Super multi-view 3D displays reduce conflict between accommodative and vergence responses

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Abstract

A conflict between accommodation and vergence is one possible cause of visual fatigue and discomfort while viewing conventional three-dimensional (3D) displays. Previous studies have proposed the super multi-view (SMV) display technique to solve the vergence-accommodation conflict, in which two or more parallax images enter the pupil of the eye with highly directional rays. We simultaneously measured accommodative, vergence and pupillary responses to SMV 3D displays to examine whether they can reduce the conflict. For comparison, responses to two-view stereo images and real objects were also measured. The results show that the range of the accommodative response was increased by the SMV images compared with the two-view images. The slope of the accommodation-vergence response function for the SMV images was similar to that for the real objects rather than the two-view images. We also found that enhancement of the accommodative range by the SMV images is noticeable with binocular viewing, indicating that vergence-induced accommodation plays an important role in viewing SMV displays. These results suggest that SMV displays induced a more natural accommodative response than did conventional, two-view stereo displays. As a result, SMV displays reduced the vergence-accommodation conflict.

Keywords: Super multi-view, 3D display, Accommodation, Vergence, Vergence-accommodation conflict,

1 Introduction

The vergence stimulus of real objects usually coincides with its accommodative stimulus under natural viewing conditions, as shown in Figure 1 (a). Conventional three-dimensional (3D) displays suffer from a conflict between vergence and accommodative stimuli. Although an accommodative stimulus always remains fixed on the screen where the image is displayed, a vergence stimulus might change depending on the degree and the sign of the screen disparity, as shown in Figure 1 (b). This vergence-accommodation conflict is one possible cause of visual fatigue and discomfort while viewing 3D displays.[1-4]

Insert Figure 1 about here.

The super multi-view (SMV) display technique has been proposed to ameliorate this conflict.[5] This technique increases the number of parallax images and decreases the pitch of the viewpoints—so that they become narrower than the pupil diameter—with highly directed rays, so that more than two parallax images can simultaneously enter the pupil of the viewer's eye. Two factors contribute to solve the vergence-accommodation conflict of SMV displays. One is that the viewer's eye focuses on the distance to the 3D image, using two or more incoming parallax images to the pupil.[5] If the eye focuses on the display screen, a point on the 3D image is projected onto the retina as two or more separated points, as shown in Figure 2 (a). If the eye focuses on the 3D image's distance, the point on it is projected onto the same location on the retina as a single point, as shown in Figure 2 (b). Therefore, both vergence and accommodation are focused on the distance to the 3D image to see a clear single image of the object.

Insert Figure 2 about here.

The second factor is that the SMV technique increases the depth of field (DOF) of the eye.[6] As shown in

Figure 3 (a), the DOF is usually determined by the pupil diameter. As pupil size decreases, the DOF increases. If the ray extent at the pupil is smaller than the actual pupil size, the ray extent at the pupil becomes an effective pupil diameter and yields an increased DOF range, as shown in Figure 3 (b). Within the DOF range, the accommodative response is always driven by the vergence response (vergence accommodation), not by the blur of the retinal image, because the image blur cannot be detected in the DOF. As a result, the vergence-accommodation conflict is solved within the enhanced DOF.

Insert Figure 3 about here.

Several studies have reported that the accommodative response to SMV displays resembles the response to real objects rather than to conventional, two-view stereo displays.[6-8] These data suggest that SMV displays enhance the range in which the accommodative response changes, so that the vergence-accommodation conflict can be solved. However, these studies did not demonstrate whether the conflict could be solved, because the vergence response was not evaluated. In this study, we simultaneously measured the vergence and accommodative responses in four participants to directly examine whether SMV displays reduce the vergence-accommodation conflict. We also measured responses to conventional, two-view stereo displays and real objects for comparison. For quantitative evaluation, we used accommodative range and slope of accommodation-vergence function as indices of the accommodative response change and vergence-accommodation conflict, respectively. The accommodative range indicates the range of accommodative response caused by changing target distance. The slope of accommodation-vergence function represents the degree of covariation of the accommodative and vergence responses.

2 Methods

2.1 Apparatus

For our experiment, we used a reduced-view SMV display that consisted of an LCD flat-panel (2.57 inch) display and a lenticular lens as shown in Figure 4.[9] Conventional flat-panel type SMV displays require ultra-high-resolution flat-panel displays, because the resolution required for them is the resolution of the 3D image multiplied by the number of views. The reduced-view SMV display reduces the resolution required for flat-panel displays by restricting the viewpoints around each eye, generating eight viewpoints for each eye with 2.6-mm intervals. Figure 5 shows the measured light intensity distribution of the 16 viewpoints. The intensity distribution was measured by using a cooled CCD camera (Apogee Alta U2000) placed at the viewpoints. The 3D resolution was 256 × 192. The distance between the display screen and the viewpoints was 350 mm. This display can change viewpoint pitch by displaying identical parallax images at several succeeding viewpoints. In this study, we also used this display as a conventional, two-view stereo scheme by displaying identical parallax images at eight succeeding viewpoints around each eye. Nakamura et al. (2013) used the same display to demonstrate the increased DOF of the eyes with reduced-view SMV displays.[8] To display real objects, we used a 2D image displayed on a smartphone screen (Toshiba, TSI-04, 4.0-inch) and changed its distance from the participant's eyes.

Insert Figure 4 and 5 about here.

