Stereoscopic Displays and Accommodative Focus

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(Received November 1, 2010; Accepted May 10, 2011)

In the present study, we examined the visual accommodation of subjects who were gazing fixedly at stereoscopic images on two different displays: a cathode ray tube (CRT) with the subjects wearing liquid crystal shutter glasses and a liquid crystal display (LCD) with the subjects not wearing liquid crystal shutter glasses. In Experiment 1, we measured accommodation in subjects viewing a moving stereoscopic image. In Experiment 2, we measured accommodation in subjects viewing moving stereoscopic images on an LCD and a CRT. In Experiment 3, we measured accommodation in subjects viewing a stereoscopic image moving from far to near on an LCD. In Experiment 4, we measured of accommodation in subjects viewing moving stereoscopic images (stereoscopic display mode) and non-stereoscopic images (2-D mode) on an LCD.

The results suggested, the ciliary muscle is repeatedly strained and relaxed while the subject views the moving target. In the present study, the subjects' accommodative amplitude was changed when the target moved from the near to far point, and vice versa.

Key words: Accommodation, Binocular Vision, Stereoscopic Image and Visual Display

1. Introduction

Various studies have been performed on the influence of stereoscopic images on visual function (Schor, 1980; Rosenfield *et al.*, 1992; Heron *et al.*, 2001). Most prior studies discussed the effects of visual image quality and extent of physical stress. These studies have employed bioinstrumentation or surveys of subjective symptoms (Iwasaki *et al.*, 1996).

Under natural viewing conditions the depth of convergence and accommodation in these studies agreed. However, when people view a stereoscopic image using binocular parallax, it has been thought that convergence moves with the position of the reproduced stereoscopic image, while accommodation remains fixed at the image display. As a result, researchers believed that there is contradictory depth information between convergence and accommodation, called discordance, in the visual system.

However, from objective measurements of the accommodation system it has been confirmed that there is a fluctuating link between accommodation and convergence (Omori *et al.*, 2003). To make viewing a stereoscopic visual system more comfortable, we are at the stage where we should view the qualitative improvements that need to be made from a different perspective. With the aim of qualitatively improving stereographic image systems, biomeasurements under stereoscopic viewing conditions are needed.

Recently a novel three-dimensional (3-D) video construction method has been developed to prevent video-induced motion sickness (Yasui *et al.*, 2006; Kakeya, 2007). Humans perceive 3-D objects by simultaneous vergence and accommodation of the lens, but stereoscopic videos generally consist of unnatural images perceived along a fixed optical axis of lens, negating such vergence and accommodation. Stereoscopic images that are prepared using the Power 3D method reduces the inconsistency between experienced and actual senses (see Appendix A).

2. Background

With the development of computers and the widespread use of the Internet, an increasing number of people need to perform near visual tasks such as operations on video display terminals (VDTs). Working under such conditions for several hours induces the contraction of the muscles involved in focus adjustment around the eyeball, such as the ciliary muscles. The abnormal contraction of ciliary muscles due to the performance of a near visual task for several hours causes various vision problems such as asthenopia and visual loss. Further, this contraction has been reported to induce the cervicobrachial and psychoneurotic syndromes (Gomzi, 1994; Nakazawa *et al.*, 2002).

For persons afflicted with pseudomyopia, performing stretching exercises of the ciliary muscles alleviates strain and temporarily improves the myopic condition. These exercises can be performed by alternately repeating negative and positive accommodation of the eye.

It has been commonly explained that lens accommodation makes us focus on the surface of a display although the

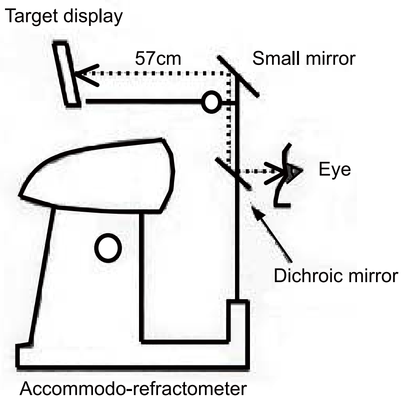


Fig. 1. Schematic view of the device developed for the present expreiment.

optical axes of lens are crossed at the virtual image (see Appendix A) while viewing stereoscopic images (Cruz-Neira *et al.*, 1993). There is discrepancy between vergence and accommodative focus. That is, there is contradictory depth information between vergence and accommodation, called discordance, in the visual system. According to previous textbooks on 3-D imaging, visually induced motion sickness (VIMS) and asthenopia are caused by this discordance. However, it seems to be wrong explanation. It has been shown that our focus is not always fixed on the surface of a display while viewing stereoscopic image as follows.

Under natural viewing conditions with binocular vision, we measured lens accommodation for 40 seconds (Hasegawa *et al.*, 2009; Omori *et al.*, 2009) while sphere images moved virtually toward and away from the subject on a head-mounted display (HMD), a liquid crystal display (LCD) and a cathode ray tube (CRT). Displays were positioned so that it appeared in the upper portion of a dichroic mirror placed in front of the subject's eyes. 2-D and 3-D moving images were observed through reflection in the dichroic mirror, and refraction could be measured at the same time by transmitting infrared rays. The refractive index of the right lens accommodation was measured by using a modified version of an original apparatus with an accommodo-refractometer (Nidek AR-1100) when the subjects gazed at the presented image via a small mirror with both eyes (Miyao *et al.*, 1992). The subjects refraction was less than +0.5 Diopter (D), so both were emmetropic. As a result, accommodation was made to approximately 3 (D) in front of the eyes even when the stereoscopic sphere reached to the nearest point. Immediately after the sphere flew across the distant sky, the accommodation was about 1 (D). The accommodation synchronizing with the movement process of the sphere is shown only in the 3-D movie. Thus, the ciliary muscle is repeatedly strained and relaxed while that vision is with virtual movement of 3-D images. Moreover, focal accommodation in near vision did not differ greatly with the different types of display. It was also shown, regardless of the whether or not liquid crystal shutter glasses were used, that accommodation was easy and comfortable when focusing on virtually distant movements on those displays.

