Comparison of Simultaneous Measurement of Lens Accommodation and Convergence in Stereoscopic Target with Sine Curve Movement

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Abstract—**Recently, many advances have been made in 3D technology. However, the influence of stereoscopic vision on human sight remains insufficiently understood. "Accommodation convergence discrepancy theory" states that when a person views stereoscopic images, a visual discrepancy occurs because convergence focuses at the position of the virtual object, while lens accommodation is fixed on the screen. It is widely accepted in the field that this is the main reason for visual fatigue caused while viewing 3D images. However, we have not found such a mismatch in experiments with young subjects. The aim in this study was to compare the fixation distance of accommodation and convergence in viewing real objects and 3D video clips. We measured accommodation and convergence in subjects who watched both real objects and 3D video clips with similar movements. From the result of this experiment, we found that no discrepancy exists in viewing either 3D video clips or real objects. We argue that the symptoms that occur when viewing stereoscopic vision may not be due to a discrepancy between lens accommodation and convergence. To compare the accommodative response and amplitude in different age groups, we fit the experimental results to the operation of a sine curve.**

Keywords- accommodation; convergence; simultaneous measurement; stereoscopic vision; depth of field; sine curve fitting

I. INTRODUCTION

Investigations of the influences of stereoscopic vision on the human body are essential in order to ensure safe and comfortable viewing of virtual 3D objects. In a previous study with associates, we verified that both convergence and lens accommodation are connected with the motion of the virtual object when viewing 3D images [1][2][3][4].

On the other hand, when viewing stereoscopic images, people sometimes feel visual fatigue, 3D sickness, or other discomfort [5]. And one of the main theories for the cause of this visual fatigue is still the "accommodation convergence discrepancy theory". According to this theory, when viewing 3D images lens accommodation remains fixed on the screen while convergence moves to the position of the virtual object [6][7].

The relationship between accommodation and convergence is one factor that enables humans to see one object with both eyes. Toates [8][9] said that the proximity of the target appears 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). The recent methods of 3-dimensional images, for example, liquid crystal shutter systems, lenticular systems, and polarized filter systems have improved to make it easier for human convergence. The latest technology in this area in visual 3D production has shown many improvements focusing on convergence [10][11].

We conducted these experiments and discussion shown below based on our previous work.

1. Lens accommodation was measured and compared with both a real object and a 3-D image.

2. More than 100 subjects were divided into four age groups and were tested. We applied the lens accommodative response data from these subjects to fit the operation of a sine curve. Then we summarized the fitting of the sine curve by age group. After this, we evaluated the accommodative ability or the delay in accommodative response by age.

3. Rejection of the "accommodation convergence discrepancy theory" leads to the question of whether the subjects saw blurred images when they focused on the virtual object instead of display. One reason for not seeing any blurring would be the existence of depth of field. When subjects watch the target, the pupil is contracted by the luminance. It is advantageous in order to obtain a deep depth of field [12][13].

II. MATERIALS AND METHODS

Explanation of the instrument used for the experiment and the experiment method was shown below.

A. Instruments

1) WAM-5500

We used the WAM-5500 by Shigiya Machinery Works, Ltd. in this experiment (Figure 1a).

This instrument can measure the refractive value (accommodation value) of a single eye when the subject gazes at a target of a given distance. It can measure pupil diameter continuously and monocular accommodation and pupillary diameter at a sampling interval of 0.2 seconds. The WAM-5500 has also been used in investigations of eyestrain and transient myopia [14][15] 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 [16][17], and its reliability was found to be sufficient.

2) EMR-9

The EMR-9 Eye Mark Recorder (NAC Image Technology Inc.) can measure the binocular scan paths (eye movements) using the pupillary/corneal reflex method. The resolution for eye movement is 0.1 degrees, with a measurement range of 40 degrees and sampling rate of 60 Hz. The convergent focus distance can be easily calculated from the obtained binocular eye movement data based on the calibration for 9 points (3×3), as shown in Figure 1b.

3) WMT-1

The WMT-1 by Shigiya Machinery Works, Ltd. is a target movement viewing system. It consists of a movable plate (about 1 m in length), a control device, and software that can be connected to a PC, and is the same as that of a numerical control (NC) robot.

By combining the WAM-5500 and WMT-1, we built a system to measure the accommodation value for a moving visual target. By connecting with the PC and having controls from exclusive communication software (WCS-1) (Figure 1c), it was possible to ascertain the position information for visual targets at 0.01-second intervals. Accommodation was measured continuously and pupil diameter was measured at 0.2 seconds intervals.

B. Methods

1) Experiment I. Simultaneous Measurement of Accommodation and Convergence for a 3D Video Clip in Diopter Sine Drive and Step Drive

For the simultaneous measurement of accommodation and convergence, we combined the WAM-5500 and EMR-9 and connected them with a link cable. We set the start times of the two data collecting devices.

The images used were from OLYMPUS Advanced POWER 3D™, which is a CG 3-dimensional video. The images were created using the stereo image fabrication technique from OLYMPUS Memory Works, Ltd. This technique involves the use of two cameras showing a background image, and two cameras showing an object in motion so that the views are superimposed (Figure 2).