Figure 6~~5~~ shows a binocular open-view Shack–Hartmann wavefront sensor that measures vergence and accommodative responses while viewing displays.[10] This instrument consists of two optical systems used for measuring the right and left eyes, a motor controlled stage, and three personal computers. Each optical system contains Shack–Hartmann wavefront sensors for measuring accommodation, and analog CCDs of the anterior segment camera for measuring vergence and pupil diameter. Prior to the measurement, we calibrated this instrument for each eye and measured the inter-pupillary distance of the participant. These are needed for calculating vergence in units of meter angle (MA). Thus, we simultaneously recorded the vergence, accommodative, and pupillary responses for both eyes. This technique's accuracy equaled or surpassed other techniques.[10] The vergence and pupillary responses were recorded at 30 Hz, and the accommodative responses were recorded at a 24-Hz sampling rate. A dichroic mirror was located in front of each eye to separate the near infrared light for the measurements and the visible light from a display in front of the participant, so that the display could be seen directly. A head and chin rest stabilized the participant's head during the measurements. We used corrective lenses with near infrared antireflection coating for participants who needed refractive correction.

Insert Figure 6~~5~~ about here.

2.2 Stimulus

The visual target was a static, green "Maltese cross," which subtended 2.8° × 2.8° (Figure 4). Its 3D images were displayed at −92, −57, −26, 0, +23, +43, and +61 mm from the display screen, where minus and plus signs represent behind and in front of the screen, respectively. These locations corresponded to distances of 442 mm (2.26 MA), 407 mm (2.46 MA), 376 mm (2.66 MA), 350 mm (2.86 MA), 327 mm (3.06 MA), 307 mm (3.26 MA), and 289 mm (3.46 MA) from the eyes. The luminances of the target and background were 70 cd/m^2 and 11 cd/m^2, respectively.

2.3 Procedure

There were three display conditions (SMV, two-view, and real object) and two viewing conditions (binocular and monocular). The SMV and two-view stereo images were displayed using the reduced-view SMV display. The real objects were 2D images displayed on a smartphone screen, and image distance was varied by changing location of the screen in the depth direction. In the monocular viewing condition, a black opaque piece of paper occluded the non-dominant eye, so that the participant only saw the target from their dominant eye. In each experimental trial, we measured the vergence, accommodative, and pupillary responses while the participant fixated on the center of the static target for 1 sec. Participants were instructed to focus on a clear single image of the target. Each of the four participants performed three trials for each condition. The order of stimulus presentation was randomized to prevent order effects. All of the measurements were done in a dark room.

Four participants, three male and one female (ranging from 35 to 42 years old), participated in the experiment. All had corrected-to-normal visual acuity and normal stereoscopic vision.

3 Results and discussion

We first calculated the time average of each recorded vergence, accommodative, and pupillary response for the participant's dominant eye, and then averaged them again across the three trials to analyze the data. Because of a very similar trend for all participants, the vergence, accommodative, and pupillary responses shown in this paper are averaged across participants (results for each participants are shown in Appendix).

3.1 Binocular viewing

Figure 7~~6~~ shows the results of the binocular viewing of (a) the SMV images, (b) the two-view stereo images, and (c) the real objects. The abscissa denotes the distance in meters to the target from the eyes represented in the length's reciprocal. The ordinate denotes the vergence and the accommodative responses (left) and the pupil diameter (right). The vergence and accommodation are represented in MA and diopters (D), respectively. As in the case with the abscissa, they are also defined as the reciprocal of the length in meters. Open circles, filled squares and open triangles represent the measured responses of the accommodation, vergence and pupils, respectively. Error bars represent the standard error of the mean. The gray diagonal line indicates the response if it completely coincides with the target distance, that is, the vergence stimulus for the two-view images, and the vergence and accommodative stimuli for the real objects. The gray horizontal dashed line indicates the response, i.e., if it always stays on the fixed display screen for the SMV and two-view images.

Insert Figure ~~6~~ 7 about here.

For all display conditions, the pupil diameter decreased with decreasing target distance as shown in Figure ~~6~~7. This pupillary constriction that accompanied the vergence and accommodative responses resembles a pupillary near response.[11] The vergence responses varied along with the target distance in all the display conditions. The accommodative responses to the real objects varied with the vergence responses; however, the eye consistently focused on a distance farther than the target (accommodative lag) as shown in Figure ~~6~~ 7 (c). Although the slope is somewhat shallower, the accommodative responses to the SMV images also varied with the vergence responses, like for real objects, in the middle of the measured range of target distance.

3.1.1 Accommodative range

We defined the "accommodative range" as the difference between the maximum and minimum values of the accommodative response. The accommodative range of each condition was calculated for each participant. Figure ~~7~~ 8 shows the accommodative ranges averaged across the participants. A one-way repeated-measures analysis of variance (ANOVA) on the accommodative range revealed a significant main effect of display condition, $F(2, 6) = 5.65$, $p < 0.05$. Multiple comparisons using Shaffer's method revealed that the mean value of the accommodative range increased more for the SMV images than for the two-view stereo images ($p < 0.05$). However, the difference between the mean accommodative ranges of the real objects and the SMV images was not statistically significant, but the difference between the mean accommodative ranges of the two-view stereo images and the real objects was statistically significant (p <

0.01).

Insert Figure ~~7~~ 8 about here.

We consider two possible causes of increased accommodative range for the SMV images. One is the "real" enhancement of accommodative range induced by SMV. The other is the accommodative enhancement caused by increasing vergence response. Because accommodation and vergence are cross-linked with each other, accommodation responses can be driven by vergence. To exclude the latter possibility, we examined the "vergence range" corresponding to the accommodative range. Figure ~~8~~ 9 shows the vergence range averaged across participants. We performed a one way repeated measures ANOVA on the vergence range and found no significant main effect of display condition, $F(2, 6) = 0.744$, $p = 0.51$. This result suggests that there was no difference in vergence range among the three display conditions.~~,~~ This suggests that difference in accommodative range among the three display conditions is not due to difference of vergence, and we can conclude that the enhancement of accommodative range was not because of increased vergence responses.

Insert Figure ~~8~~ 9 about here.

This study showed the enhancement of the accommodative range using SMV displays. Nakamura et al. (2013) also reported an increase in DOF using the same reduced-view SMV display.[8] Their increased DOF (0.86 D) is comparable to the accommodative range observed in our study (0.95 D). Their study showed that a narrower interval of viewpoints yielded an increased DOF range. The DOF obtained for a 7.9-mm viewpoint interval, which exceeded the pupil diameter, was 0.57 D. This value is comparable to the accommodative range of the two-view images in our study (0.49 D).