3. Main Focus of the Chapter

To investigate the influence of stereoscopic images on visual function in humans, we measured accommodation in people gazing at a target under both binocular and natural viewing conditions.

3.1 Accommodative measurement and stimulus

Using a customized accommodo-refractometer, we measured and recorded accommodation in the subjects while they were viewing stereoscopic images on two different displays for 60 second periods. The subjects viewed a CRT while wearing liquid crystal shutter glasses and an LCD while not wearing liquid crystal shutter glasses. Visual function was tested using a custom-made apparatus (Fig. 1).

This apparatus combined an automated infrared accommodo-refractometer (Nidek AR-1100) and original binocular dichroic mirror system (Fig. 2) (Miyao *et al.*, 1992, 1996). The display images were placed in front of a small mirror for the tests (Fig. 1). Subjects gazed at each type of display through a dichroic mirror and an ordinary small mirror (Fig. 1). The instrument objectively measured visual accommodative changes of the right eye at a 12.5 Hz sampling rate in binocular viewing conditions (Otake *et al.*, 1993). The distance between the subjects' eyes and the target on the screen was 57 cm (1.00/0.57 = 1.75 Diopters (D)) (Note: Diopter (D) = 1/distance (m); MA (meter angle) = 1/distance (m)). Figure 2 shows the situation when measurements are being taken and the measurement equipment.

In the present study, two different types of display were used: a parallax barrier display (LCD, Sharp PC-RD1-3D) and stereoscopic image system with a CRT (SONY KV-14AF-1) with the use of liquid crystal shutter glasses (accessory of Dr. REX CR-001-S). Using the stereoscopic image "Sky Vision" (Eye Power Sports Ltd.), the following four experiments were conducted.

3.2 Experimental procedure

The stereoscopic sphere image used had a reciprocating movement with the image appearing to move on the monitor (LCD or CRT) toward and away from the subjects in a ten-second period (Fig. 3).

Gaze time was 60 seconds, and the accommodation of the right eye was measured and recorded continuously while the subjects gazed at the stereoscopic image with both eyes. The subjects were instructed to focus on the stereoscopic image.

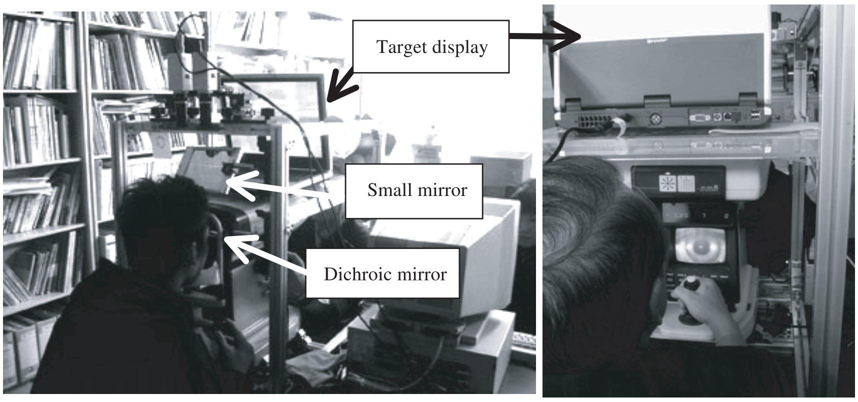
We obtained informed consent from all subjects and approval from the Ethical Review Board of the Graduate School of Information Science at the Nagoya University.

Experiment 1. Measurement of accommodation while the subjects gazed at the stereoscopic image on LCD

The subjects were two males aged 21 years, with normal vision (Table 1). The subjects' refraction was less than +0.5 Diopter (D), so both were emmetropic.

Experiment 2. Measurement of accommodation while the subjects gazed at the stereoscopic image on LCD and CRT

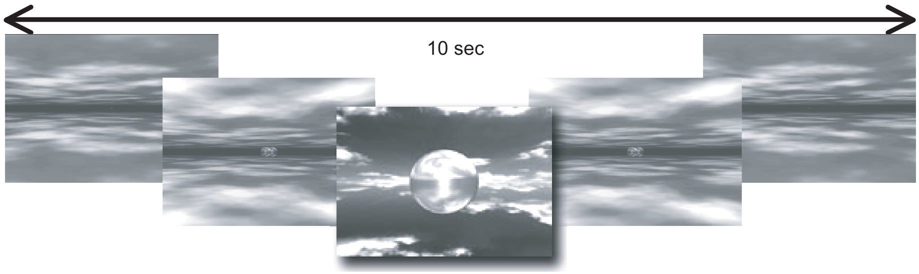
The subjects were two people aged 19 and 20 years, with normal vision (Table 1). The subjects' refraction was less than +0.5 Diopter (D), so both were emmetropic.



(a) Measuring instrument machine for subject.

(b) Measuring instrument machine for experimenter.

Fig. 2. Measurement scene and measurement equipment.



Note. There was reciprocating movement with the image appearing to move on the LCD toward and away from the subjects in a ten-second period.