In a previous study, we found that the reaction of the subject's lens accommodation with OLYMPUS Advanced POWER 3D shows a nearer value to natural vision than conventional 3D images [2].

Fujine et al. [18][19] 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. The specification of the display and the 3D image are shown in tables I and II).

For the first 10 seconds, subjects viewed a white circle in the center of a black screen. Then a moving sphere appeared, going back and forth between 1.0D (1 m) and 2.0D (50 cm). The subjects used binocular vision, and simultaneous measurements of accommodation and convergence were made with the WAM-5500 and the EMR-9, respectively.

There were three patterns of movement. The first pattern was a sine curve drive in a 10-second period for 30 seconds. The second pattern was a sine curve drive in a 2.5-second period for 10 seconds. The third pattern stopped for 10 seconds at distances of 1.0 D (1 m), 1.5 D (67 cm), and 2.0 D (50 cm) from the front of the eye of the subject (step drive). The order of precise stoppage was 1.0 D, 1.5 D, and 2.0 D.

The low-screen brightness was 12.7 cd/m^2 and the high-screen brightness was 70.4 cd/m^2. We measured the luminance in a white part of the sphere through a circular polarized filter and a dichroic mirror on the WAM-5500.

2) Experiment II. Simultaneous Measurement of Accommodation and Convergence for a Real Object in Sine Curve Drive and Step Drive

A Rubik's Cube was used as the real visual target because of its ease of recognition as a geometric form. This visual target was fixed to the movable plate of the WMT-1, and the PC controlled the movement of the target forward and backward. During measurement, the subjects were instructed to gaze at the visual target.

The PC recorded various data, including the time code from the measurement start time, the position information on

(a) WAM-5500 (b) EMR-9 (c) WMT-1 and WAM-5500

Figure 1. Instruments used in the experiments: (a) WAM-5500, (b) EMR-9, and (c) WMT-1 and WAM-5500.

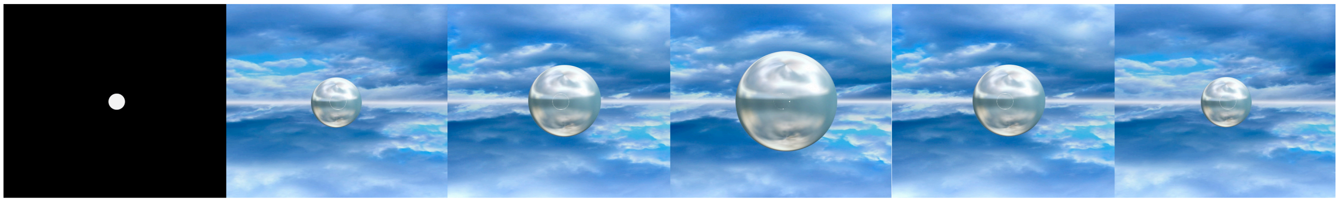

Figure 2. Movement of 3D images

TABLE I. SPECIFICATIONS FOR DISPLAY

System	Circularly Polarizing Filter (CPF)
Manufacturer	Mitsubishi
Model	RDT233WX-3D
Screen Size	23-Inch
Resolution	1920x1080
Refresh Rate	60Hz

TABLE II. SPECIFICATIONS FOR 3D IMAGES

Viewing Distance	1.0 m (1.0 D)
Interpupillary Distance Setting	60 mm
3D Data Format	Side by Side
Stereoscopic Effect (Popping)	In Front of Eye 50 cm (2.0 D) Parallax Angle 3.5°
Stereoscopic Effect (Retraction)	In Front of Eye 1.0 m (1.0 D) Parallax Angle 0°
Background	1.21 m (0.83 D)
Video Brightness	High Luminance
Screen Luminance (cd/m^2) (Over the grass)	70.4

the visual target from the WMT-1, the accommodation value and the pupil diameter from the WAM-5500. The WMT-1 was used in two movement patterns (the diopter-sine drive and the step-drive). The diopter-sine drive includes two different periods (10 and 2.5 seconds) of movement, the same as in Experiment I. The step drive suspended a real object for 10 seconds at three points: 1.0 D, 1.5 D, and 2.0 D, the same as in Experiment I.

3) Experiment III. Measurement of Accommodation for Diopter Sine Drive of Real Object and Fitting to a Sine Curve

We measured accommodative change while the subjects gazed at a moving object (the Rubik's Cube). At this time, the subjects were asked to gaze at the center of the Rubik's Cube. The moving object oscillated between 1.0D and 2.0D from the front of the eye of the subject.

There were two patterns of movement, as in Experiment I. The first pattern was a sine curve drive with a 10-seconds period for 30 seconds. The second pattern was a sine curve drive with a 2.5-seconds period for 10 seconds.

4) Subjects

For Experiments I and II, the subjects were seven individuals from the age of 21 to 47 years old who participated in the simultaneous measurement of accommodation and convergence when viewing the 3D video clip and real object.

For Experiment III, the subjects were 135 individuals from the age of 17 years old to 85 years old who participated in the accommodation measurement with the real object.

