Comparison of 2D and 3D Vision Gaze with Simultaneous Measurements of Accommodation and Convergence

Hiroki Hori[1], Tomoki Shiomi[1], Satoshi Hasegawa[2], Hiroki Takada[3], Masako Omori[4], Yasuyuki Matsuura[1], Hiromu Ishio[1] and Masaru Miyao[1]*

[1]*Department of Information Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan*
[2]*Department of Information and Media Studies, Nagoya Bunri University, 365 Maeda, Inazawa-cho, Inazawa, Aichi 492-8520, Japan*
[3]*Graduate School of Engineering Human and Artificial Intelligent Systems, University of Fukui, 3-9-1 Bunkyo, Fukui 910-8507, Japan*
[4]*Facility of Home Ergonomics, Kobe Women's University, 2-1 Aoyama, Higashisuma, Suma-ku, Kobe 654-8585, Japan*
E-mail address: miyao@nagoya-u.jp

Accommodation and convergence were measured simultaneously while subjects viewed 2D and 3D images. The aim was to compare fixation distances between accommodation and convergence in young subjects while they viewed 2D and 3D images. Measurements were made three times, 40 seconds each, using 2D and 3D images. The result suggests that ocular functions during viewing of 3D images are very similar to those during natural viewing. Previously established and widely used theories, such that within a VR system eyes must maintain accommodation on the fixed LCD screen, may need to be corrected.
Key words: Accommodation, Convergence, Simultaneous Measurement, Visual Fatigue

1. Introduction

In 2009, the 3D movie "Avatar" was a record mainstream hit. Since then, many 3D movies have been seen in cinemas all over the world. We may now be entering a time called the "Era of 3D." Many home appliance makers have started to sell 3D TVs, and the general public has also started to become very comfortable with stereoscopic vision. One reason for this is that we have perceived images by not in 3D but in 2D in cinemas or on TVs until now. 3D is addition of one dimension to 2D. In other words, in stereoscopic vision, the direction of depth is given in addition to the vertical and horizontal directions. People can therefore perceive stimulation with more presence in stereoscopic vision than in plane vision when they capture an image as a "form" on the retina.

However, there are concerns about the effects on the human body from continuously watching 3D images. Examples of these concerns include weakening eyesight, visual fatigue, headache, and nausea. There are great differences between individuals in the appearance of these symptoms and their mechanisms are still not fully understood.

Stereoscopic vision is generally explained to the public as follows: "During natural vision, lens accommodation (Fig. 1) is consistent with convergence (Fig. 2). During stereoscopic vision, while accommodation is fixed on the display that shows the 3D image, convergence with left and right eyes crosses at the location of the stereoimage. Hence, accommodation and convergence are mismatched. This is the main reason for the visual fatigue caused by stereoscopic vision (Wann *et al.*, 1995; Simon *et al.*, 2005; David *et al.*, 2008; Hong and Sheng, 2010)." According to the findings

presented in our previous reports, however, such an explanation is mistaken (Miyao *et al.*, 1996; Hasegawa *et al.*, 2009).

It is also commonly said that if accommodation coincides with convergence and focuses on the fusional points of stereoimages, focus is not on the display and blurred images are seen. This can happen occasionally and is a cause of visual fatigue. We pointed out, according to our findings presented in a previous report, however, such a theory is also mistaken (Miyao *et al.*, 2009). Nevertheless, it is still often said that the mismatch between accommodation and convergence is the main reason for visual fatigue. This may be because the experimental evidence obtained in our previous studies, where we did not measure accommodation and convergence simultaneously, was not strong enough to convince people.

In this paper, we report experimental results obtained using a newly developed device that can simultaneously measure accommodation and convergence, in order to compare the fixation distances during viewing of 2D and 3D images.

