Simultaneous measurement of lens accommodation and convergence in natural and artificial 3D vision

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Abstract — Recent advances in 3D technology have been accompanied by increasing complaints of visual fatigue. The usual explanation for such fatigue is that accommodation and convergence are mismatched during stereoscopic vision.

The aim of this study was to measure fixation distances between lens accommodation and convergence in young subjects while they viewed real objects and 3D video clips. Measurements were made using an original instrument. The 3D video clips were presented to subjects using a liquid crystal shutter glass system. The results showed that when viewing real objects, the diopter values of subjects' accommodation and convergence were similar and changed periodically. This measurement method was thus considered to be appropriate for the measurement of stereoscopic vision. We also investigated lens accommodation and convergence when subjects viewed 3D video clips. Both accommodation and convergence were found to move along with the virtual position of 3D video clips. Therefore, there was little discrepancy between accommodation and convergence during the viewing of 3D images.

Keywords *— simultaneous measurement, accommodation, convergence, 3D, stereoscopic vision.*

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1 Objective and Background

Advanced three-dimensional (3D) displays such as those used in 3D films and televisions are becoming increasingly common today. Manufacturers of electric appliances, aiming at market expansion, are strengthening their lines of products with 3D digital devices. Stereoscopic vision devices can deliver more information than conventional two-dimensional displays. This ability to deliver greater volumes of information may be one reason for the development of 3D technology. However, when viewing stereoscopic images, people sometimes feel visual fatigue, 3D sickness, or other discomfort.[1]

Lens accommodation and convergence are important systems in human vision. Toates reviewed accommodation and vergence and noted that accommodation involves focusing the eyes so that a target is seen clearly, whereas vergence entails moving the eyes so that the two eyes foveate the same object. Accommodation is achieved as a result of the action of the *musculus ciliaris* of the eye and the elasticity of the lens. The result is that an image in the external world is focused on the retina (Fig. 1). Vergence is the simultaneous movement of both eyes in opposite directions (either toward or away from each other) to obtain or maintain single binocular vision. Convergence is movement where both eyes rotate internally and vice versa (Fig. 2).

The relationship between accommodation and convergence is one factor that enables humans to see one object with both eyes. Toates[2,3] said that the proximity of the target appears to be able to cause vergence and that accommodation, to be a specific accommodative effort, is associated with innervation to vergence. Accommodation and vergence are mutually interacting control systems. It is possible under normal conditions for accommodation to depend on convergence to a certain extent.

Convergence occurs when an image is captured differently with both eyes (parallax). This is one of the main methods of presenting 3D images, for example, in liquid crystal shutter systems, lenticular systems, and polarized filter systems. It is an area where many improvements have been made.[4,5]

As the use of 3D has increased, many studies have been carried out on stereoscopic vision. In many of these studies, it is considered that lens accommodation and convergence are inconsistent during the viewing of 3D images (Fig. 3), with lens accommodation always fixed on the screen where

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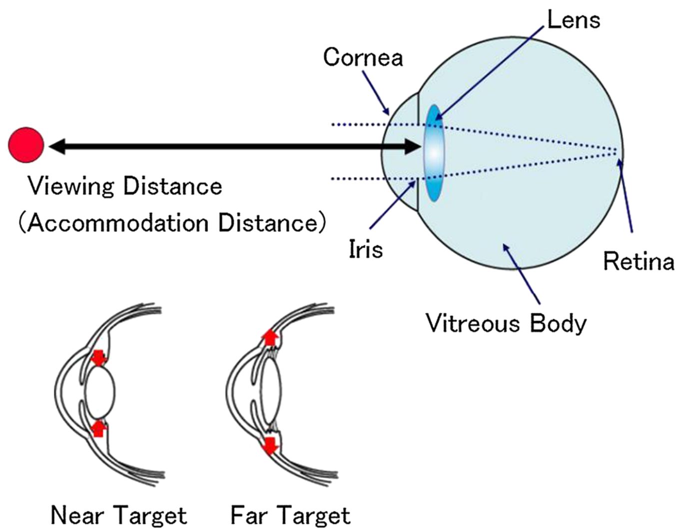

FIGURE 1 — Principle of lens accommodation.