Even though the vergence responses of our participants almost coincided with the target distance, the participants constantly focused their eyes on a distance farther away than the visual target. This accommodative lag was observed even for the real objects. Such an accommodation lag is not considered a conflict between the vergence and accommodative responses caused by viewing the 3D images, because a similar phenomenon has been reported for real objects in a number of previous studies.[12-17] No participant claimed to see blurry images of the target, probably because the target location was within the range of the DOF.

3.1.2 Slope of accommodation-vergence function

To further examine the conflict between accommodative and vergence responses, we replotted the accommodative response in the binocular viewing condition as a function of the vergence response. Figure 109 shows the data averaged across the participants. The horizontal and vertical axes denote the vergence and accommodative responses, respectively. The data would lie along the diagonal line if the accommodative responses completely coincided with the vergence responses. However, most of the data points lie below the diagonal line because of the accommodative lag. The accommodative response monotonically increased with increasing vergence response.

Insert Figure 109 about here.

Linear regression analysis was performed for each condition and each participant to assess the covariation of the accommodative and vergence responses. If they vary at the same rate, the slope of the regression line would be 1. Figure 1110 shows the slope of the regression line for each condition averaged across participants. The regression line was calculated using all the data within accommodative range of the SMV images for each participant. We performed a one-way repeated-measures ANOVA on the slope of the regression line, and found a significant main effect of display condition, $F(2, 6) = 9.16$, $p < 0.05$. Multiple comparisons using Shaffer's method revealed that the mean slope of the SMV images was higher than that of the two-view images ($p < 0.05$). However, the difference between the mean slopes of the SMV images and those of the real objects was not statistically significant. The mean slope of the two-view images was lower than that of the real objects ($p < 0.01$).

Insert Figure ~~10~~ 11 about here.

The slope of the accommodation-vergence function is one of the indices for evaluating the mismatch of the rates of change between the accommodative and vergence responses. The mean slope of the SMV images (0.53) was larger than that of the two-view images (0.22). This result indicates that the SMV displays reduced the mismatch of the rates of change between the accommodative and vergence responses relative to the two-view displays. The mean slope of the real objects was 0.71. This value is larger than the slope of the SMV images, although the two are not significantly different. One possible reason for the larger slope of the real objects is that the SMV display only had horizontal parallax. Horizontal blur on the retinal image induces accommodative responses to the distance of the simulated 3D objects, as previously noted, but the vertical blur on the retinal image induces accommodative responses to the screen distance. Perhaps the eyes were focusing on the distance between the 3D images and the display screen to simultaneously satisfy these conflicting requirements.

3.1.3 Pupil diameter

Figure 12~~11~~ shows the changes in the pupil diameter within the accommodative range averaged across participants. A positive value indicates a decrease in the pupil diameter when the target approached the participant's eyes. Although no statistical significance was found because of the large variance (i.e., large individual differences), the tendencies resemble those of the accommodative range.

Insert Figure 12~~11~~ about here.

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(0.86 D) is comparable to the accommodative range observed in our study (0.95 D). Their study showed that a narrower interval of viewpoints yielded an increased DOF range. The DOF obtained for a 7.9-mm viewpoint interval, which exceeded the pupil diameter, was 0.57 D. This value is comparable to the accommodative range of the two-view images in our study (0.49 D).

Even though the vergence responses of our participants almost coincided with the target distance, the participants constantly focused their eyes on a distance farther away than the visual target. This accommodative lag was observed even for the real objects. Such an accommodation lag is not considered a conflict between the vergence and accommodative responses caused by viewing the 3D images, because a similar phenomenon has been reported for real objects in a number of previous studies.[12-17] No participant claimed to see blurry images of the target, probably because the target location was within the range of the DOF.

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3.2 Monocular viewing

Figure 1312 shows accommodative, vergence and pupil responses to (a) SMV images, (b) two-view images and (c) real objects in the monocular viewing condition (results for each participants are shown in Appendix). Although the stimulus itself was identical to that used for binocular viewing, target distance is no longer a vergence stimulus because the non-dominant eye was occluded.

Insert Figure 1312 about here.

The pupil diameter was approximately 0.5–1.0 mm larger than that in binocular viewing, because no light entered the occluded eye. Noticeable individual differences were observed in the vergence responses because the visual target was not seen from the non-dominant eye, and the vergence angle was not specified by the visual information. Nevertheless, the vergence responses to the real objects systematically varied with target distance. We attributed this result to the accommodation-driven vergence (accommodative vergence), because the accommodative responses to the real objects varied with target distance. As is the case with binocular viewing, the accommodative range for each display condition was calculated. Figure 13 14 shows the accommodative range for monocular viewing averaged across participants. We performed a one-way repeated-measures ANOVA on the accommodative range and found a significant main effect of display condition, $F(2, 6) = 10.07$, $p < 0.05$. Multiple comparisons using Shaffer's method revealed that the ranges of the SMV images ($p < 0.05$) and the two-view stereo images ($p < 0.01$) were smaller than those of the real objects. However, the difference between the accommodative ranges of the SMV and two-view images was not statistically significant, indicating that the increase in the accommodative range using SMV displays was limited in monocular viewing.

Insert Figure 13 14 about here.

Even in the monocular viewing condition, the SMV images induced an accommodative response.

However, it was smaller than that in the binocular viewing condition because the stimulus did not drive vergence responses and the accommodative responses were driven only by retinal image blur, not by vergence. These results suggest that accommodative responses to the SMV images observed in the binocular condition consists of a blur-driven component and a vergence accommodation component, which works within the enhanced DOF range.