2. Method

The subjects in this study were 6 healthy young men and women in their twenties (2 with uncorrected vision, 4 who used soft contact lenses). The aim was to compare fixation distances between accommodation and convergence in young subjects while they viewed 2D and 3D images. We obtained informed consent from all subjects and approval from the Ethical Review Board of the Graduate School of Information Science at the Nagoya University. The details of experimental setup were as follows:

We set an LCD monitor 1 m in front of subjects, and presented 2D or 3D images where a spherical object moves for-
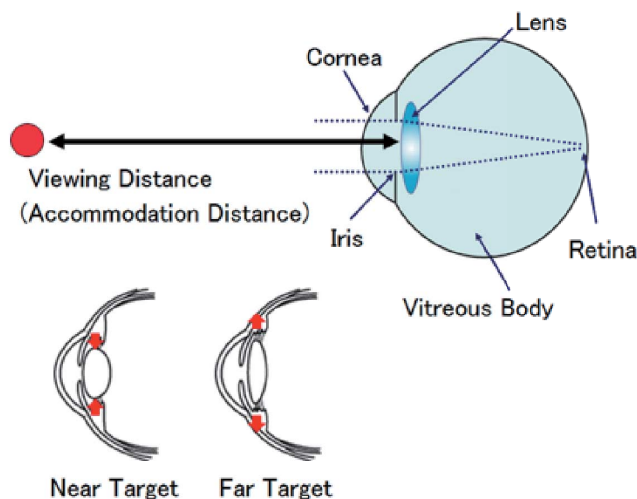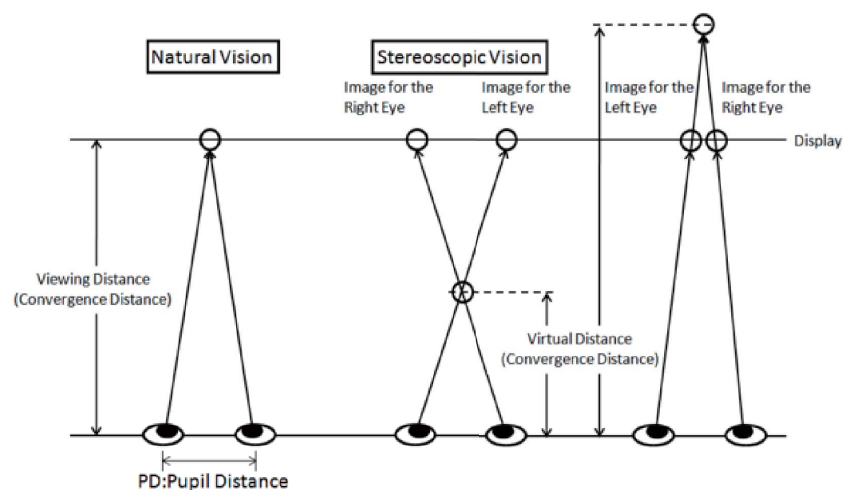
Fig. 1. Lens accommodation.
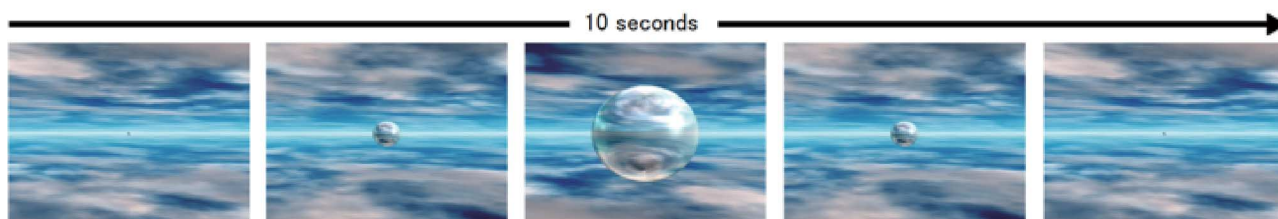

Fig. 2. Convergence.

