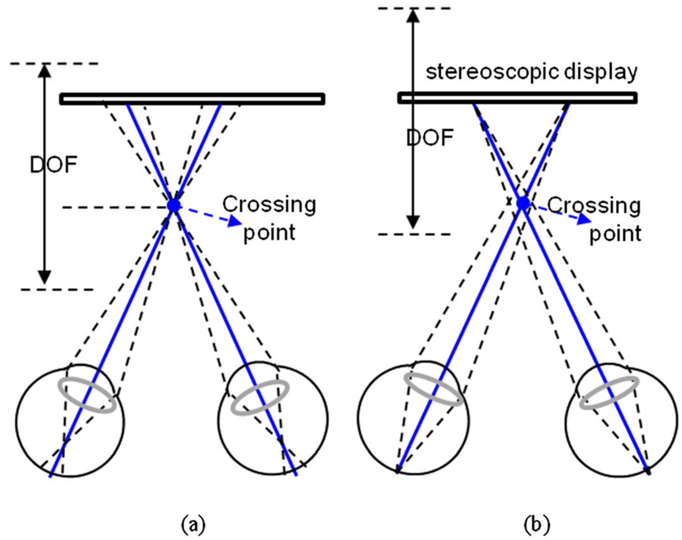


FIGURE 9 — Examples where the crossing point and the stereoscopic display are within DOF. The center of DOF is (a) near the crossing point and (b) near the stereoscopic display.

5 Conclusion

The accommodation was measured to be affected by the position of the crossing points of the stereoscopic image only when the crossing points are quite close to the participant. If the crossing points are quite close to the participant, the crossing point or stereoscopic display will be outside the range of DOF and the accommodation will change.

The accommodation change implies the possible occurrence of fatigue that may be related to the accommodation–convergence conflict while the constant accommodation within the range of DOF implies no conflict between the accommodation and convergence. This measurement scheme may be used to define the range of DOF where the accommodation remains little changed. This range of DOF may be useful to define the depth of 3D object in 3D image which does not cause the accommodation–convergence conflict for the given stereoscopic display.

Acknowledgment

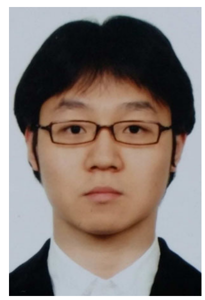
This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2013R1A1A2005812).

References

1 B. Javidi and F. Okano, "Three-dimensional television, video and display technologies," Springer: New York (2002).
2 A. Woods, "3-D displays in the home," *Inform. Displ.* **25**, 8–12 (2009).
3 K. Ukai and P. A. Howarth, "Visual fatigue caused by viewing stereoscopic motion images: background, theories and observations," *Displ.* **29**, 106–116 (2008).

4 M. Lambooij *et al*., "Visual discomfort and visual fatigue of stereoscopic displays: a review," *J.Imaging Sci.Technol.* **53**, 030201-1-030201-14 (2009).
5 R. Patterson, "Review paper: human factors of stereo displays: an update," *J. SID* **17**, 987–996 (2009).
6 T. Shibata *et al*., "The zone of comfort: predicting visual discomfort with stereo displays," *J. Vis.* **11**, 1–29 (2011).
7 G. Collins, "The electronic refractionometer," *Br.J.Physiol.Opt.* **11**, 30–42 (1937).
8 K. Zadnik, D. Mutti and A. J. Adam, "The repeatability of measurements of the ocular components," *Invest.Ophthalmol.Vis.Sci.* **33**, 2325–2333 (1992).
9 W. Charman and J. Tucker, "Dependence of accommodation response on the spatial frequency spectrum of the observed object," *Vis.Res.* **17**, 129–39 (1977).
10 T. Inoue and H. Ohzu, "Accommodative responses to stereoscopic three-dimensional display," *Appl. Optics* **36**, 4509–4515 (1997).
11 K. Ukai and Y. Kato, "The use of video refraction to measure the dynamic properties of the near triad in observers of a 3-D display," *Ophthal. Physiol.Opt.* **22**, 385–388 (2002).
12 S. Hasegawa *et al*., "Stereoscopic vision induced by parallax images on HMD and its influence on visual functions," *Virt. and Mixed Real.-New Trends, Lecture Notes in Comp. Sci.* **6773**, 297–305 (2011).
13 M. Miyao *et al*., "3D vision gaze with simultaneous measurements of accommodation and convergence among young and middle-aged subjects," in *Advances in Human Aspects of Healthcare*, V. G. Duffy (ed.). CRC Press, New York, 2012, 509–514.
14 Y. Kim *et al*., "Accommodative response of integral imaging in near distance," *J. Displ. Technol.* **8**, 70–78 (2012).
15 T. Shiomi *et al*., "Simultaneous measurement of lens accommodation and convergence in natural and artificial 3D vision," *J. SID* **21**, 120–128 (2013).
16 M. Rosenfield and N. Logan, "Optometry: science, techniques and clinical management," Butterworth Heineman Elsevier: London, (2009).
17 H. K. Hong *et al*., "Analysis of angular dependence of 3-D technology using polarized eyeglasses," *J. SID* **18**, 8–12 (2010).
18 W. J. Benjamin, "Borish's clinical refraction," Butterworth Heinemann Elsevier: Philadelphia, (2006).
19 S. H. Kang and H. K. Hong, "In watching 3D stereoscopic display using the binocular disparity, the effect of papillary distance of adults and children on the perception of 3D image," *J.Korean Oph.Opt.Soc.* **16**, 299–305 (2011).
20 J. Häkkinen *et al*.,"Determining limits to avoid double vision in an autostereoscopic display: disparity and image element width," *J. SID* **17**, 433–441 (2009).
21 H. Kang and H. K. Hong, "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," *J. SID* **21**, 317–323 (2013).
22 S. Endrikhovski, "Predicting individual fusional range from optometric data," *Proc. SPIE 5664, Stereoscopic Displ. and Virt. Real. Sys.* **XII**, 36–47 (2005).
23 S. H. Schwartz, "Visual perception," McGraw-Hill: New York, (2004).

Hyungki Hong is an associate Professor at the Department of Visual Optics, Seoul National University of Science and Technology since 2010 and a member of SID. He received his B. S. in Physics in Seoul National University and Ph. D in Physics from Korea Institute of Science and Technology (KAIST). After receiving Ph.D 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. He is a member of SID.



Seok Hyon Kang received his B. S. degree in 2011 and received his M. S. degree in 2014 in the Department of Optometry of Seoul National University of Science and Technology.