Figure ~~14~~ 15 shows the changes in the pupil diameter within the accommodative range averaged across participants in the monocular viewing condition. Although no statistical significance was found, mean change in pupil diameter for real objects was 0.2 mm larger than those for SMV and two-view.

Insert Figure ~~14~~ 15 about here.

Accommodative and pupillary responses showed a similar trend (Figs. ~~7~~ 8 and ~~11~~12, and Figs. ~~13~~ 14 and ~~14~~15). This indicates that the SMV images, especially in binocular viewing, also induce a natural near pupil response as well as an accommodative response.

4 Conclusion

We measured accommodative, vergence and pupillary responses while viewing static visual images displayed by a SMV display, a two-view stereo display, and a moveable 2D display. The range of the accommodative response (accommodative range) was enhanced by the SMV display, compared with the two-view display, especially in binocular viewing. The slope of the accommodation-vergence function for the SMV images was similar to that for real objects, indicating a decreased vergence-accommodation conflict in the response. This means that the SMV display can reduce vergence-accommodation conflict and induce more natural response of visual function. The SMV technique is promising to ameliorate visual fatigue and discomfort caused by viewing 3D displays.

Appendix

Figure A1 and A2 show all results separately for participants on Figure 7 and 13, respectively. Each row corresponds to each participant. Each column corresponds to display condition of (a) the SMV images, (b) the two-view stereo images, and (c) the real objects. Each plot is based on average value of three trials.

Insert Figures A1 and A2 about here.

References

1 S. Yano, S. Ide, T. Mitsuhashi, and H. Thwaites, “A study of visual fatigue and visual comfort for 3D HDTV/HDTV images,” *Displays* **23**, No. 4, 191-201 (2002).

2 D. M. Hoffman, A. R. Girshick, K. Akeley, and M. S. Banks, “Vergence-accommodation conflicts hinder visual performance and cause visual fatigue,” *J. Vision* **8**, No. 3(33), 1-30 (2008).

3 K. Ukai and P. A. Howarth, “Visual fatigue caused by viewing stereoscopic motion images: Background, theories, and observations,” *Displays* **29**, No. 2, 106-116 (2008).

4 T. Bando, A. Iijima, and S. Yano, “Visual fatigue caused by stereoscopic images and the search for the requirement to present them: A review,” *Displays* **33**, No. 2, 76-83 (2012).

5 Y. Kajiki, H. Yoshikawa, and T. Honda, “Hologram-like video images by 45-view stereoscopic display,” *Proc. SPIE* **3012**, Stereoscopic Displays and Virtual Reality Systems IV, 154-166 (1997).

6 Y. Takaki and K. Kikuta, “3D images with enhanced DOF produced by 128-directional display,” *Proc. IDW* **13**, 1909-1912 (2006).

7 Y. Takaki, “High-density directional display for generating natural three-dimensional images,” *Proc. IEEE* **94**, No. 3, 654-663 (2006).

8 J. Nakamura, K. Tanaka, and Y. Takaki, “Increase in depth of field of eyes using reduced-view super multi-view displays,” *Appl. Phys. Express* **6**, No. 2, 22501-1-3 (2013).

9 Y. Takaki, K. Tanaka, and J. Nakamura, “Super multi-view display with a lower resolution flat-panel display,” *Opt. Express* **19**, No. 5, 4129-4139 (2011).

10 M. Kobayashi, N. Nakazawa, T. Yamaguchi, T. Otaki, Y. Hirohara, and T. Mihashi, “Binocular open-view Shack-Hartmann wavefront sensor with consecutive measurements of near triad and spherical aberration,” *Appl. Opt.* **47**, No. 25, 4619-4626 (2008).

11 G. A. Myers and L. Stark, "Topology of the near response triad," *Ophthalmic Physiol. Opt.* **10**, No. 2, 175-181 (1990).

12 H. W. Leibowitz and D. A. Owens, "Night myopia and the intermediate dark focus of accommodation," *J. Opt. Soc. Am.* **65**, No. 10, 1121-1128 (1975).

13 C. Nakatsuka, S. Hasebe, F. Nonaka, and H. Ohtsuki, "Accommodative lag under habitual seeing conditions: Comparison between adult myopes and emmetropes," *Jpn. J. Opthalmol.* **47**, No. 3, 291-298 (2003).

14 J. C. He, J. Gwiazda, F. Thorn, R. Held, and F. A. Vera-Diaz, "The association of wavefront aberration and accommodative lag in myopes," *Vision Res.* **45**, No. 3, 285-290 (2005).

15 S. Plainis, H. S. Ginis, and A. Pallikaris, "The effect of ocular aberrations on steady-state errors of accommodative response," *J. Vision* **5**, No. 5, 466-477 (2005).

16 Y. Okada, K. Ukai, J. S. Wolffsohn, B. Gilmartin, A. Iijima, and T. Bando, "Target spatial frequency determines the response to conflicting defocus- and convergence-driven accommodative stimuli," *Vision Res.* **46**, No. 4, 475-484 (2006).

17 M. Torii, Y. Okada, K. Ukai, J. S. Wolffsohn, and B. Gilmartin, "Dynamic measurement of accommodative response while viewing stereoscopic images," *J. Mod. Optics* **55**, No. 4-5, 557-567 (2008).

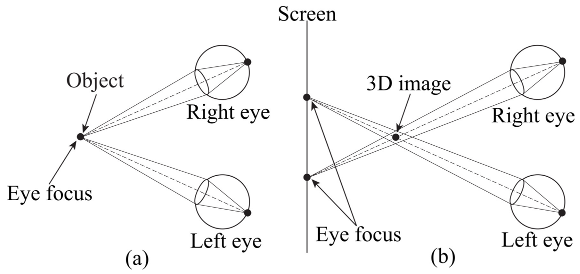


FIGURE 1 Vergence and accommodation to (a) a real object, and (b) a 3D image presented by a traditional two-view stereo display.