The subjects were divided into the following four groups: young (n=40, 17-29 years old), young-middle age (n=23, 30-44 years old), middle-aged (n=37, 45-64 years old), and the elderly (n=34, aged 65 and over).

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 to 2 D at the age of 50 and thereafter [20][21]. Therefore, these groups were divided according to visual function characteristics, especially accommodative ability. For example, the young group had sufficient accommodative power. The young-middle age group had somewhat weak accommodation power and does not suffer from presbyopia. They can clearly see close objects 20 to 30 cm from their eyes without much effort. The middle-aged group had mild difficulty in seeing near objects because of presbyopia.

In this group, some individuals wore glasses for near-sighted issues and others did not. The elderly group had severe presbyopia, so they generally wore convex glasses.

5) Method of Analysis for Experiment III

We selected samples that successfully measured two periods or more. Each datum was fitted to a sine curve. The processed data were averaged for each age group.

In the following equations, α represents the average, κ_0 represents half the amplitude, and κ_1 represents delay.

$$y = \alpha + \kappa_0 \cdot \sin(36 \cdot x + \kappa_1) \quad (1)$$

$$y = \alpha + \kappa_0 \cdot \sin(144 \cdot x + \kappa_1) \quad (2)$$

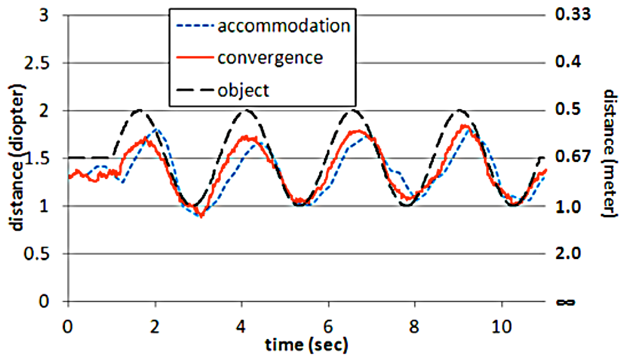

Figure 3. Simultaneous measurement values for accommodation and convergence with a real object (24-year-old male)

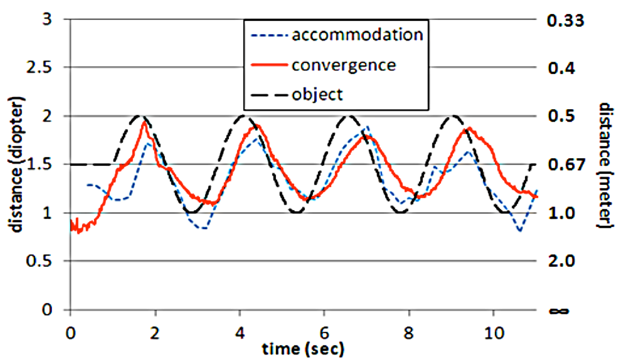

Figure 4. Simultaneous measurement values for accommodation and convergence with 3D images (24-year-old male)

Since the movement of the visual target was a sine curve, each subject's measurement data was fitted to the sine curve.

The Rsquare.exe of the software used a curved reliance panel with a least-squares method for fitting to a sine curve.

The amplitude and delay of the measurement data were totaled and averaged for every group, and modeling based on equations (1) and (2) which were performed for the 10-seconds period (1) and 2.5-seconds period (2).

6) Technical Limit of the Measuring Instrument

The sampling frequency of the WAM-5500 during operation is 5 Hz. This value is not sufficient to measure the frequency of accommodative reaction, especially in 2.5-second period movement. In the lower sampling rate, when measuring rapid reciprocating motion as a 2.5-seconds period, careful operation is required to obtain accurate measurements. (According to H. Anderson et al., the delay of an accommodative reaction is about 0.3 seconds [22]).

However, the time resolution for the accommodation value of WAM-5500 (0.2 seconds) is considered relatively low. Furthermore, since the pupil diameter becomes smaller with age, the measurement success rate with elderly subjects is reduced. Therefore, the number of samples decreases.

The data in this study were restricted to subjects in whom measurements were possible under the following conditions: visual performance is high and pupil diameter is sufficiently large.

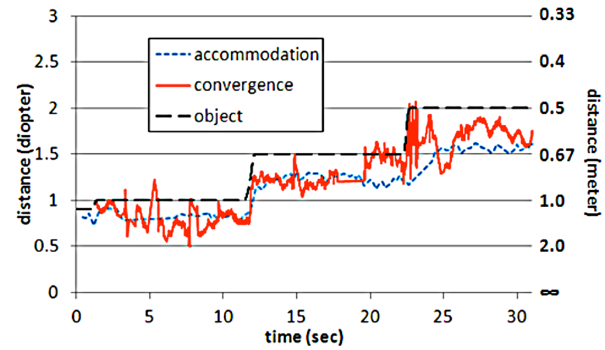

Figure 5. Simultaneous measurement values for accommodation and convergence with a real object in step movement (23-year-old male)

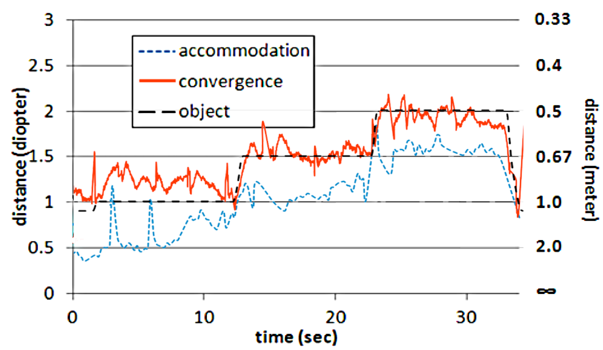

Figure 6. Simultaneous measurement values for accommodation and convergence with 3D images in step movement (24-year-old male)

III. RESULTS

The experiments I and II compared the real object with the 3-D image, and experiment III was based upon the age group.