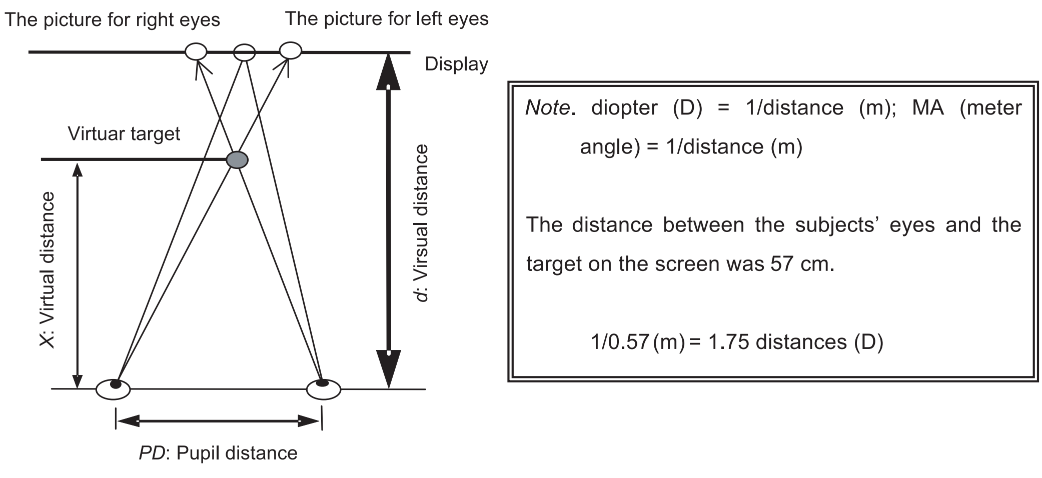


Fig. 3. Stereoscopic sphere image and the principle of a parallax barrier.

Experiment 3. Measurement of accommodation when still stereoscopic image moved from far to near

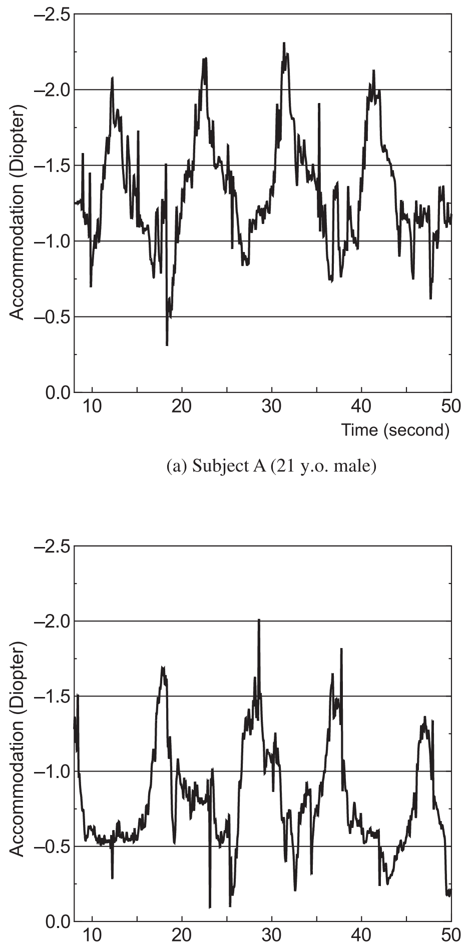
The subjects were two people aged 20 and 36 years, with normal vision (Table 1). The subjects' refraction was less than +0.5 Diopter (D), so all were emmetropic. In this experiment, subjects' accommodation was measured while they gazed first at a distant stereoscopic still image for 30 seconds and then at a near stereoscopic still image for 30 seconds on an LCD.

Experiment 4. Measurement of accommodation in subjects viewing moving images in stereoscopic and 2-D modes on an LCD

The subjects were two people aged 21 and 22 years, with normal vision (Table 1). The subjects' refraction was less than +0.5 Diopter (D), so all were emmetropic. In this experiment the stereoscopic image display could be switched between 2-D mode and stereoscopic display mode, so the accommodation over 60 seconds while subjects viewed

Table 1. Subject's condition.

	Age	Sex	Condition	Experiment
Subject A	21 y.o.	Male	Normal vision	1
Subject B	21 y.o.	Male	Normal vision	1
Subject C	19 y.o.	Male	Normal vision	2
Subject D	20 y.o.	Male	Normal vision	2
Subject E	20 y.o.	Male	Normal vision	3
Subject F	36 y.o.	Male	Normal vision	3
Subject G	21 y.o.	Male	Normal vision	4
Subject H	22 y.o.	Female	Normal vision	4



(a) Subject A (21 y.o. male)

(b) Subject B (21 y.o. male)

Fig. 4. Accommodative change in subjects viewing a moving stereoscopic image (Experiment 1). X-axis shows time: 0–50 sec, Y-axis shows diopter: 0–2.5 diopter.

the stereoscopic image was measured in both the 2-D and stereoscopic display mode. The subjects were instructed to gaze at the center of the sphere, and the total gazing time was 60 seconds. Subjectively, all subjects obtained full stereoscopic viewing. Accommodation of the right eye was measured and recorded while subjects viewed the stereoscopic image with both eyes.

3.3 Results

Experiment 1. Measurement of accommodation while the subjects gazed at the stereoscopic image on LCD