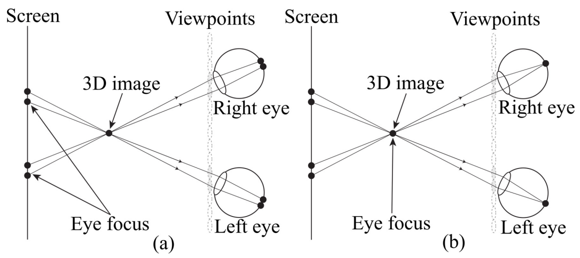


FIGURE 2 Vergence and accommodation to a super multi-view display: (a) eyes focus at screen distance, and (b) eyes focus at 3D image.

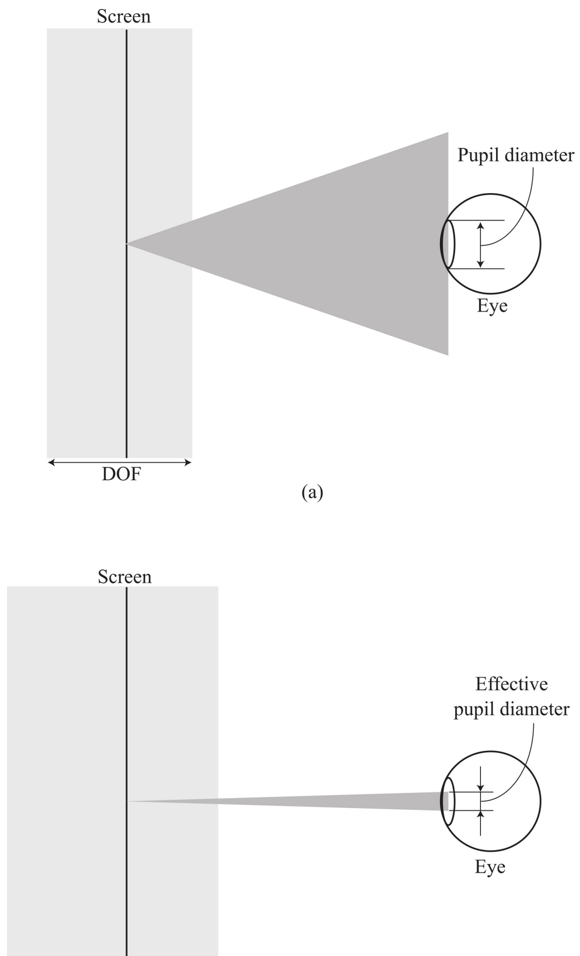


FIGURE 3 Depth of field of eyes: (a) when viewing a normal multi-view display (viewpoint pitch > pupil diameter); and (b) when viewing a super multi-view display (viewpoint pitch < pupil diameter).

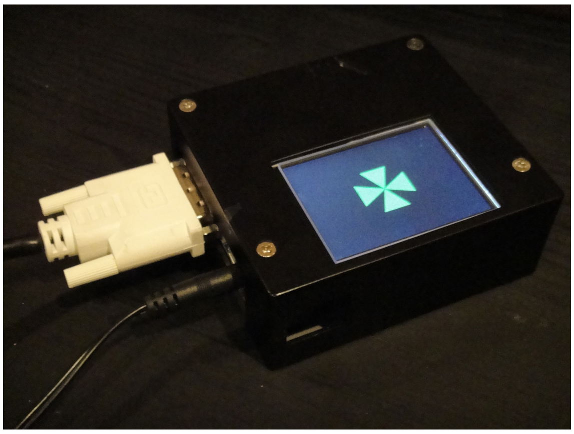


FIGURE 4 Reduced-view super multi-view display used in our experiment.

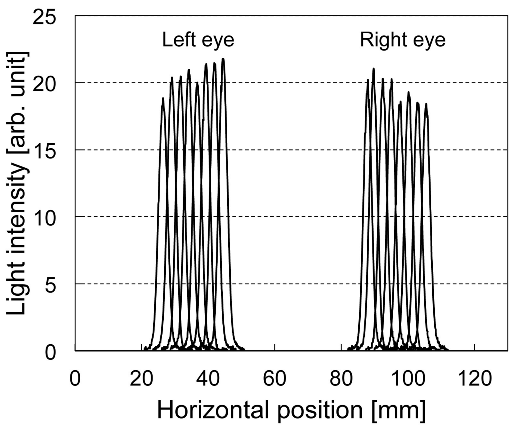


FIGURE 5 Light intensity distribution of viewpoints generated by the reduced-view SMV display used in our experiment.

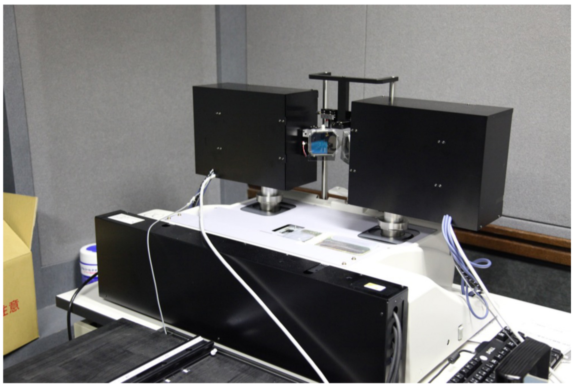
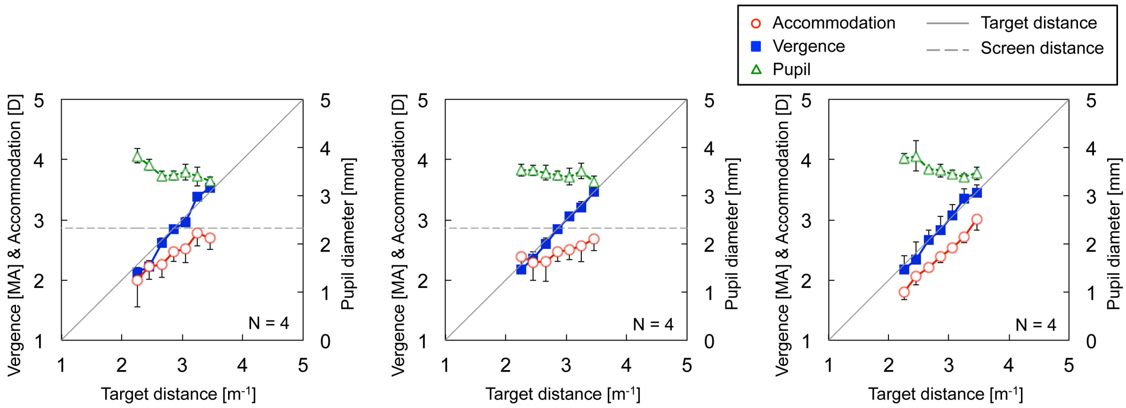