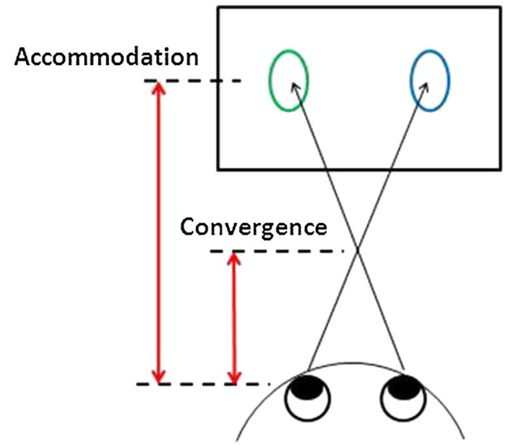

FIGURE 3 — Inconsistency between lens accommodation and convergence.

the image is displayed while convergence intersects at the position of the stereo images. As a result, eye fatigue and other related symptoms occur.[6,7] This view of inconsistency between lens accommodation and convergence is very well known.

However, as in a few other studies, we previously obtained results indicating that this presumed inconsistency between accommodation and convergence does not occur.[8] Patterson found that while a conflict in accommodation–vergence may exist for the viewer of such images, such problems would likely only occur with a display near to the eye because the depth of field is small with short viewing distances. Patterson also showed that the accommodation–vergence conflict would likely not occur under most conditions of viewing stereoscopic displays because of the depth of field.[9–12] The measurements performed in our previous study were in the range of the depth of field and thus concur with Patterson's findings.

We could not simultaneously measure accommodation and convergence in our previous study. In order to further investigate the discrepancy between accommodation and convergence, however, such measurements are needed. We therefore developed a method to simultaneously measure accommodation and convergence.

In investigating artificial stereoscopic vision, a comparison with accurate measurements with natural vision is essential. We therefore made simultaneous, accurate measurements of lens accommodation and convergence in natural vision. We then performed similar simultaneous measurements in subjects viewing 3D images and investigated whether a discrepancy between lens accommodation and convergence exists.

2 Methods

We conducted two experiments. The first experiment was performed in order to confirm whether this method of simultaneous measurement can be carried out accurately. The second experiment was performed to investigate whether a discrepancy between lens accommodation and convergence exists when subjects viewed 3D video clips. The devices used in

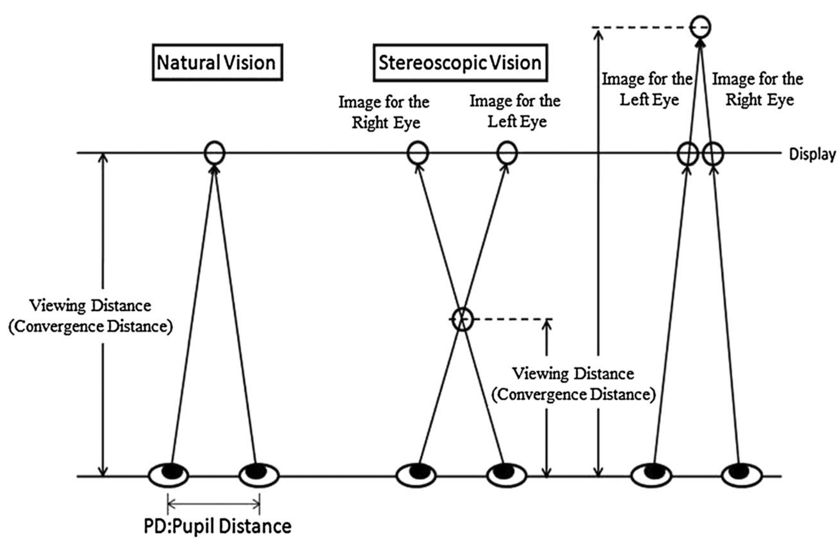

FIGURE 2 — Principle of convergence.

these experiments were an auto ref/keratometer, WAM-5500 (SHIGIYA MACHINERY WORKS LTD., Hiroshima, Japan; Fig. 4) and an eye mark recorder, EMR-9 (NAC Image Technology Inc., Tokyo, Japan; Fig. 5).