Fig. 3. Spherical object movies.

ward and back with a cycle of 10 seconds (Fig. 3). In theory, the spherical object appears as a 3D image at 1 m (i.e., the location of LCD monitor) and moves toward the subjects to a distance of 0.35 m in front of them. We asked them to gaze at the center of the spherical object for 40 seconds, and measured their lens accommodation and convergence distance during that time. The 3D image was presented by using a liquid crystal shutter system and a circular polarizing filter system. The 2D image was presented by using only a liquid crystal shutter system. Measurements were made three times each. The performance of the monitor used in the experiment is shown in Table 1. For the measurements, we made an original machine by combining WAM-5500 and EMR-9.

WAM-5500 is an auto refractometer (Grand Seiko Co., Ltd.) that can measure accommodative power with both eyes opened under natural conditions. It enables continuous recording at a rate of 5 Hz for reliable and accurate measures of accommodation. Some previous studies used WAM-5500: measurement of state accommodative re-

Table 1. Performance of the monitor.

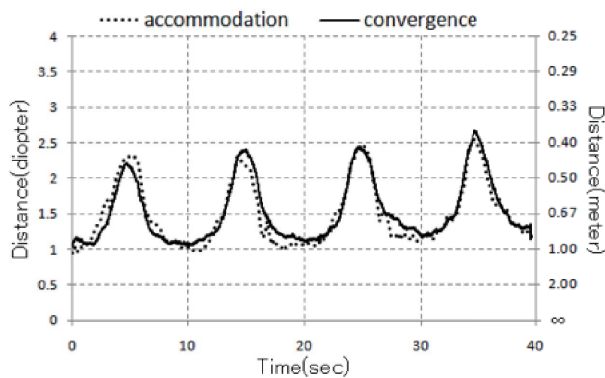| Target	FlexScanS1911	ZM-M220W
Screen resolution	1280 × 1024	1680 × 1050
Color usage	16190000	16770000
Size	19 inch	22 inch Wide
Pixel pitch	0.294 × 0.294 mm	0.282 × 0.282 mm
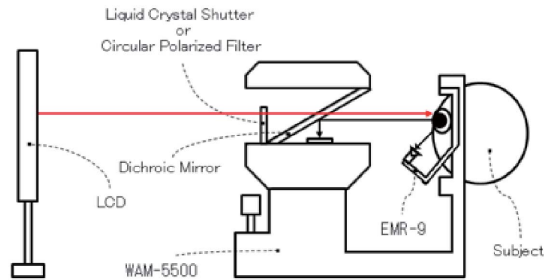
Fig. 4. Experimental environment.

Fig. 6. Circular polarizing filter system (Subject A).

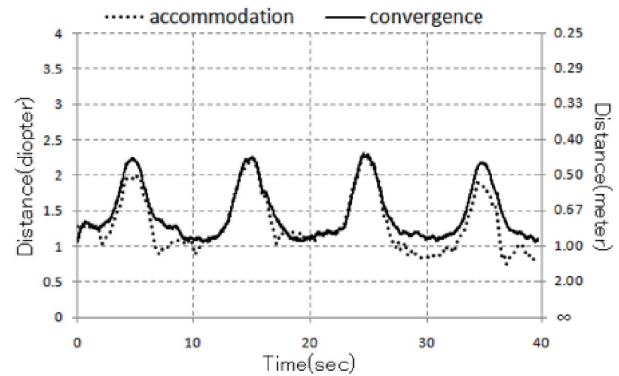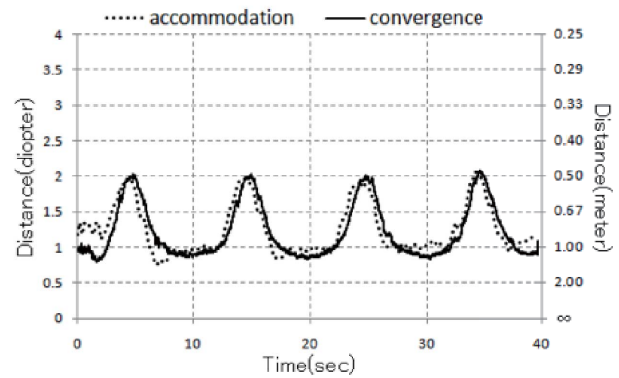Fig. 7. Liquid crystal shutter system (Subject B).