A. Experiments I and II: Comparison of Accommodation and Convergence about Real and 3D Objects

1) Sine Curve Drive

In the case of the young subjects, convergence and accommodation were similar and synchronized for the movements of both real and 3D image objects. The convergence values were in agreement with the position of the visual target in a bright environment. The accommodative values were in a similar position to convergence or slightly distant from the visual target (Figures 3 and 4).

2) Step Drive (1.0D, 1.5D, and 2.0D)

Figure 5 shows the values of the simultaneous measurements of accommodation and convergence with the real object during the step drive. Figure 6 shows the simultaneous measurement values for accommodation and convergence with 3D images during the step drive.

In the case of the younger subjects, accommodation and convergence were similar for the step movements of both the real and 3D image objects. The convergence values were in agreement with the position of visual targets (real and virtual targets). Accommodative values were slightly further away from the visual target.

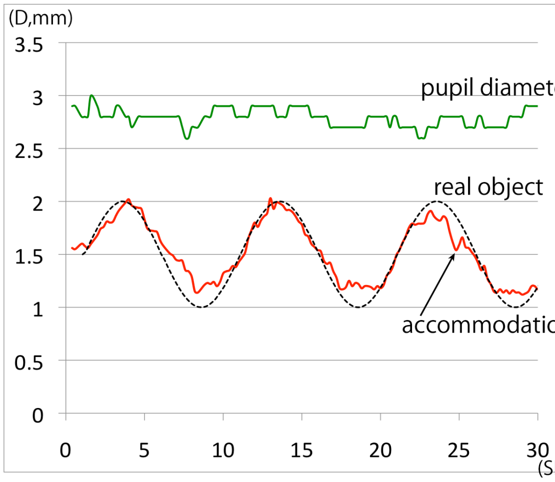

Figure 7. Typical example of younger subject, 10 seconds period (23-year-old male)

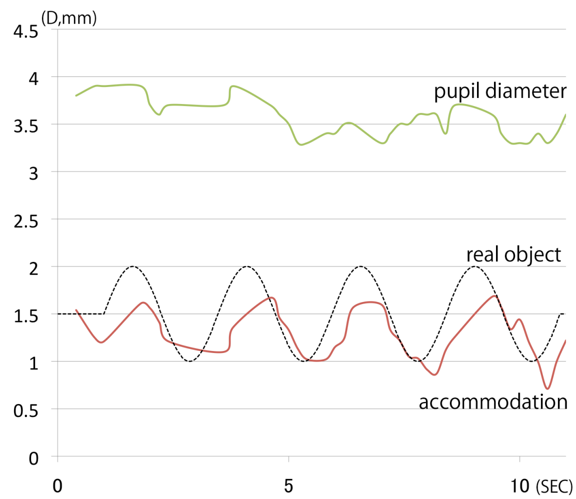

Figure 8. Typical example of younger subject, 2.5 seconds period (24-year-old male)