The WAM-5500 provides an open binocular field of view while a subject is looking at a fixed distant target. This instrument has two measurement modes: a static mode and a dynamic mode. We used the dynamic mode in this experiment. The WAM-5500 calculates refractive error in two stages. A ring target of infrared light is imaged after reflection off the retina. The wavelength of the infrared light is 950 nm. On the initial measurement, a lens is rapidly moved on a motorized track to place the ring approximately in focus. The image of the ring target is then analyzed digitally, on these initial and subsequent measurements, in multiple meridians to calculate the toroidal refractive prescription.

The manufacturer's supplied model eye (of power −4.50 D) assisted in evaluating the accuracy of the WAM-5500 in measuring refraction in the dynamic mode of operation. The WAM-5500 was set to hi-speed (continuous recording), allowing for refractive data collection at a temporal resolution of 5 Hz. The software recorded results in dynamic mode, including time for the reading of each pupil size (in seconds) and the mean spherical equivalent refraction in the form of an Excel comma-separated values file.[13,14]

Meanwhile, the EMR-9 was used to measure the eye movement with the pupillary/corneal reflex method. The horizontal measurement range was 40°, the vertical range was 20°, and the sampling rate was 60 Hz. This instrument consisted of two video cameras fixed to the left and right sides of the subject's face, plus another camera (field-shooting unit) fixed to the top of the forehead. Infrared light sources were positioned in front of each lower eyelid. The side cameras recorded infrared light reflected from the cornea of each eye, while the camera on top of the forehead recorded pictures shown on the screen. A camera controller superimposed these three recordings with a 0.01-s electronic timer and combined them onto a memory card. The EMR-9 scored eye movement greater than 1° and with a duration of greater than 0.1 s. The instrument also defined the gaze time when exceeding 0.1 s. This technique enabled us to determine eye fixation points. The wavelength of the infrared light was 850 nm, whereas that of WAM-5500 was 950 nm. All of these data were preserved on an SD memory card and then read into a personal computer.[15,16]

FIGURE 5 — EMR-9, eye mark recorder.

FIGURE 4 — WAM-5500, auto ref/keratometer.

Subjects were given a full explanation of the experiment in advance, and consent was obtained. Subjects used uncorrected vision or wore soft contact lenses or glasses as needed, and their refraction was corrected to within ±0.25 diopter. (A diopter (D) is the refractive index of a lens and an index of accommodation power. It is the inverse of meters; for example, 0 D stands for infinity, 0.5 D stands for 2 m, 1 D stands for 1 m, 1.5 D stands for 0.67 m, 2 D stands for 0.5 m, and 2.5 D stands for 0.4 m.) The two devices (WAM-5500 and EMR-9) were combined to measure accommodation and convergence simultaneously. We measured the focal distances of accommodation and convergence at the same time while subjects gazed at objects with the two devices (Fig. 6).

2.1 Simultaneous measurement of accommodation and convergence of real objects

The first experiment included six healthy young men (age: 20–37 years). The experiment was conducted according to the following procedures. The accommodation and convergence of the subjects were measured as they gazed in binocular vision at an object (tennis ball: diameter 6.6 cm) presented in front of them. The initial position of the object was 1 m from the subject to match conditions of the experiment with stereoscopic vision. The object started from an original position of 1 m (1 D) from the subject, moved 0.5 m (2 D) toward the subject, and then back to the original position of 1 m. The range of this movement was equivalent to 1 diopter, so this binocular target provided a sufficient stimulus for accommodation. This movement was repeated four times per measurement, totaling 40 s. A WMT-1 system (Grand Seiko Co. Ltd., Hiroshima, Japan) was used to move the tennis ball (Fig. 7). This device is a transfer machine and can move visual targets in a sine curve, chopping waves, or step movement. In the present study, we used the sine curve movement. The illuminance of the experiment was based on the ISO standard. The subjects' eyes received 103 lx (vertical illuminance), while horizontal illuminance was 683 lx. The luminance of the tennis ball in this environment was 46.9 cd/m^2. The luminance of the background was 56.7 cd/m^2 and resulted in a contrast ratio of 0.173.