FIGURE 6 Binocular open-view Shack–Hartmann wavefront sensor for measuring vergence, accommodation and pupillary response.



(a) Super multi-view (b) Two-view (c) Real object

FIGURE 7 Vergence, accommodation and pupil responses in the binocular viewing condition: (a) super multi-view (SMV); (b) two-view; (c) real object.

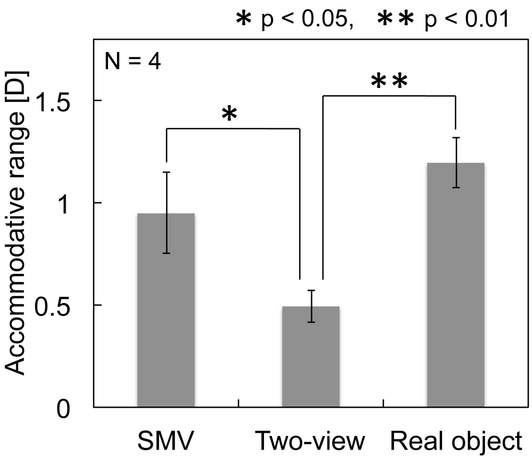


FIGURE 8 Accommodative range for binocular viewing averaged across participants.

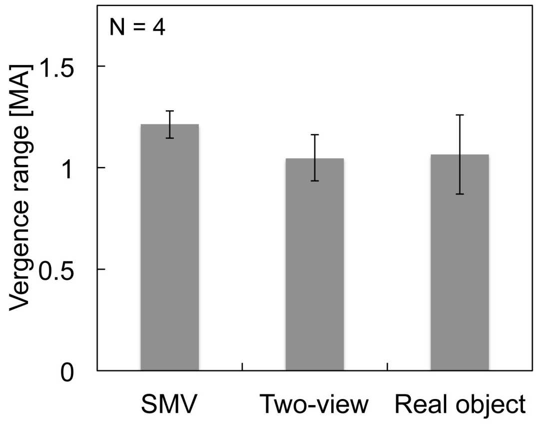


FIGURE 9 Vergence range for binocular viewing averaged across participants.

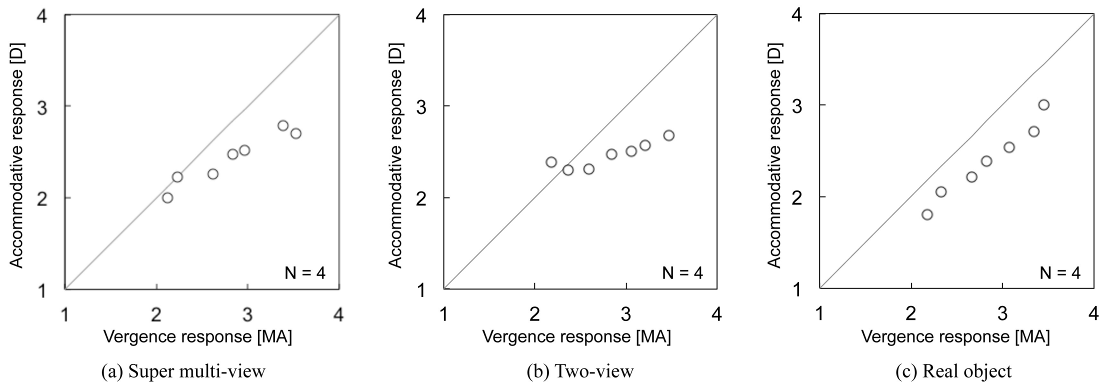


FIGURE 10 Accommodation-vergence functions averaged across participants.

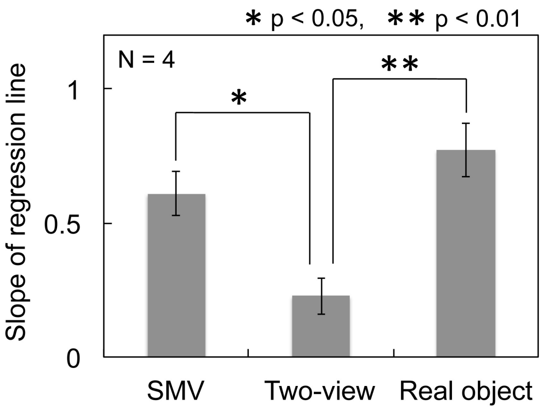


FIGURE 11 Slope of linear regression line for accommodation-vergence function averaged across participants.

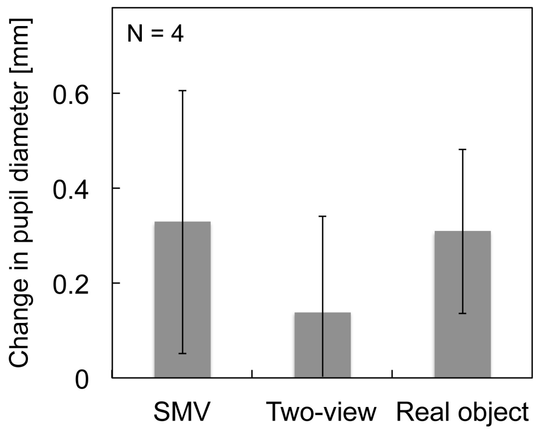


FIGURE 12 Change in pupil diameter for binocular viewing averaged across participants.