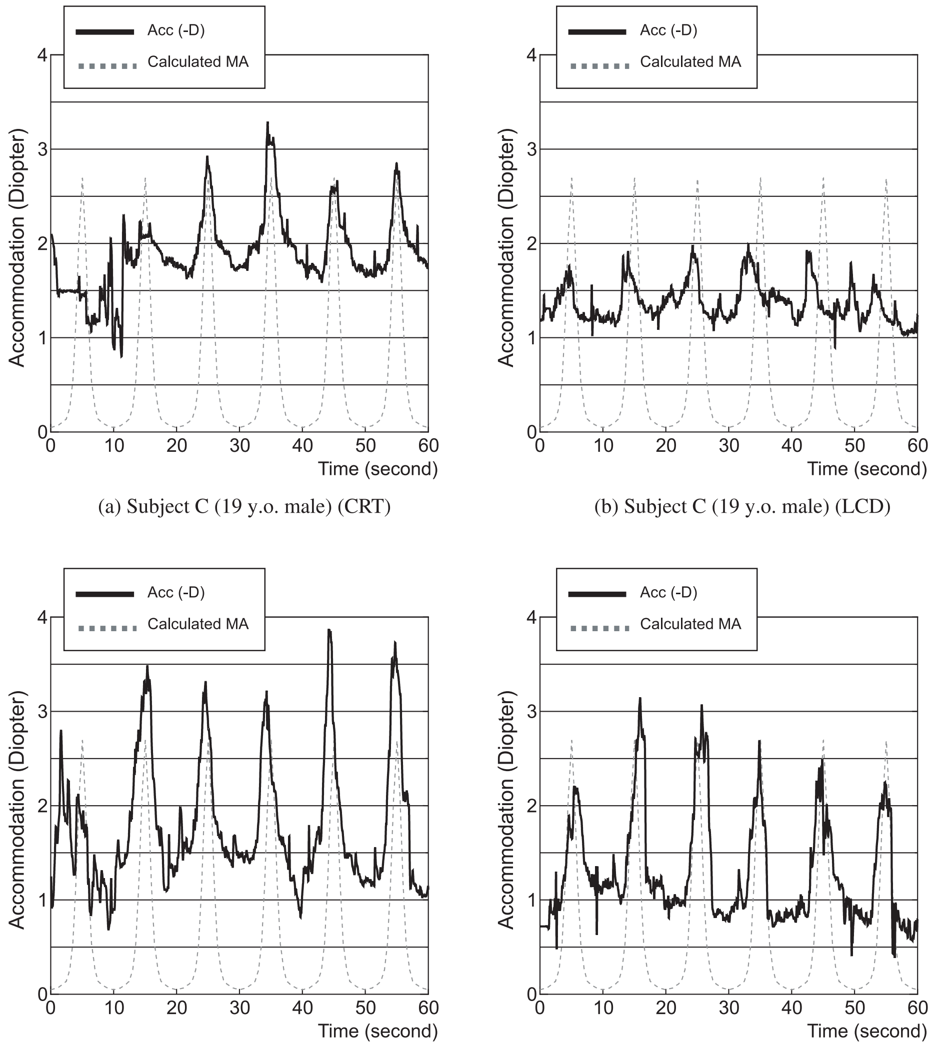
When the subject's viewed the target "moving" progressively closer, the right eye of both subjects was accommodated to the near point. Figure 4(a) shows the objective changes in accommodation of subject A (21 years old), and Fig. 4(b) shows the objective changes in accommodation of subject B (21 years old). When subject B viewed the progressively receding target, his accommodation was about 0.5 D at the virtual furthest point, which was 2 m beyond the actual screen. Thus, they were confirmed to have an accommodative focus with a visual distance of approximately 2 m when they gazed at the stereoscopic, virtually distant images.

When subject A recognized the target that appeared at a near point, his eyes were accommodated about −2.2 D. This suggests that accommodation range comes at about 45 cm from subjects' eyes. In this experiment, the display was set at a distance of 57 cm from the subject's eyes and the stereoscopic image appeared to "fly" 20 cm out from screen. However, it has been shown experimentally that young people have an accommodation range of 0.3 D or 0.5 D from the actual distance. In fact, the accommodative near point of one subject was 2.7 D, which is 37 cm in front of the subject's eyes. With this level of accommodation, the ciliary muscle is stressed. When subject B recognized the target as being at the near point, his eyes were accommodated about −2 D.

This suggests that the accommodation range came at about 50 cm from the subjects' eyes. However, considering the accommodation range of some 0.3 D or 0.5 D, the accommodative near point of one subject was −2.5 D, and the subjective near point of subject B was about −2.5 D, or about 40 cm in front of the eyes. With this level of accommodation, the ciliary muscle is stressed. Thus, the ciliary muscle is repeatedly strained and relaxed while a subject views a moving target.

Experiment 2. Measurement of accommodation while subjects gazed at the stereoscopic image on LCD and CRT

In this experiment, the subjects' accommodative amplitudes changed when the target moved from the near to far point on the CRT (Figs. 5(a) and (c)). In subject C, the accommodative near point approached the angle of convergence. In subject D, it was larger than the angle of conver-



(a) Subject C (19 y.o. male) (CRT)

(b) Subject C (19 y.o. male) (LCD)

(c) Subject D (20 y.o. male) (CRT)

(d) Subject D (20 y.o. male) (LCD)

Fig. 5. Accommodative change in subjects viewing moving stereoscopic images on an LCD and a CRT (Experiment 2). X-axis shows time: 0–60 sec, Y-axis shows diopter: 0–4 diopter.

gence. When the target was virtually most distant, accommodation was equivalent to a screen distance of about 1.7 D in subject C and about 1.4 D in subject D. A tendency was thus seen to focus on a place more distant than the actual screen.

On the LCD, the subject's accommodative amplitude also changed when the target moved from the near to far point (Figs. 5(b) and (d)). In subject C, accommodation was smaller than with the CRT. In subject D, a tendency was seen for accommodation to decrease at the near point with each cycle of the target.

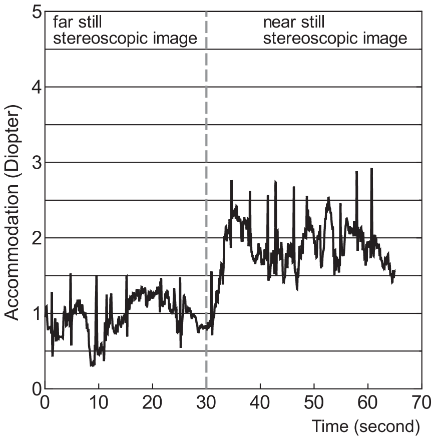
Thus, it was shown that accommodation is strongly influenced by angle of convergence when subjects gaze at a stereoscopic image. It was also shown, regardless of the whether or not liquid crystal shutter glasses were used, that accommodation was easy and comfortable when focusing on virtually distant movements on both the LCD and CRT.

Experiment 3. Measurement of accommodation when still stereoscopic image moved from far to near

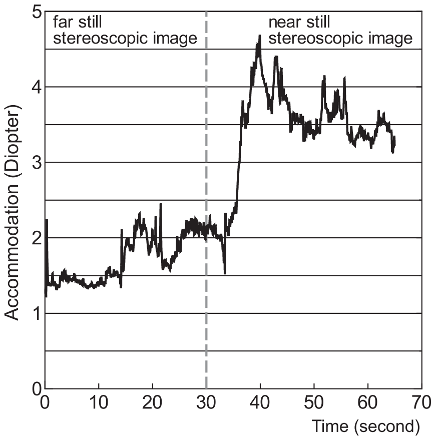
Figure 6 shows the results when accommodation was measured as subjects gazed at near and far still stereoscopic images for 30 seconds.