2.2 Simultaneous measurement of lens accommodation and convergence of 3D video clips

Another experiment was performed with six healthy young men (same subjects as in Experiment 1). As with the previous experiment, subjects' accommodation and convergence were measured when they gazed at the spherical object on the LCD monitor in binocular vision and at a 3D video clip presented in front of them. A stereoscopic 3D video clip

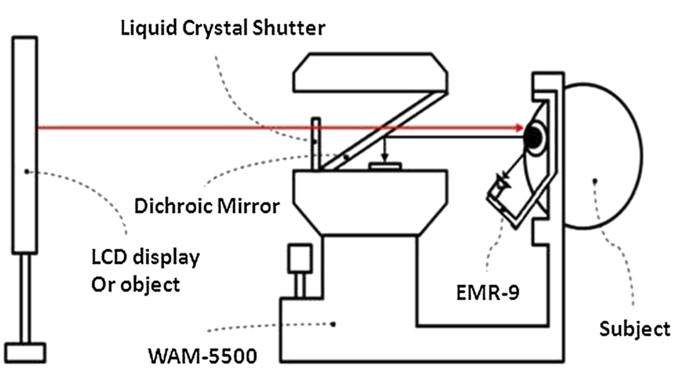

FIGURE 6 — The diagram of experiments.

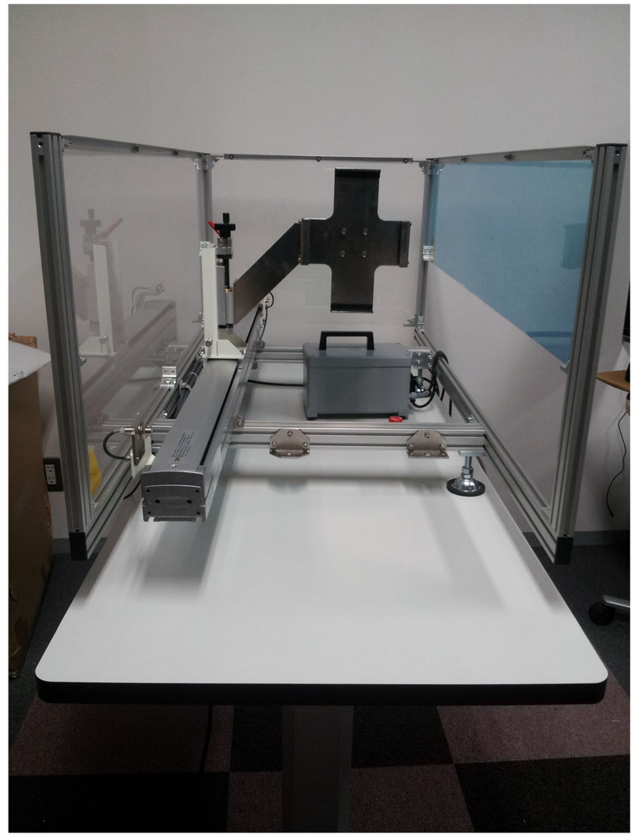

FIGURE 7 — WMT-1, instrument moving the visual target.

showed a similar motion to that of the real objects with a cycle of 10 s (Fig. 8). The LCD monitor was placed at 1 m from the subjects. A liquid crystal shutter system, 19-in. monitor (FlexScanS1911, EIZO Inc., Cypress, CA) was used in this experiment. The performance of this monitor is shown in Table 1.

Fujine *et al.*[17,18] suggested that the viewing distance should be a minimum of three times the absolute display height. We decided to follow this recommendation as part of our procedure. As shown in Table 1, the height of the monitor was 33.4 cm, or one-third of the height of 1 m (the viewing distance). The angle of convergence was 8.2° at the nearest position (about 45 cm from the subject, when the subjects' inter-pupillary distance (IPD) was 65 mm) and 3.7° at the farthest (1 m from the subject with the aforementioned pupil distance).

Four measurements were made for each subject as they viewed the moving object for 40 s. During this time, subjects were asked to gaze at the center of the virtual target. Their accommodation and convergence were then measured. The illuminance of the environment was the same as in the first experiment. The monitor slightly changed the luminance of the spherical object in the 3D video clips. The luminance of the virtual target was 3.1 cd/m^2 when it moved closest to the subject and 3.6 cd/m^2 at the furthest point. The luminance of the screen background was 10.8 cd/m^2 and resulted in a contrast ratio of 0.667.