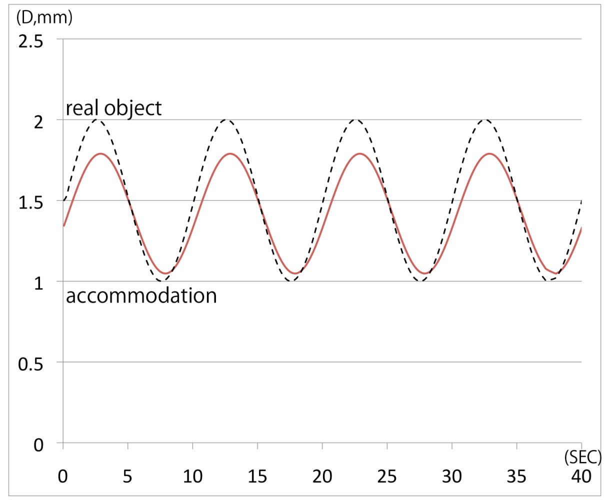

Figure 9. Younger subject fitting results, 10 seconds period

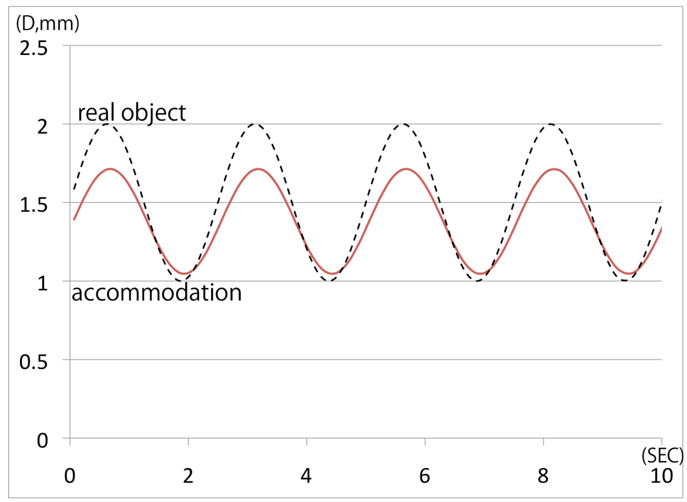

Figure 10. Younger subject fitting results, 2.5 seconds period

With both the real object and 3D images, lens accommodation had focused at a place 0.3-0.4D distant from the position of the visual target [4][21]. In step movement with 3D images, the value for accommodation moved clearly away from the visual target.

B. *Experiment III: Comparison between Age Groups of Lens Accommodation while Gazing at Sine Curve Movement of a Real Object*

1) *Younger Subjects (17-29 years of age)*

Figures 7 (10 seconds period) and 8 (2.5 seconds period) show the results for accommodation and pupil diameter in the younger subjects for sine curve real object movement.

The accommodation and pupil diameter values in 15 of 40 subjects are superimposed and averaged in Figure 9 (10 seconds period). Figure 10 shows an analysis of 20 of the 40 subjects (2.5 seconds period).

Figure 7 shows the results for a subject (23 years old, male) who viewed a visual target during a period of 10 seconds.

The values for accommodation matched those with the real object movement. On the other hand, the pupil diameter showed little variation, with a mean value of 2.8 mm.

Figure 8 shows of the results for a different subject (24 years old, male) who viewed visual target with a period of 2.5 seconds.

The values for lens accommodation were synchronized with the movement of the visual target. The visual target of the real object moved back and forth from 2.0 D (50 cm) to 1.0 D (1 m). The mean for the lens focus was recorded from 1.80 D (56 cm) to 0.87 D (1.15 m). The pupil diameter showed a slight variation with a similar phase to the sine curve movement of the visual target.

As explained in the Methods section, we used Rsquare.exe software, which performs a curved reliance panel using a least-squares method. It was fit to a sine curve.

Figure 9 shows the fitting results for the young subjects with a period of 10 seconds.

We superimposed the data of the 15 cases that were successfully measured out of 40 people.

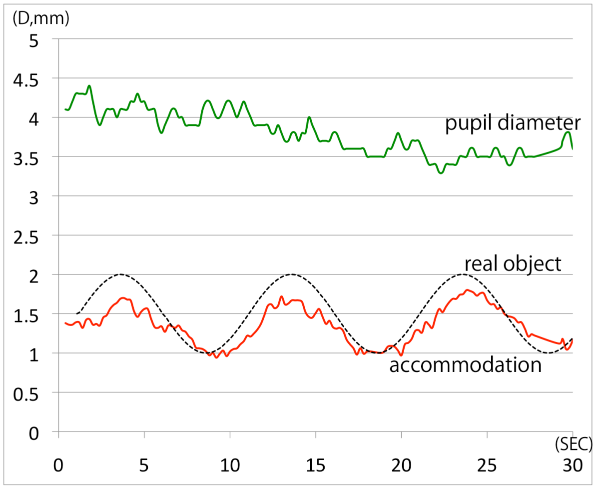

Figure 11. Typical example of young middle-aged subject, 10 seconds period (41-year-old male)

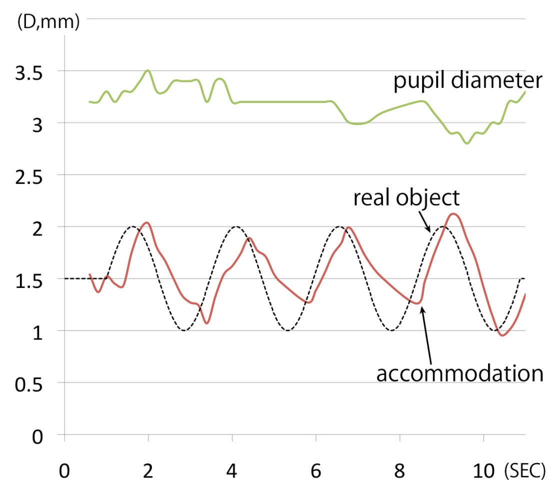

Figure 12. Typical example of young middle-aged subject, 2.5 seconds period (36-year-old female)

The calculated values of the sine curve fitting showed a movement of between 1.05 D (95 cm) and 1.80 D (56 cm). The value of the amplitude is reduced to 75% of the visual target, and the average value of the sine curve was reduced approximately 0.075 D. The delay was about 0.4 seconds for the visual target.

Figure 10 shows the fitting results for the young subjects with the period of 2.5 seconds. We superimposed data of the 20 cases that were successfully measured out of 40 people. The calculated values of the sine curve fitting were between 1.05 D (95 cm) and 1.70 D (59 cm). The value of the amplitude was reduced to 65% of the amplitude of the visual target (1.0-2.0 D), and the average value of the sine curve was reduced approximately 0.13 D. The delay was about 0.2 second against visual target.