Fig. 5. Liquid crystal shutter system (Subject A).

sponses among a college population with visual discomfort over a 90-s time period (Tosha *et al.*, 2009); comparison of clinical subjective findings with objective measurements of AR (Jaclyn *et al.*, 2009); evaluation of validity and repeatability (Amy and Leon, 2010); comparison of refractive values measured with and without cycloplegia, or with fogging lenses (Queirós *et al.*, 2008); and measurement of near-induced transient myopia response with significant visual discomfort (Eric *et al.*, 2010). WAM-5500 has two measurement modes. One is a static mode, and the other is a dynamic mode. We used the dynamic mode. The instrument was connected to a PC running the WCS-1 software via an RS-232 cable with the WAM-5500 set to Hi-Speed (continuous recording) mode. During dynamic data collection, we simply depress the WAM-5500 joystick button once to start recording, and once to stop at the end of the desired time frame.

EMR-9 is an eye mark recorder (NAC Image Technology Inc.) that can measure convergence distance using the pupillary/corneal reflex method. The specifications are resolution of eye movement of 0.1 degrees, measurement range of 40 degrees, and measurement rate of 60 Hz. Small

optical devices of 10 mm width and 30 mm long for irradiation and measurement of infrared are supported by a bar attached to the cap mounted on the head of the subject. Some previous studies used EMR-9 (or 8) in development of occlusion-free animation of driving routes for car navigation systems (Takahashi *et al.*, 2006); examination of exploratory eye movements for evaluating the development of visual cognitive function in childhood (Egami *et al.*, 2009); and estimation of user arm motion supported by the wearable type robot (Sakaki, 2009).

We used a liquid crystal shutter system or a circular polarizing filter system combined with the respective binocular vision systems for 2D and 3D. The experimental environment is shown in Fig. 4 and Table 2. Here, we note that brightness (cd/m^2) is a value measured through the liquid crystal shutter or the circular polarizing light filter, and that the size of the spherical objects (deg) is not equal because the binocular vision systems for 2D and 3D have different display sizes.

The images we used in the experiment are trademarked as Power 3D^{TM} (Olympus Visual Communications, Corp.). This is an image creation technique that combines near and far views in a virtual space, and has multiple sets of virtual displays, the position of which can be adjusted. When subjects view a close target (crossed view), far view cannot be fused. When they see a far view, the close target (crossed view) is split and two targets are seen. Therefore, Power 3D presents an image that is extremely similar to natural vision.

Table 2. Experimental environment.

System		Liquid crystal shutter	Circular polarizing filter
Brightness of spherical object (cd/m^2)	Far	3.6	34.5
	Near	3.0	31.1
Illuminance (lx)	Far	126	129
	Near	″	″
Size of spherical object (deg)	Far	0.20	0.17
	Near	7.70	6.44
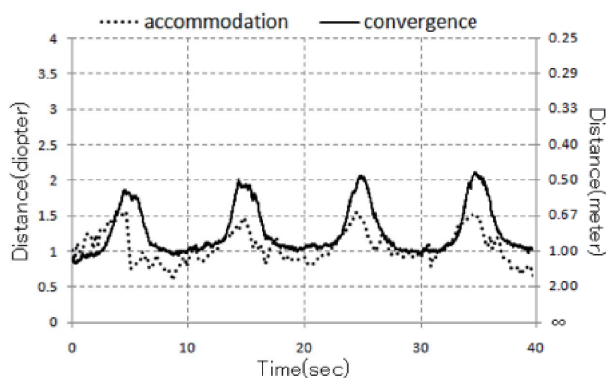
Fig. 8. Circular polarizing filter system (Subject B).

Fig. 10. 3D vision.

Fig. 9. 2D vision.

Table 3. Mean value of accommodation and convergence.