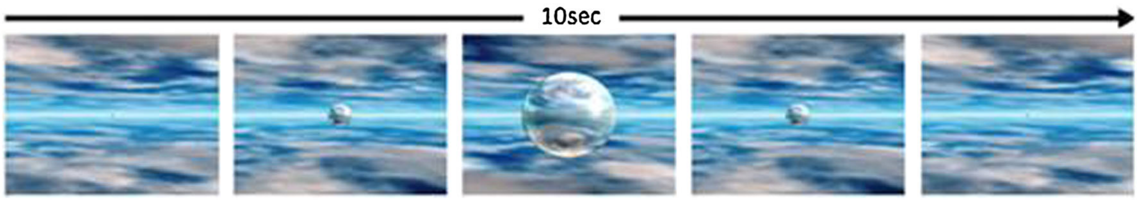

FIGURE 8 — 3D video clips.

TABLE 1 — Display performance.

Characteristics	Value
Screen resolution	1280 × 1024
Color usage	16,190,000
Size	19 in.
Pixel pitch	0.294 × 0.294 mm
Contrast	700:1
Frame rate	29.97 fps
Antialiasing	No
Refresh rate	75 Hz
Height	33.4 cm
Width	40.5 cm

Note: The shutter glass used in this paper was made by Sharp Corporation. The viewer can see 1000 times greater luminance through the light shutter than a dark shutter. Thus, the effect of cross-talk is negligible.

3 Results

In this study, we simultaneously measured the accommodation and convergence of subjects while they were gazing at real objects and 3D video clips in binocular vision. The results of these measurements were roughly similar for all subjects.

3.1 Simultaneous measurement of accommodation and convergence of real objects

The results of this experiment are shown in Figs. 9 and 10, whereas the average for all subjects is seen in Fig. 11. In all of these figures, "accommodation" and "ac_ave" refer to focal length of lens accommodation; "convergence" and "con_ave" refer to convergence distance; and "spherical object" refers to the location of the object. These figures show that the accommodation and convergence of subjects changed in agreement. The change in the diopter value occurred within a cycle of 10 s. Moreover, the value nearly agreed with the distance from the subject to the object.

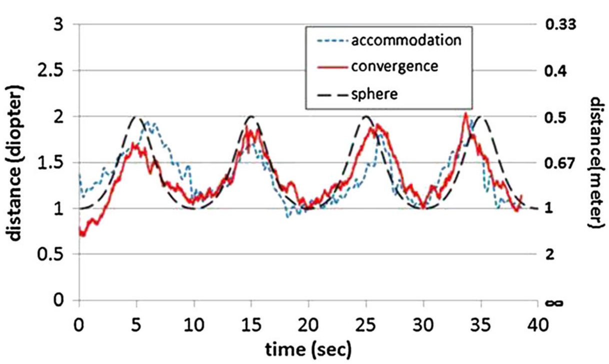

FIGURE 9 — Typical example of simultaneous measurement of lens accommodation and convergence for real objects (age 22 years, male).

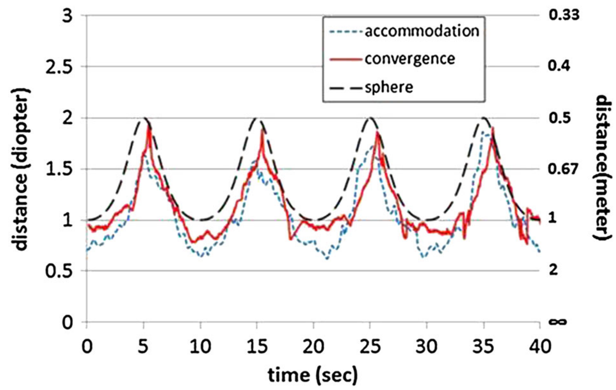

FIGURE 10 — Typical example of simultaneous measurement of lens accommodation and convergence for real objects (age 25 years, male).

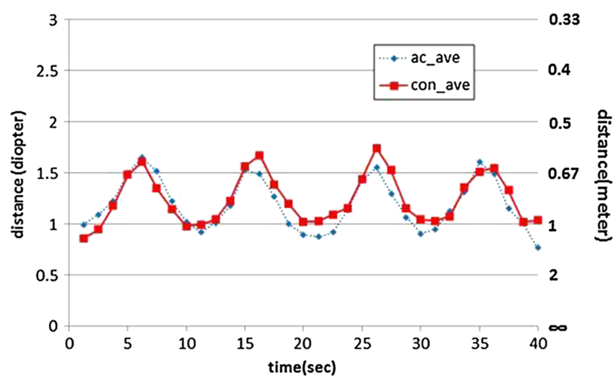

FIGURE 11 — Average of simultaneous measurement of lens accommodation and convergence in all subjects for real objects.