The far point was about 0.5 D in subject E, shown in Fig. 6(a). This suggests that the point of focus was at a distance of about 2 m, indicating a tendency for focus to be at a point more distant than the actual screen. The maximum accommodation for the near point was about 2.6 D, suggesting accommodation was for a distance 38 cm in front of the subjects' eyes. However, young people have been shown experimentally to have an accommodation range of 0.3 D or 0.5 D from the actual distance. Therefore, the accommodation of subject E was probably 3.1 D, or 32 cm in front of the subject's eyes.

Subject F (Fig. 6(b)) had accommodation of the far point of about 1.6 D, which was equivalent to the visual distance of the screen, but accommodation of the near point was a maximum of 4.6 D, a distance of 21 cm from the eyes. Consequently, focus was on a distant point with still pictures also. Moreover, accommodative focus was on a near point even with the still stereoscopic image. This suggests that with still stereoscopic images accommodation is greater with near images than with distant images.



(a) Subject E (20 y.o. male)



(b) Subject F (36 y.o. male)

Fig. 6. Accommodative change in subjects viewing a stereoscopic image moving from far to near on an LCD (Experiment 3). X-axis shows time: 0–70 sec, Y-axis shows diopter: 0–5 diopter.

Experiment 4. Measurement of accommodation in subjects viewing moving images in stereoscopic and 2-D modes on an LCD

When subjects viewed a stereoscopic image in stereoscopic display mode, accommodation in their right eyes was consistent when the visual target was at the virtual nearest point, and accommodation occurred so as to focus on the near point. When the target was virtually moving further away the lens also tracked the target and focused on the distance. With subject G in Fig. 7(a) the far point was about 0.65 D. This suggests that the focus is on a far point of about 1.5 m, and that there is a tendency to focus on a place more distant than the actual monitor. In subject H (female) in Fig. 7(c), the near point was about 1.9 D (55 cm) and the far point was 0.25 D (4 m), demonstrating that the focal accommodation went from nearer than the actual monitor to farther than the monitor.

However, when gazing at a stereoscopic image in 2-D mode, accommodation did not show the changes in focal accommodation following the target that was seen in stereoscopic display mode (Figs. 7(b) and (d)). There was, however, a momentary change in focus when the target moved from far to near point (Figs. 7(b) and (d)).

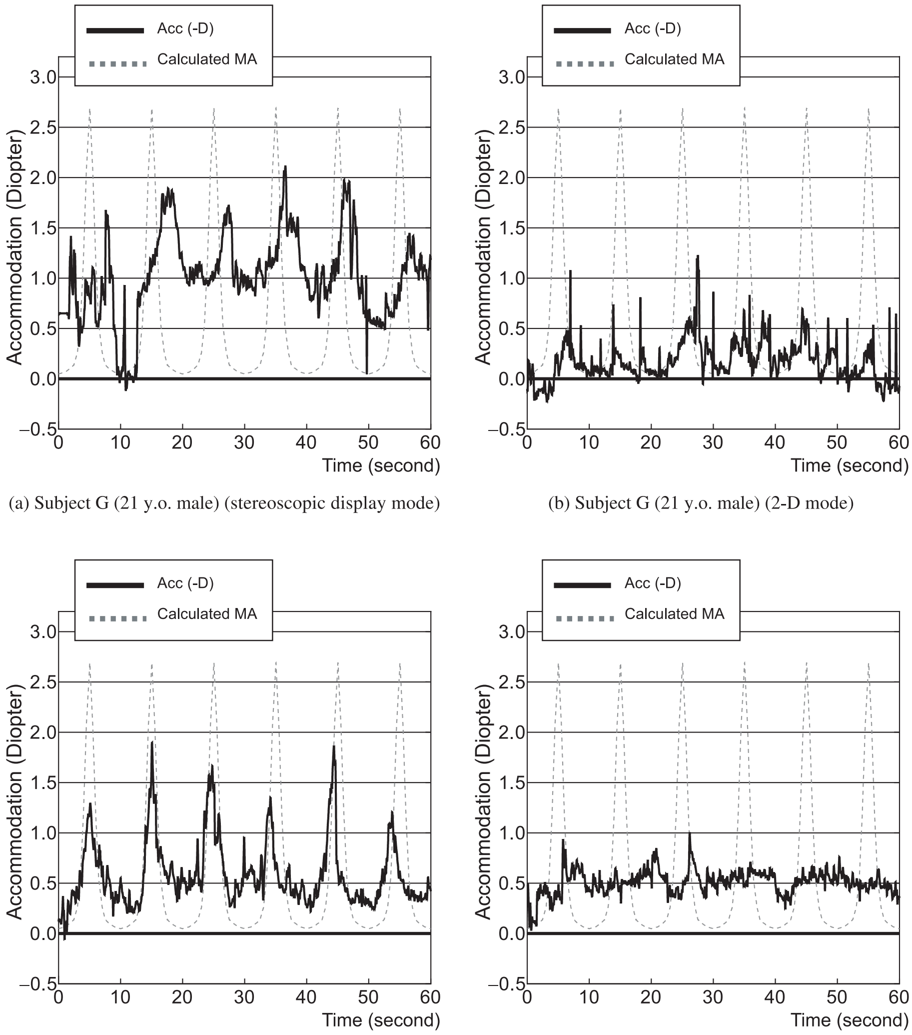
3.4 Discussion

Few studies have examined the state of accommodation in people viewing stereoscopic images (Hiruma, 1990; Inoue and Ohzu, 1990; Iwasaki *et al.*, 1996). In the present study, we measured lens focal accommodation when subjects were viewing a stereoscopic image on a display set at a fixed distance.