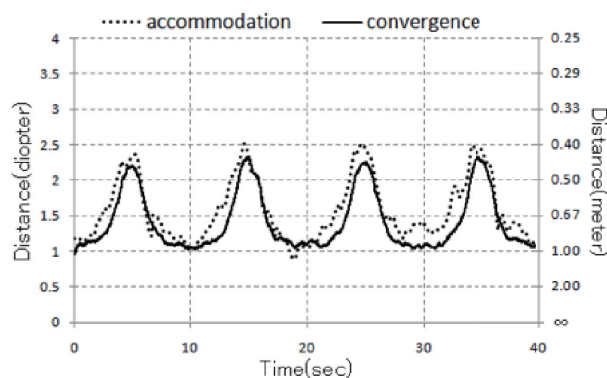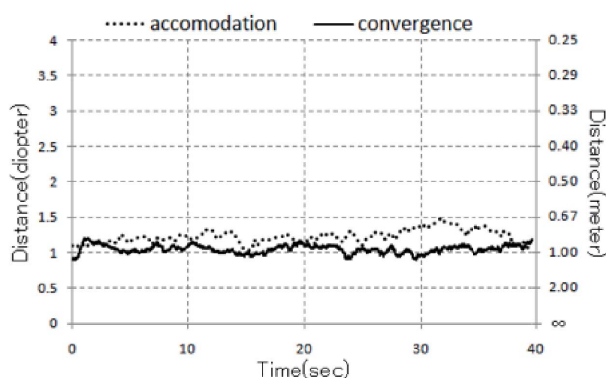|	Accommodation	Convergence	Difference
2D	0.96 D	0.96 D	0 D
	(104.2 cm)	(104.2 cm)	(0 cm)
3D	1.29 D	1.32 D	0.03 D
	(77.5 cm)	(75.8 cm)	(1.7 cm)

3. Results

The measurements for the 6 subjects showed roughly similar results. For 3D vision, results for Subjects A and B are shown in Figs. 5–8 as examples. When Subject A (23 years old, male, soft contact lenses) viewed the 3D image with the liquid crystal shutter system (Fig. 5), accommodation changed between about 1.0 Diopter (100 cm) and 2.5 Diopters (40 cm), while convergence changed between about 1.0 Diopter (100 cm) and 2.7 Diopters (37 cm). The changes in the respective diopter values have almost the same amplitude and are in phase, fluctuating synchronously with a cycle of 10 seconds corresponding to that of the 3D image movement. In the same subject but with the circular polarizing filter system (Fig. 6), accommodation changed between about 0.8 Diopters (125 cm) and 2.3 Diopters (43 cm) while convergence changed between about 1.0 Diopter (100 cm) and 2.3 Diopters (43 cm). The changes in the re-

spective diopter values have almost the same amplitude and are in phase, fluctuating synchronously with a cycle of 10 seconds corresponding to that of the 3D image movement.

Similarly, when Subject B (29 years old, male, soft contact lenses) viewed the 3D image with the liquid crystal shutter system (Fig. 7), both accommodation and convergence changed in almost the same way between about 0.8 Diopters (125 cm) and 2.0 Diopters (50 cm). The changes in the respective diopter values have almost the same amplitude and are in phase, fluctuating synchronously with a cycle of 10 seconds corresponding to that of the 3D image movement. In the same subject but with the circular polarizing filter system (Fig. 8), accommodation changed between about 0.7 Diopters (143 cm) and 1.6 Diopters (63 cm), while convergence changed between about 1.0 Diopter (100 cm) and 2.0 Diopters (50 cm). The changes in the respective diopter values are a little different in amplitude, but are in phase, fluctuating synchronously with a cycle of 10 seconds corresponding to that of the 3D image movement.