3.2 Simultaneous measurement of lens accommodation and convergence of 3D video clips

The results of this experiment are shown in Figs. 12 and 13, whereas the average for all subjects is seen in Fig. 14. In all of these figures, "spherical object" refers to the location of the virtual position of the spherical object in 3D video clips. In Figs. 12 and 13, "accommodation" and "convergence" refer to lens accommodation and convergence distance, respectively. In Fig. 14, "ac_ave" and "con_ave" also refer to lens accommodation and convergence distance.

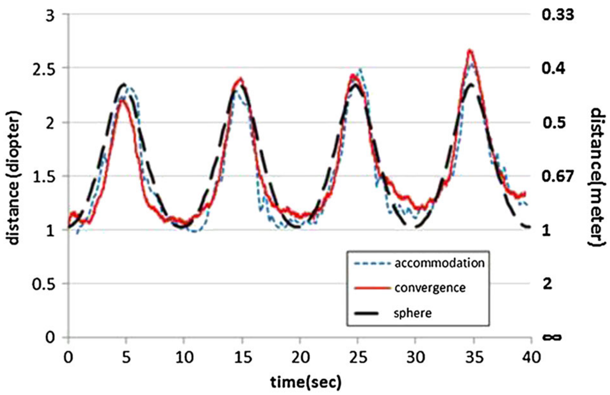

FIGURE 12 — Typical example of simultaneous measurement of lens accommodation and convergence for 3D video clips (age 23 years, male, IPD = 63 mm).

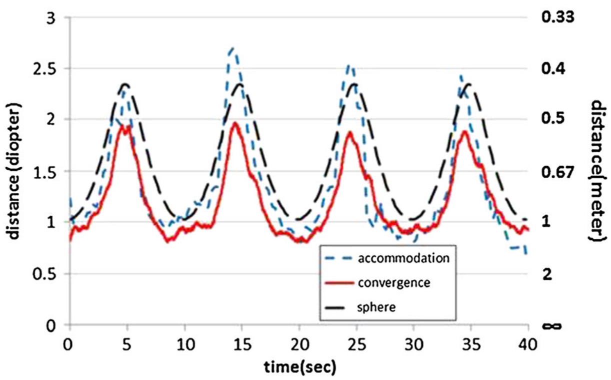

FIGURE 13 — Typical example of simultaneous measurement of lens accommodation and convergence for 3D video clips (age 25 years, male, IPD = 68 mm).

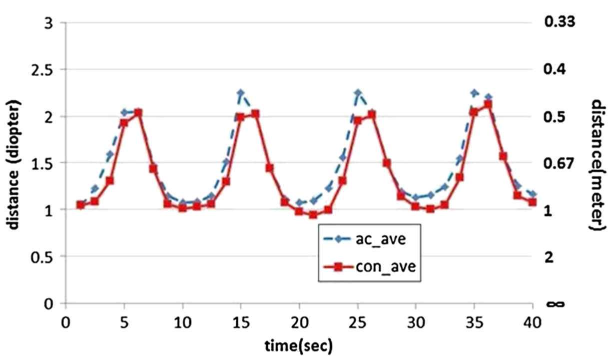

FIGURE 14 — Average of simultaneous measurement of lens accommodation and convergence in all subjects for 3D video clips.

In these graphs, the nearest virtual image position of 3D video clips varied slightly according to the difference of subjects' IPD. In Fig. 12, the nearest point was 44 cm, about 2.3 D, because IPD of this subject was 63 mm. In Fig. 13, the nearest point was 47.5 cm, about 2.1 D, because IPD of this subject was 68 mm. These figures show that the accommodation and convergence of subjects changed in agreement. The change in the diopter value occurred within a cycle of 10 s. Moreover, the value nearly agreed with the distance from the subject to the virtual position in 3D video clips. The agreement between accommodation and convergence is shown in Fig. 14. None of the subjects reported a blurred image.