Experiment 1 demonstrated that focal accommodation of the lens accompanying virtual near and far movement of a stereoscopic image was similar to that which occurs when viewing a real object. In an earlier study using a 3-D figure that moved on a depth axis, it was shown that as the retinal size became larger the distance was sensed to be nearer (Brenner *et al.*, 1996). (Only when target image size changed on its own, however, was the final perceived target distance significantly smaller than that for the static targets.) It has also been reported that the visual target is felt to grow larger as the visual angle increases in stereoscopic vision (Oyama, 1974). However, another report said that, by imagining whether the visual distance to the target is near or far, the distance of accommodation when gazing changes to match the range of the imagined distance (Malmstrom and Randle, 1976).

In the present study, eye accommodation when a distant stereoscopic image appeared was about 2 D (distance: about 50 cm). It was shown that as the target moved virtually more distant, the point of focus was further than the actual monitor. Moreover, as the stereoscopic image moved farther, just before it disappeared the accommodative power was a focal accommodation of about 0.3 D (distance: about 3.3 m). In other words, from measurements of focal accommodation movement in response to a stereoscopic image moving farther and nearer, a viewing distance of about 3 m on a computer display was confirmed. This objectively demonstrates that, together with movement of the stereoscopic image, the ciliary muscle and ciliary zonule tense when viewing near distances and relax when viewing far distances.

In many methods of displaying stereoscopic images, the relation between accommodation and the angle of convergence formed by the two eyes when gazing differs from that required under natural conditions (Miyao *et al.*, 1996; Oohira and Ochiai, 1996). For example, when gazing through liquid crystal shutter glasses at a stereoscopic image display set 60 cm in front of the eyes, the angle of convergence of the two eyes is 2.0 MA when the image "flies out" 10 cm from the display screen. However, accommodation of 1.67 D is required from the viewpoint of ophthalmologic optics, and if other values are adopted the retinal image becomes blurry. The results of Experiment 2 indicate that the accommodation when viewing a stereoscopic image strongly affects angle of convergence. Subjects, however, did not have a subjective sense that the image was blurry. Thus, it is often observed that images which are not perceived to be blurry even under conditions that are "inappropriate" from the viewpoint of ophthalmologic optics (Mallot *et al.*, 1996). However, Wopking (Wopking, 1995) showed that discomfort increased with increasing binocular disparity, and indicated that sense of fatigue increased



(a) Subject G (21 y.o. male) (stereoscopic display mode)

(b) Subject G (21 y.o. male) (2-D mode)

(c) Subject H (22 y.o. female) (stereoscopic display mode)

(d) Subject H (22 y.o. female) (2-D mode)

Fig. 7. Accommodative change in subjects viewing moving stereoscopic images (stereoscopic display mode) and non-stereoscopic images (2-D mode) on an LCD (Experiment 4). X-axis shows time: 0–60 sec, Y-axis shows diopter: –0.5–3.0 diopter.

with image blurriness. (Larger disparities lead to a marked drop in comfort ratings unless critical parts of the image are heavily blurred.)

With respect to the type of apparatus, it has been suggested that accommodation is more relaxed without the use of liquid crystal shutter glasses, and earlier studies have reported a sense of fatigue with the use of liquid crystal shutter glasses (Yamazaki *et al.*, 1990; Miyao *et al.*, 1996; Oohira and Ochiai, 1996). It has also been indicated that stress and fatigue occur with the use of liquid crystal shutter glasses even when gazing at stereoscopic images on head-mounted displays (Rushton *et al.*, 1994; Kern and Reidel, 1996).

Since the subjects in this study were young people, the effect of age was not investigated. There are findings indicating that fluctuations in accommodation for stereoscopic images do not appear uniformly in all people (Coutant and Westheimer, 1993; Matozaki and Tanisita, 1996; Omori *et al.*, 2003), so further investigations with larger numbers of subjects will be needed to examine individual differences.

From the results of Experiment 3, focal accommodation was on the visual target in static stereoscopic images at a virtually near distance. It is suggested that when the virtual distance of the stereoscopic image is near, the focal accommodation of the lens accommodation is at a nearer distance.

Experiment 4 showed that when the visual target moved from near to far there was a momentary change in focal accommodation. In previous studies it is reported that in subjects viewing a flat screen with a strong stereoscopic effect, focal accommodation occurs unconsciously in correspondence with the perceived stereoscopic effect (Jong *et al.*, 1994; Omori *et al.*, 2003). In the present study as well, a momentary change in focal accommodation was seen when the visual target moved from far to near. However, the changes in accommodation did not continue. Previous studies have reported the difficulty of maintaining a uniform distance of accommodation (Malmstrom and Randle, 1976). And, there was not gender difference though the subjects in Experiment 4 were a Male and a Female.

In previous studies the tension in the ciliary muscle and ciliary zonule that occurs with VDT work was said to cause subjective eye strain and decreased lens accommodation function in VDT users (Gunnarsson and Soderberg, 1983;

Owens and Wolf-Kelly, 1987; Ishikawa, 1990; Tsuchiya *et al.*, 1992). The results of the present study objectively demonstrate that, together with movement of the stereoscopic image, the ciliary muscle and ciliary zonule tense with near viewing and relax with far viewing. This suggests that a stretching effect of the eye ciliary muscles and zonules can be achieved with repeated far and near viewing. Therefore, repeatedly stretching between near and far vision may be useful in easing the fatigue of VDT work (Omori *et al.*, 2003).

Patterson and Martin (1992) reviewed stereopsis and pointed out that perceived depth for crossed disparity follows predictions derived from constancy in most cases, whereas for uncrossed disparity perceived depth is frequently less than predicted. They reported that among several possible distance cues relating to the computation of perceived depth, one set of cues involves proprioceptive information from accommodation, vergence, or both.