2) Young Middle-aged Subjects (30−44 years old)

Figures 11 (10 seconds period) and 12 (2.5 seconds period) show the results of the accommodation and the pupil diameter for sine curve real object movement of the young middle-age subjects.

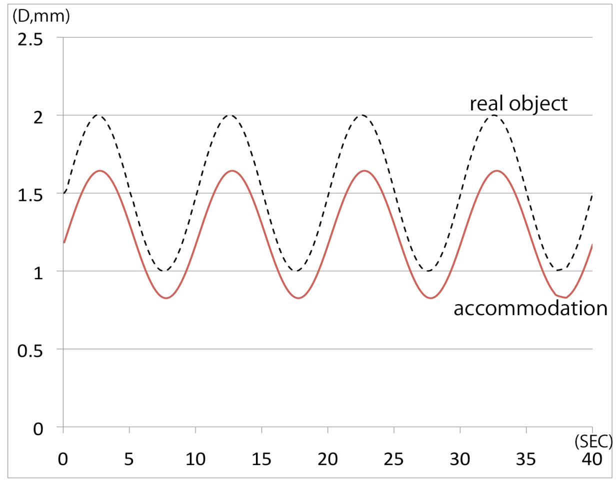

Figure 13. Young-middle subject fitting results, 10 seconds period

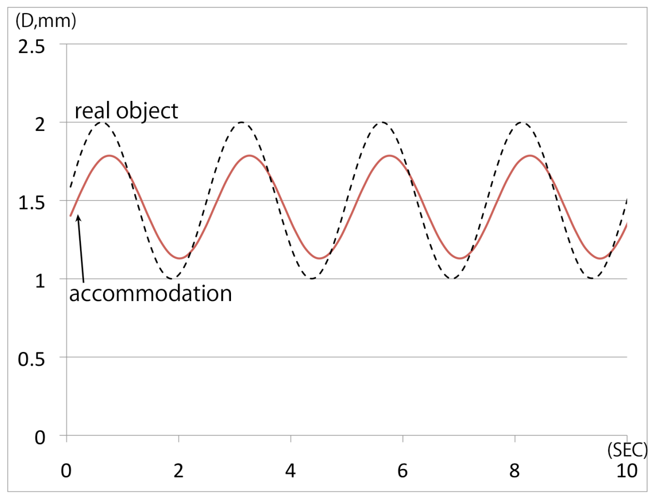

Figure 14. Young-middle subject fitting results, 2.5 seconds period

The accommodation and pupil diameter values in 10 subjects out of 23 were superimposed and averaged.

Figure 11 shows the example of one subject (41 years old, male) who viewed visual target with a 10-seconds period for 30 seconds. The values for accommodation were partially matched with the real object movement.

The values for accommodation were between 0.94 D (1.06 m) and 1.80 D (56 cm). The average value of the sine curve was reduced approximately 0.29 D. On the other hand, the pupil diameter showed little variation and had a mean value of 3.8 mm.

Figure 12 shows the results from a subject (36 years old, female) who viewed the visual target with a 2.5-seconds period for 10 seconds. The lens accommodation values were synchronized with the movement of the visual target.

The visual target of the real object moved back and forth from 1.0 D (1 m) to 2.0 D (50 cm). The mean lens focus (accommodation) was recorded from 0.96 D (1.04 m) to 2.11 D (47 cm). The pupil diameter showed no relation to the visual target. A characteristic reaction was seen during the 4th period.

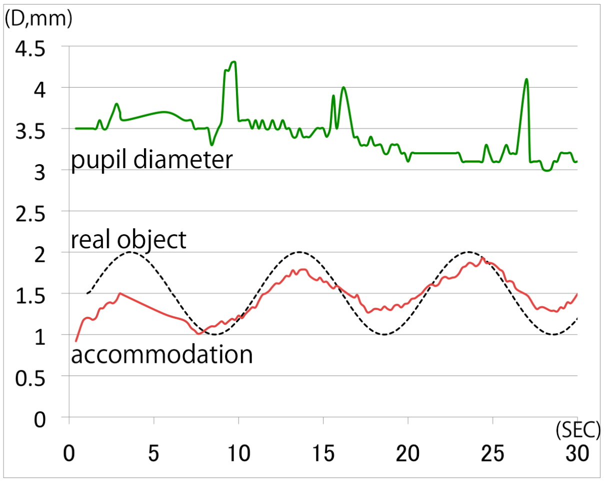

Figure 15. Typical example of middle-aged subject, 10 seconds period (46-year-old female)

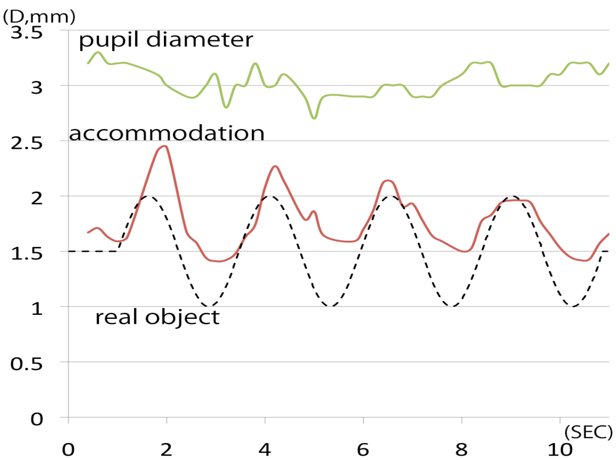

Figure 16. Typical example of middle-aged subject, 2.5 seconds period (46-year-old female)

The pupil seemed to be constricted pupil like in a near reaction.