4 Impact

4.1 Simultaneous measurement of accommodation and convergence of real objects

In this experiment, the WAM-5500 auto ref/keratometer was used to examine the accuracy of the accommodative power for each subject. It was previously shown experimentally that the WAM-5500 showed the accuracy of $-0.01\,D \pm 0.38\,D$, and it can take measurements within the range of -6.38 to $+4.88$ D.[14] The WAM-5500 has also been used in investigations of eyestrain and transient myopia[19,20] based on accommodative values. Moreover, the WAM-5500 has been used in investigations of lens accommodation response under near work conditions and visual discomfort over a year,[21,22] and its reliability was found to be sufficient.

The EMR-9 eye mark recorder used in this study has been employed in various types of past research. For example, Egami *et al*.[15] investigated differences in eye movement according to age, visual exhaustion, and learning effects after subjects were shown several kinds of pictures. Sasaki[16] predicted human eye movement from glance data obtained from an eye mark recorder and improved the operation of a support robot on the basis of this usage. Thus, many researchers have investigated various vision issues using the performance and characteristics of these instruments.

In this experiment, we measured the accommodative and convergent distance while subjects watched a real object. We calculated convergence distance on the basis of coordinated data for both eyes from the IPD.

The crystalline lens loses elasticity with age, and its refractive power also decreases. The clinically measured amplitude of accommodation, which includes both the true dioptric change in the power of the eye and ocular depth-of-focus, decreases fairly steadily from about 13 D at the age of 16 years to 2 D at the age of 50 years and thereafter.[23,24] People with severe myopia, hyperopia, or other conditions cannot accommodate accurately, but none of the subjects in this experiment had such problems. Thus, all subjects should have been able to accommodate for the real object, a tennis ball.

Furthermore, convergence may not be achieved in people with insufficient convergence, convergence palsy, or other conditions.[25–27] None of our subjects reported such conditions. Therefore, if our measurements were performed accurately, both accommodation and convergence should have agreed with the position of the real object.

Our results showed that the accommodation and convergence of subjects changed to the positions between the nearest and farthest points as the subjects gazed at the object. Moreover, these changes occurred at a constant cycle, tuned to the movement of the object. Therefore, subjects viewed the object with binocular vision, and we were able to measure the results.

Although these distances were nearly consistent with the distance from the subject to the object, they often were located a little beyond the object. This may stem from the fact that the subjects see the index even when the focus is not accurate because of the depth of field. The depth of field is the range that an individual can see clearly, and it has been investigated from various aspects for many years. The depth of field and the pupil diameter are related and have been found to vary with the illuminance of the surroundings.[10,28,29] On this point, the findings of this study appear to be nearly in agreement with our previous findings,[8,24] which indicate that the lens may not be accommodated strictly at about 0.4 D.

In conclusion, it was possible to simultaneously measure both accommodation and convergence when subjects gazed at an object. The present measurement method is an effective technique for the measurement of visual function, and correct values can be obtained even during stereoscopic vision. Following this step, we performed next simultaneous measurement of lens accommodation and convergence for stereoscopic vision, as described later.

4.2 Simultaneous measurement of lens accommodation and convergence of 3D video clips

Hoffman *et al*. stated that there is an inconsistency between accommodation and convergence.[6] According to their paper, lens accommodation in viewing 3D images would be fixed at the position of the display. However, they used a very short viewing distance (30 cm) that produced a small depth of field. Shibata *et al*. also reported an inconsistency between accommodation and convergence.[30] Their experimental stimuli were random dot stereograms depicting sinusoidal depth corrugations. They used a unique test stimulus that was a spatial-frequency modulated depth stimulus of small amplitude. They used random dot stereograms depicting sinusoidal depth corrugations. The amplitude was small (peak–trough disparity = 4 arcmin), and spatial frequency was high (1, 1.4, and 2 cpd). Their stimuli were displayed on two static image planes, spaced 1.2 D apart. Thus, neither of these studies actually measured accommodation and vergence in their subjects, whereas the present study did so. In contrast, we used Power 3D™ (Olympus Memory Works, Corp. Sasazuka, Shibuya-ku, Tokyo, Japan) for the stimulus in the present experiment. This imaging technique is able to show multiple focal planes corresponding to different focal lengths and convergence angles. It presents a very natural dynamic moving image made in consideration of the nature of the human eye. Therefore, the accommodation in the present experiment for artificial 3D closely followed the virtual position of the moving target, as if the image were a real moving object.