Depending on the audiovisual condition, stereoscopic videos that use binocular stereoscopic vision often induce unpleasant symptoms of asthenopia, such as headache and vomiting (Ukai and Howarth, 2008). Ataxia in stereoscopic video-induced sickness has been reported previously. The influence of video-induced motion sickness on the body has been measured by employing subjective scales such as the simulator sickness questionnaire (SSQ) (Kennedy *et al.*, 1993). Further, it is also measured by quantitatively investigating the relationship between external factors and internal conditions using physiological indices such as respiratory functions, electrocardiograms, skin electrical activity, fluctuation of the center of gravity, and electrogastrograms (Holomes and Griffin, 2001; Himi *et al.*, 2004; Yokota *et al.*, 2005). By using the SSQ and stabilometry (body sway), we examined whether the VIMS was induced by a stereoscopic movie in this study. The aim of this study is to propose a methodology to measure the effect of 3-D images on the equilibrium function. Moreover, we wondered if noise terms vanished from the mathematical model of the body sway. Using our Double-Wayland algorithm (Takada *et al.*, 2006), we evaluated the degree of visible determinism for the dynamics of the sway. We also investigated the relationship between the body sway and head acceleration by using transfer function analysis (Takada *et al.*, 2010). Our previous studies have shown that the degree of video-induced motion sickness is reduced in body sway by viewing stereoscopic videos prepared using this method on the HMD (Takada *et al.*, 2009a) and on an LCD (Takada *et al.*, 2009c), respectively.

3.5 Problems

Asthenopia and video motion-induced sickness have been considered to occur due to fixation of the lens on viewing the stereoscopic image display despite the focus being accommodated to the virtual distance of the stereoscopic image by binocular convergence. However, the lens accommodated the focus at a site near the virtual distance of the stereoscopic image when it is gazed upon, suggesting that the stereoscopic image-induced asthenopia and sickness were due to a factor other than the inconsistency between the binocular convergence and lens accommodation. However, the accommodated focus of the lens was not completely identical to the virtual distance of the stereoscopic image, suggesting that the difference between the focus accommodated by the lens and virtual distance of the stereoscopic image induced asthenopia and sickness, for which it is necessary to clarify the relationships between the virtual distance of stereoscopic images, binocular convergence, and lens focus accommodation.

It is also considered that the stereoscopic image-induced asthenopia and sickness caused are influenced by differences in the image preparation method, long-term exposure, and fixation of posture while gazing. These remain to be investigated (Takada *et al.*, 2009b).

3.6 Solutions and recommendations

To clarify the relationship between the binocular convergence and lens focus accommodation while gazing at stereoscopic images, a device which simultaneously measures the convergence and lens is under development. On trial measurement, the synchronization of measurement initiation was incomplete. We will improve the device to achieve the simultaneous measurement of convergence and the lens.

Regarding stereoscopic image-induced asthenopia and sickness, we are planning to investigate the influences of differences in the image preparation method, long-term exposure, and posture fixation while gazing employing subjective evaluation scales, such as SSQ. In addition, we will investigate a stereoscopic image preparation method, the standard duration of gazing, and optimum content of subjective evaluation. No evaluation method of stereoscopic images has been established. The development of a stereoscopic image evaluation method employing physiological indices and subjective evaluation is expected.

The study results may be utilized for eye stretch because the lens is being accommodated while gazing at stereoscopic images. However, the duration of gazing at stereoscopic images was short in this study. The investigation of changes in lens accommodation with time on long-term gazing is necessary.

4. Future Research Directions

There are many dangerous industrial activities, such as maintenance work at nuclear power plants, high-place work at construction sites, and work near an iron mill blast furnace, for which the use of remote-controlled industrial robots is being investigated to secure safety. In the health care field, surgery employing remote-controlled devices has become applied. The transmission of accurate information on conditions from the practice sites to distant places is essential for these remote-controlled activities, for which the use of stereoscopic images may be adopted. Therefore, stereoscopic images may become utilized in various fields including the industrial and health care fields.

Since stereoscopic images have become utilized for eye stretch, the inhibition of VDT-induced asthenopia may be investigated.

5. Conclusion

To investigate the effect of stereoscopic images on human visual function, we measured accommodation in both binocular and natural viewing conditions. It was con-

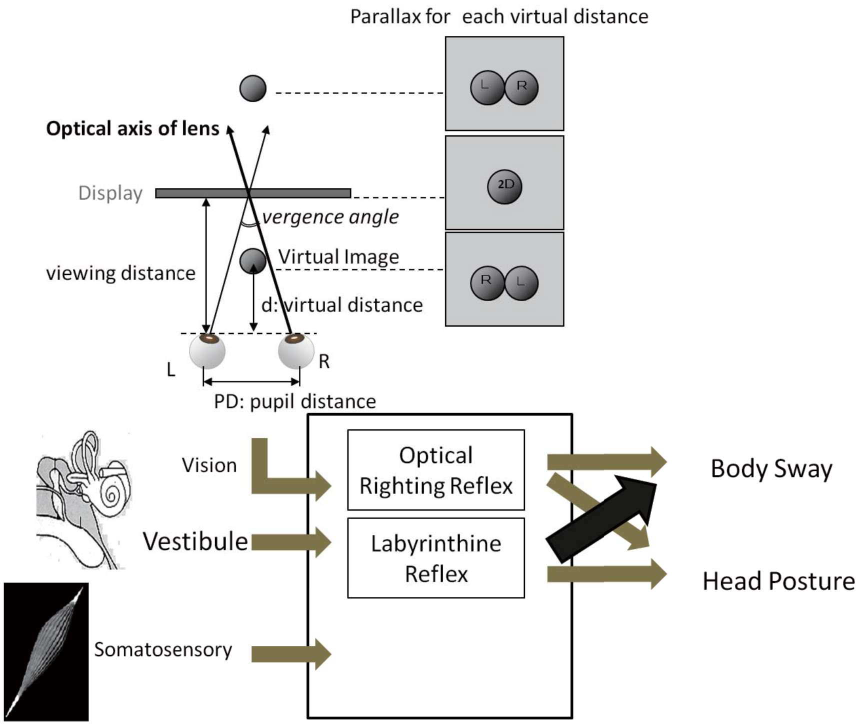


Fig. A.1. Measurement of physiology index when viewing stereoscopic images.

firmed that when following a moving target, accommodation changes to focus on far and near distances.