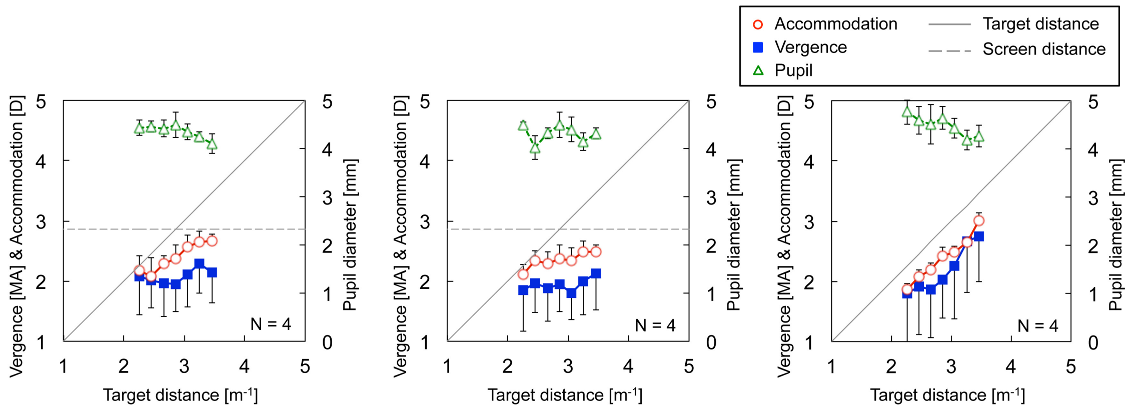


FIGURE 13 Vergence, accommodation and pupil responses in the monocular viewing condition: (a) super multi-view (SMV); (b) two-view; (c) real object.

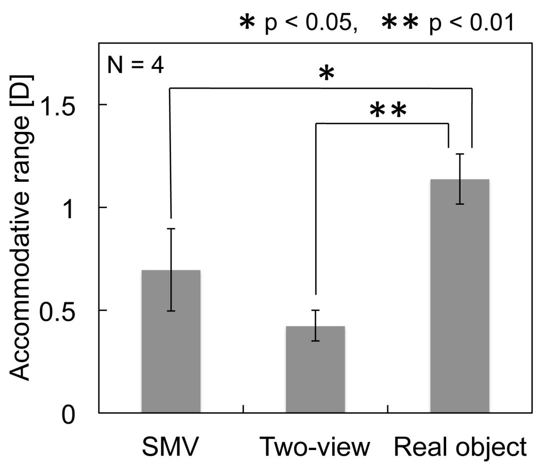


FIGURE 14 Accommodative range for monocular viewing averaged across participants.

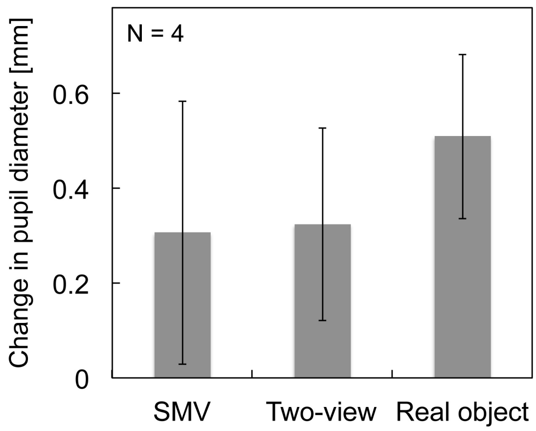


FIGURE 15 Change in pupil diameter for monocular viewing averaged across participants.