Other researchers have reported that an accommodation–vergence mismatch can create problems such as eyestrain and visual discomfort due to the discrepancy between accommodation and convergence.[2,3,31,32] However, in this experiment, we found no mismatch in accommodation and vergence, at least in the young subjects used.

According to our previous studies, accommodation does not agree strictly with the real object (also, with the virtual image) but does agree with a position slightly behind the object.[8,33] These studies showed that the gap of accommodation behind the object in young subjects was within 0.4 D. The gap in the present experiment was also in this range. When subjects viewed 3D video clips in this study, both accommodation and convergence nearly agreed with the virtual position of 3D video clips.

Patterson[9] reported that the accommodation–vergence conflict should be a problem only in near-eye displays and that it likely would not occur under most stereo display viewing conditions because of the depth of field.

Two factors that affect a person's perception of depth of field are pupil size and resolution.[9] A person's depth of field changes as the pupil diameter decreases linearly according to an increase in luminance.[34,35] Pupil diameter will be slightly over 6 mm for a luminance level of 0.03 cd/m^2 and near 2 mm for a luminance level of 300 cd/m^2. For each millimeter of decrease in pupil diameter, the depth of field increases by about 0.12 diopters.[9,11] The depth of field is also affected by the space resolution. Ogle and Schwartz found that the total depth of focus increased by approximately 0.35 diopters per 0.25 as the arcmin increased in the angular target size. These two researchers showed that the total depth of focus was an average of 0.66 diopters for a 1.0-arcmin target and 2.0 diopters for a 2-arcmin target.

Patterson[9] stated that the interval of depth of focus was on the order of 1.0 diopter on average. Therefore, when the gazing point is at 0.5 m, the range of total depth of field would be from a distance of about 0.1 m in front of a fixed point to about 0.17 m behind the fixed point. For a fixed distance of 1 m, the interval of the depth of field would be from a distance of about 0.33 m in front of the point to about 1.0 m behind the point. For a fixed distance of 2 m, the interval of the depth of field would be from about 1 m in front of the point to an infinite distance behind the fixed point. Wang *et al*.[12] also showed that the depth of field increased with age because of the constriction in pupil diameter. According to them, the typical values for young observers are approximately 0.8 D to 1.2 D in the depth of field. None of the subjects reported blurred images in the present study. This might be because the target was set in the depth of field range when a subject was viewing 3D images.

Patterson[9] and Patterson and Silzars[36] proposed that the eye strain and viewing discomfort that accompany the viewing of stereo displays come from a high level of conflict between the presence of binocular parallax in the display and the absence of motion parallax. In the future, we would like to study in more detail how this high level of conflict may contribute to visual fatigue, 3D sickness, or other discomfort in people who view 3D images.

5. Conclusions

In this study, we were able to simultaneously measure both lens accommodation and convergence when subjects viewed real objects. Using these methods, we measured accommodation and convergence distance when subjects viewed 3D video clips. The results showed that little discrepancy existed between accommodation and convergence in young subjects as they viewed 3D video clips. None of the subjects saw the images as blurred when they focused on the virtual position. On the basis of Patterson's findings and related studies, this lack of blurred images without mismatch between accommodation and convergence would be explained by the assumption that the variation of accommodation was within the range of the depth of field.

It is possible that lens accommodation is affected in other ways that in turn affect the accommodative cues of a subject. For example, the tips of a Rubik's cube may be used as a clearer accommodative cue than a spherical object. We plan to further investigate this in the future. In addition, we will need to examine the speed of the movement of the object and the change with illuminance of surroundings in order to further comprehend the mechanism of stereoscopic vision.

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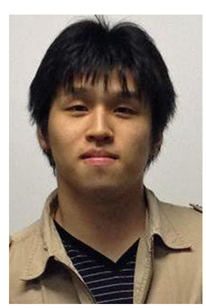

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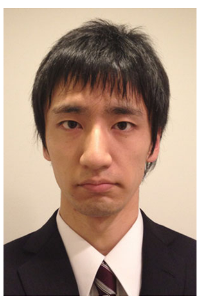

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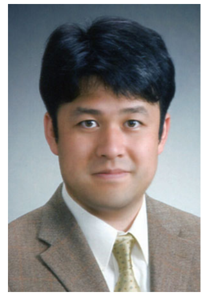

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