1) Thus, the ciliary muscle is repeatedly strained and relaxed while the subject views the moving target.

2) Irrespective of the use of liquid crystal shutter glasses, accommodation was shown to occur with both far and near virtual motion.

3) It was also confirmed that there was accommodation for still stereoscopic images with both distant and near images.

4) It was shown that accommodation occurred near the position of the virtual distance in the stereoscopic display mode more than in the 2-D mode of the apparatus displaying the stereoscopic image.

Therefore, it is assumed that the ciliary muscles of subjects who viewed the stereoscopic image moved repeatedly between stressed and relaxed stages. In other words, the ciliary muscle was stretched effectively.

These results suggest that prolonged near work with computers may cause eyesight to shift toward a myopic state, and that the stereoscopic images might improve eyesight under working conditions.

Appendix A. Power 3D Method

Relating to a general stereoscopic view, the images are composed of photographs taken by two cameras or by computer graphics (CG). Camera axes are fixed and crossed at the point of the virtual image at which the creator expects viewers to gaze. That is, viewers would suffer from finding the anomalous vergence if they looked at the other elements in a stereoscopic flame. According to International Workshop Agreement 3 (IWA3), International Organization for Standardization (ISO) suggested that the popping out effect

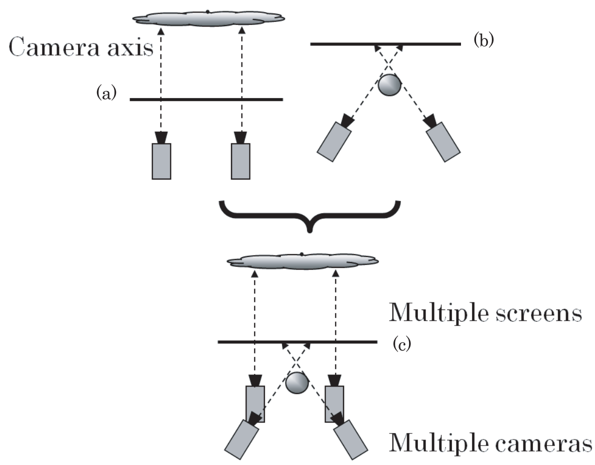


Fig. A.2. Eyesight-recovering stereoscopic movie system.

not be used considerably (Fig. A.1).

Vergence is the simultaneous movement of both eyes in opposite directions to obtain or maintain single binocular vision. When an organism with binocular vision looks at an object, the eyes must rotate around a vertical axis so that the image is projected at the centre of the retina in both eyes. To look at an object that is closer, the eyes rotate towards each other (convergence), whereas to look at an object that is farther away, the eyes rotate away from each other (divergence). Vergence is measured by the angle of inclination between these 2 lines (Fig. A.1).

Righting reflex can be subcategorized as the following: optical, neck, body on head, body on body righting reflexes, and labyrinthine reflex which plays a key part in the control of head posture (Baloh and Honrubia, 1989). The head and

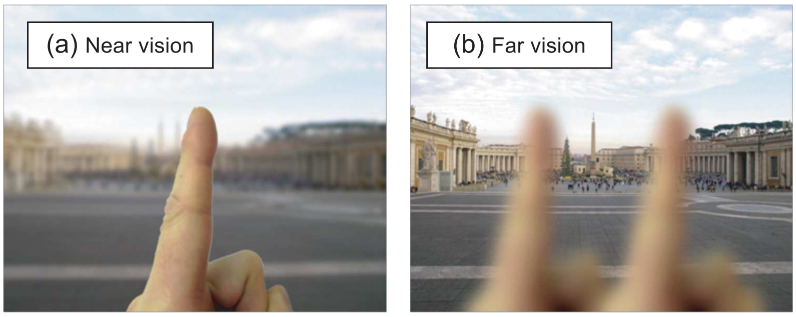


Fig. B.1. Binocular parallax. (a) Near vision and (b) far vision.

body posture is controlled by labyrinthine reflex and optical righting reflex, respectively (Fig. A.1). Some of the reflexes and neuroanatomy have been defined and illustrated separately (Morningstar *et al.*, 2005). However, collective reflex and their interactions have not been elucidated although a corporative effect was seen in their relationship between head movement and the movement of the center of gravity (Sakaguchi *et al.*, 1995). By showing a stereoscopic movie to the subjects, Takeda *et al.* verified that there is a corporative correlation between the head movement and the sway (Takeda *et al.*, 1995).

We herein introduce a new technology to construct stereoscopic movies (Power 3D). The new technology (Nishihara and Tahara, 2001) sets each camera axis as well as human beings that change the vergence angle corresponding to the visual distance of subjects for photography (Fig. A.2). Moreover, camera axes are also set to be parallel as well as natural binocular vision in order to construct background (Figs. A.2(a) and (b)). These elements of far/near visions are superimposed on the flame (Fig. A.2(c)). Viewers might not feel a sense of incongruity if they gazed at any elements in the flame. This technology has already applied to "Eyesight-Recovering Stereoscopic Movie System" produced by Olympus Visual Communications Co., Ltd.

Appendix B. Binocular Parallax

Human beings perceive three-dimensional (3-D) objects by the simultaneous vergence and lens accommodation in natural binocular vision. The depth of vergence and accommodation agreed under natural viewing conditions. They also perceive virtual images by the same mechanism. A general stereoscopic view is obtained by using the binocular parallax (Fig. B.1).

Parallax is an apparent displacement or difference in the apparent position of an object viewed along 2 different lines of sight. Exaggerated convergence, as mentioned below, is termed cross-eyed viewing (for example, focusing on the nose). As shown in Fig. B.1(a), a double background is seen during cross-eyed viewing. When looking into the distance, the eyes diverge until their lines of sight are parallel, effectively fixating the same point at infinity. In this case, 2 fingers are seen (Fig. B.1(b)).

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