Figure 13 shows the fitting results for the young middle-age subjects with the period of 10 seconds. We averaged the data of 10 cases in which measurements were successful.

The calculated values of the sine curve fitting moved back and forth between 0.83 D (1.20 m) and 1.64 D (61 cm). These values were reduced to 75 % of the amplitude of the visual target, and the average value of the sine curve was reduced approximately 0.27 D. The delay was about 0.3 seconds against the movement of the visual target.

Figure 14 shows the fitting results for the young middle-aged subjects with the period of 2.5 seconds. We averaged the data for 10 of 23 cases in which in the measurements were successful. The calculated values of the sine curve fitting moved back and forth between 1.13 D (88 cm) and 1.79 D (56 cm). The value of the amplitude is reduced to 75 % of the visual target. The delay was about 0.3 seconds against the movement of the visual target.

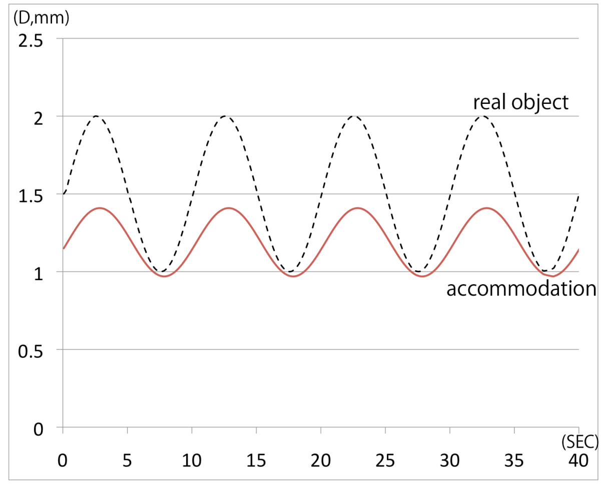

Figure 17. Middle-aged subject fitting results, 10 seconds period

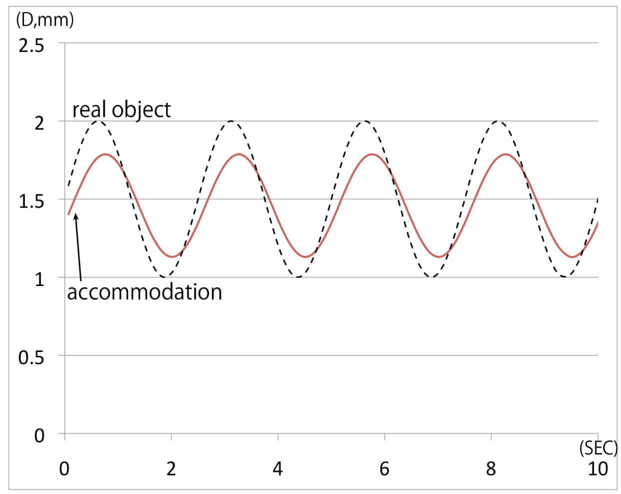

Figure 18. Middle-aged subject fitting results, 2.5 seconds period

3) Middle-aged Subjects (45−64 years old)

Figures 15 (10 seconds period) and 16 (2.5 seconds period) show the accommodation and pupil diameter results for sine curve real object movement for the middle-aged subjects.

The accommodation and pupil diameter values for 9 of 37 subjects were superimposed and averaged, as shown in Figures 15 (10 seconds period) and 16 (2.5 seconds period). Figure 15 shows an example of one subject (46 years old, female) who viewed the visual target with the period of 10 seconds. The values of accommodation were partially matched with the movement of the real object. The values of accommodation of the back and forth movement were between 1.20 D (83 m) and 1.80 D (56 cm). The pupil diameter showed little variation, with a mean value of 3.4 mm. Figure 16 shows an example of another subject (46 years old, female) who viewed the visual target for the period of 2.5 seconds. The values of lens accommodation were synchronized with the movement of the visual target.

The values of lens accommodation were synchronized with the movement of the visual target.