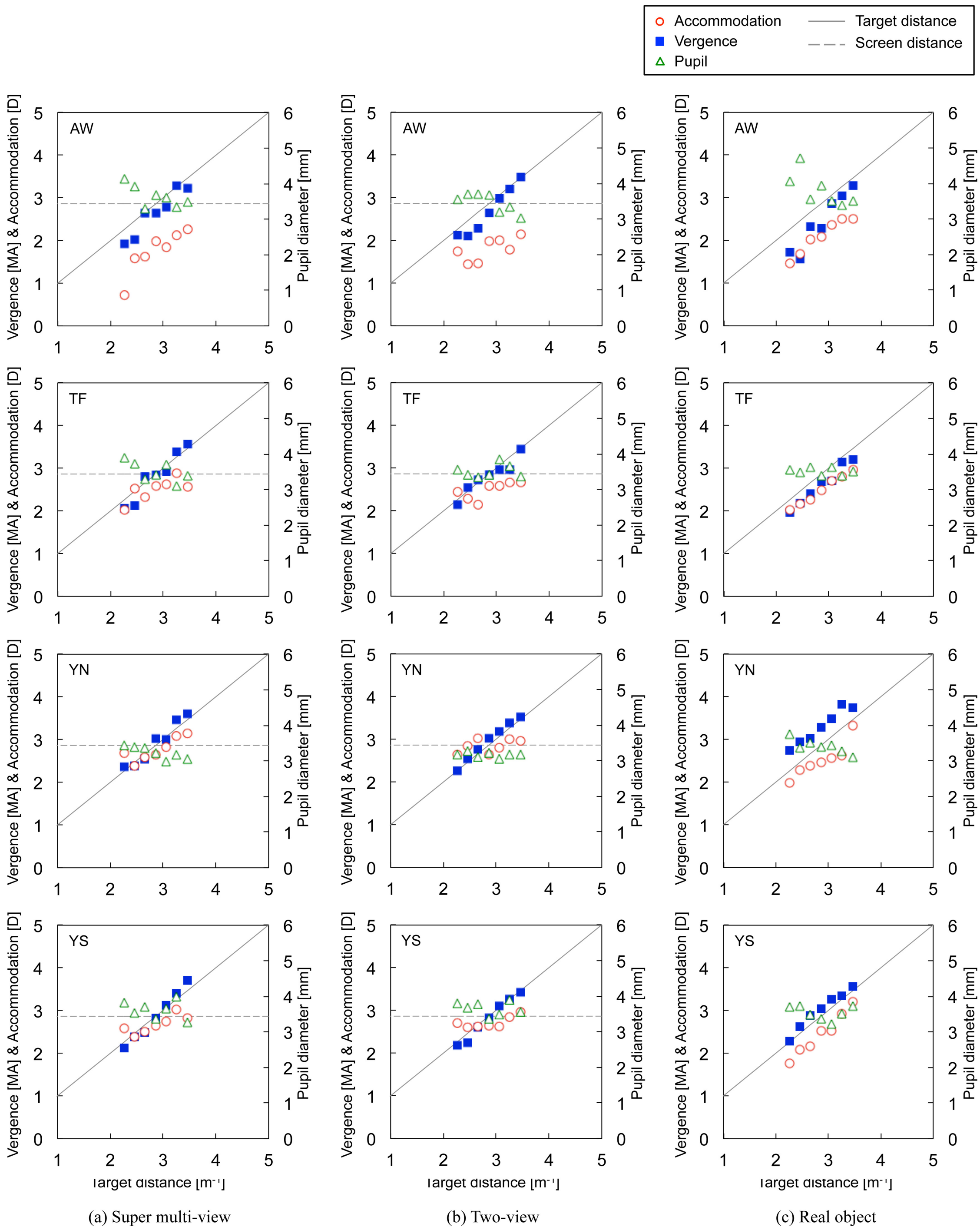


FIGURE A1 All results shown separately for participants on FIGURE 7 (binocular viewing condition): (a) super multi-view (SMV); (b) two-view; (c) real object.

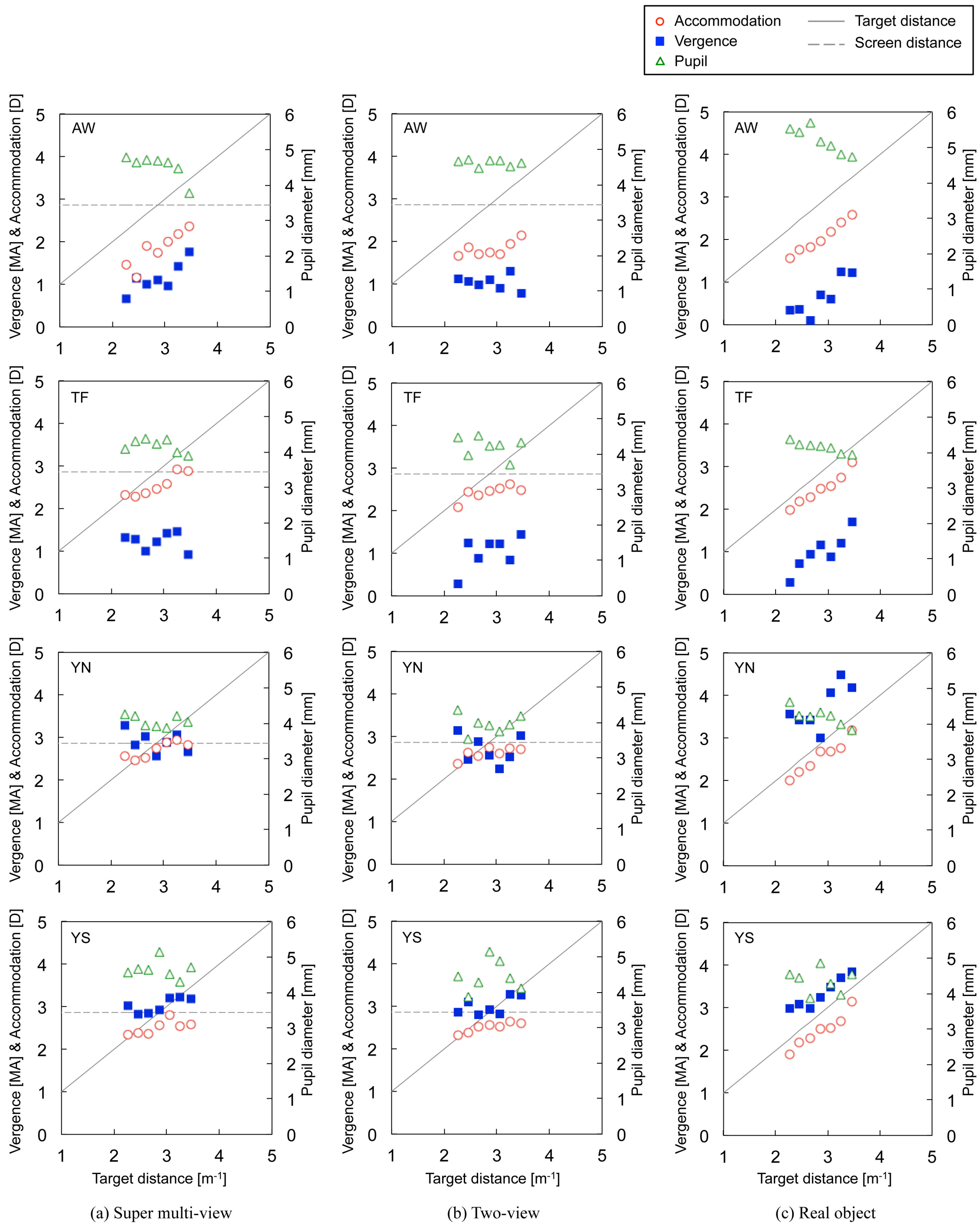


FIGURE A2 All results shown separately for participants on FIGURE 13 (monocular viewing condition): (a) super multi-view (SMV); (b) two-view; (c) real object.