For 2D vision, the results for Subject A are shown in Figs. 9 and 10 as an example. When he viewed the 3D image with the liquid shutter system, his accommodation and convergence changed between about 1.0 Diopter (100 cm) and

2.5/2.7 Diopters (40/37 cm). They had almost the same amplitude and were in phase, fluctuating synchronously with a cycle of 10 seconds corresponding to that of the 3D image movement. In contrast, when viewing the 2D image, the diopter values for both accommodation and convergence were almost constant at around 1 Diopter (1 m).

Finally, Table 3 shows mean values of accommodation and convergence in the 6 subjects when they viewed 2D and 3D images. The data for the 3D image were obtained using the liquid crystal shutter system only. As shown in Table 3, the mean values of accommodation and convergence for the 6 subjects when the viewed the 2D image were 0.96 ± 0.12 and 0.96 ± 0.07, respectively. The difference was negligible. When viewing the 3D image, the values of accommodation and convergence were 1.29 ± 0.11 and 1.32 ± 0.08, respectively. The difference was about 0.03 Diopter, which is also negligible. Therefore, we can say that there is not much quantitative difference in the results between accommodation and convergence when viewing either the 2D or 3D images. In this experiment, there were a few subjects who could recognize the stereoscopic view with the liquid crystal shutter but not with the circular polarizing filter system. There were also a few subjects who could recognize the stereoscopic view but complained that it was not easy to see with stereoscopic vision at the point where the 3D image was closest.

4. Discussion

In this experiment, we simultaneously measured accommodation and convergence while subjects viewed 2D and 3D images for comparison, since it is said that accommodation and convergence are mismatched during stereoscopic vision. Wann *et al.* (1995) said that within a VR system the eyes must maintain accommodation on the fixed LCD screens, despite the presence of disparity cues that necessitate convergence eye movements in the virtual scene. Moreover, Hong and Sheng (2010) said that the natural coupling of eye accommodation and convergence in viewing a real-world scene is broken in stereoscopic displays.

From the results in Figs. 5–8, we see that when young subjects are viewing 3D images accommodative power is consistent with the distance of convergence with both the liquid crystal shutter and circular polarizing filter systems, and that the values of focusing distances are synchronized with each other.

In addition, the results in Figs. 9 and 10 and Table 3 suggest that the ocular functions when viewing 3D images are very close to those during natural viewing. In general, it is said that there is a slight difference between accommodation and convergence even during natural viewing, with accommodation focused on a position slightly farther than that of real objects and convergence focused on the position of the real objects. This is said to originate in the fact that the index is seen even if focus is not accurate because of the depth of field (Miyao *et al.*, 1993). In our 3D vision experiments, the mean values of accommodation and convergence were found to be 1.29 ± 0.11 and 1.32 ± 0.08, respectively. This means that accommodation focuses on a position slightly farther than that of convergence by about 0.03 Diopter. Hence, our findings suggest that eye move-

ment when viewing 3D images is similar to that during natural viewing. In the light of the above, the conventional theory stating that within a VR system our eyes must maintain accommodation on the fixed LCD screen may need to be corrected. We can also say that the kind of results presented herein could be obtained because the 3D images used in the experiments were produced not by conventional means but with Power 3D, whose images are extremely close to natural viewing. Therefore, we consider that as long as 3D images are made using a proper method, accommodation and convergence should almost always coincide, even for an image that projects out significantly, and that we can view such images more easily and naturally. Conventional 3D and the Power 3D on HMD have been compared experimentally (Hasegawa *et al.*, 2009). This study also found that Power 3D is superior to conventional 3D.

Finally, we should note that the experimental value of accommodation was a little smaller in Diopters than that of convergence at the viewing positions closest and farthest to the 3D object when the circular polarizing filter system was used. This is likely because the brightness with such a system is higher than that with a liquid crystal shutter system. A previous study suggests that the lens may in many cases not be accommodated strictly when brightness is low according to the previous works (Miyao *et al.*, 1993).

5. Conclusion

In this experimental investigation, we simultaneously measured accommodation and convergence while subjects viewed 2D and 3D images for comparison. The results suggest that the difference in eye movement for accommodation and convergence is equally small when viewing 2D and 3D images. This suggests that the difference between accommodation and convergence is probably not the main reason for visual fatigue, motion sickness, and other problems. The number of subjects in this experiment was only 6, which may still be too small for our findings to be completely convincing. As said to Amy and Leon (2010), the apparatus used in this study (WAM-5500) is high reliable. If we repeat this study in the near future with a larger number of subjects, the results will have even greater reliability. In order to compare states more similar to natural vision, we also would like to simultaneously measure and compare both accommodation and convergence in subjects viewing both real objects (natural vision) and 3D images (stereoscopic vision) of those objects made with 3D cameras.

References

Amy, L. S. and Leon, N. D. (2010) Clinical evaluation of the Grand Seiko Auto Ref/Keratometer WAM-5500, *OPO*, **30**, 143–151.

David, M. H., Ahna, R. G., Kurt, A. and Martin, S. B. (2008) Vergence-accommodation conflicts hinder visual performance and cause visual fatigue, *Journal of Vision*, **8**(33), 1–30.

Egami, C., Morita, K., Ohya, T., Ishii, Y., Yamashita, Y. and Matsuishi, T. (2009) Developmental characteristics of visual congnitive function during childhood according to exploratory eye movements, *Brain & Development*, **31**, 750–757.

Eric, B., Tosha, C., Chris, C. and William, H. R., III (2010) Measuring near-induced transient myopia in college students with visual discomfort, *Optometry and Vision Science*, **87**, 10.

Hasegawa, S., Omori, M., Watanabe, T., Fujikake, K. and Miyao, M. (2009) Lens accommodation to the stereoscopic vision on HMD, *Lecture Notes in Computer Science*, **5622/2009**, 439–444.

Hong, H. and Sheng, L. (2010) Correct Focus Cues in Stereoscopic Displays Improve 3D Depth Perception, SPIE, Newsroom.

Jaclyn, A. B., Junita, D. C., Kimberley, M., Mark, R. and John, K. P. (2009) Does the dynamic cross cylinder test measure the accommodative response accurately?, *Optometry*, **80**, 630–634.

Miyao, M., Otake, Y., Ishihara, S., Kashiwamata, M., Kondo, T., Sakakibara, H. and Yamada, S. (1993) An experimental study on the objective measurement of accommodation amplitude under binocular and natural viewing conditions, *Tohoku Exp. Med.*, **170**, 93–102.

Miyao, M., Ishihara, S., Saito, S., Kondo, T., Sakakibara, H. and Toyoshima, H. (1996) Visual accommodation and subject performance during a stereographic object task using liquid crystal shutters, *Ergonomics*, **39**(11), 1294–1309.

Miyao, M., Hasegawa, S., Omori, M., Takada, H., Fujikake, K., Watanabe, T. and Ichikawa, T. (2009) Lens Accommodation in Response to 3D Images on an HMD, IWUVR.

Queirós, A., González-Méijome, J. and Jorge, J. (2008) Influence of fogging lenses and cycloplegia on open-field automatic refraction, *OPO*, **28**, 387–392.

Sakaki, T. (2009) Estimation of intention of user arm motion for the proactive motion of upper extremity supporting robot, *IEEE 11th International Conference on Rehabilitation Robotics*, Kyoto International Conference Center, Japan, June, 23–26.

Simon, J. W., Kurt, A., Marc, O. E. and Martin, S. B. (2005) Focus cues affect perceived depth, *Journal of Vision*, **5**, 834–862.

Takahashi, S., Yoshida, K., Shimada, K. and Nishita, T. (2006) Occlusion-Free Animation of Driving Routes for Car Navigation Systems, IEEE.

Tosha, C., Eric, B., William, H. R., III and Chris, C. (2009) Accommodation response and visual discomfort, *OPO*, **29**, 625–633.

Wann, J., Rushton, S. and Mon-Williams, M. (1995) Natural problems for stereoscopic depth perception in virtual environments, *Vision Res.*, **35**(19), 2731–2736.