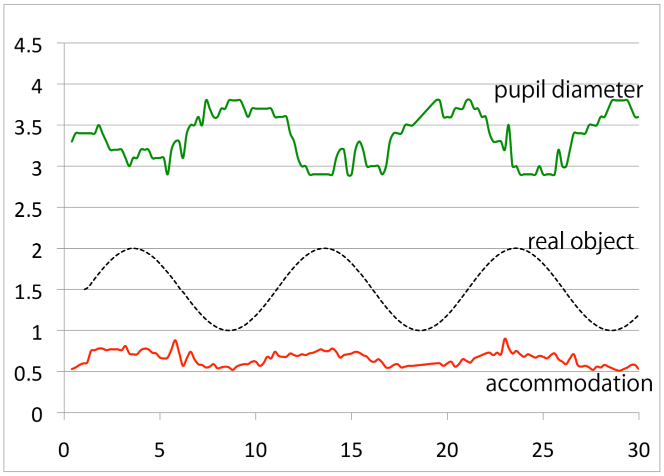

Figure 19. Typical example of elderly subject, 10 seconds period (72-year-old female)

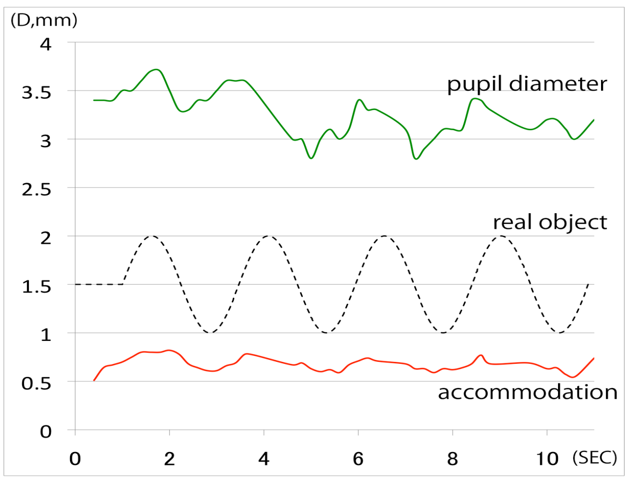

Figure 20. Typical example of elderly subject, 2.5 seconds period (72-year-old female)

The real object visual target moved back and forth from 1.0 D (1 m) to 2.0 D (50 cm). The mean lens focus (accommodation) for this movement was recorded from 1.5 D (67 cm) to 2.44 D (40 cm). The delay was about 0.2 seconds. The pupil diameter was nearly unrelated to the visual target. There seemed to be some pupil constriction that was a slight reflective reaction. This subject was near-sighted at about -1.25 D. The values of lens accommodation were synchronized with the movement of the visual target. The real object visual target moved back and forth from 1.0 D (1 m) to 2.0 D (50 cm). The mean lens focus (accommodation) for this movement was recorded from 1.5 D (67 cm) to 2.44 D (40 cm). The delay was about 0.2 seconds. The pupil diameter was nearly unrelated to the visual target. There seemed to be some pupil constriction that was a slight reflective reaction. This subject was near-sighted at approximately -1.25 D.

Figure 17 shows the fitting results for the middle-aged subjects for the period of 10 seconds. We superimposed the data for the 9 cases that were successfully measured among the 37 subjects.

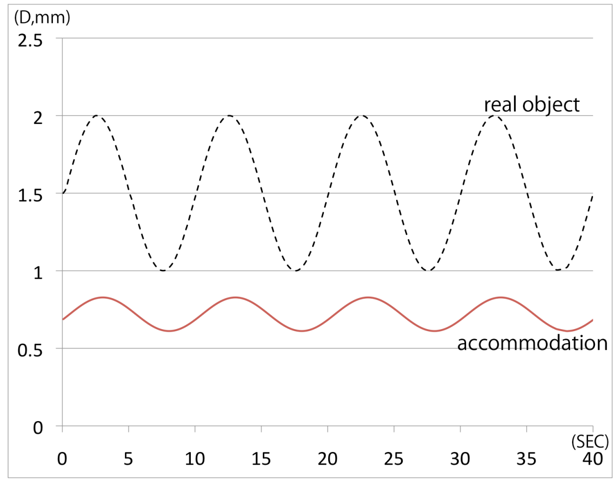

Figure 21. Elderly subject fitting results, 10 seconds period

TABLE III. FITTING RESULTS

Age	Period	Formula
17 - 29	10	y=1.42+0.37×sin(36×t-14.18)
	2.5	y=1.38+0.33×sin(144×t-7.84)
30 - 44	10	y=1.23+0.41×sin(36×t-9.72)
	2.5	y=1.46+0.32×sin(144×t-19.80)
45 - 64	10	y=1.19+0.22×sin(36×t-12.74)
	2.5	y=1.22+0.27×sin(144×t-10.64)
65 -	10	y=0.72+0.11×sin(36×t-19.68)
	2.5	y=0.80+0.14×sin(144×t+15.04)

The calculated values of the sine curve fitting showed that the back and forth movement was between 0.97 D (1.03 m) and 1.41 D (71 cm). The value of the amplitude was reduced to 44% of the visual target. The value of accommodation was reduced approximately 0.6 D on the near-point side. The delay was about 0.4 seconds against the movement of the visual target.

Figure 18 shows the fitting result for the middle-aged subjects with the period of 2.5 seconds. We superimposed data of the 9 cases that were successfully measured among the 37 subjects. The calculated values of the sine curve fitting showed back and forth movement between 0.95 D (1.05 m) and 1.50 D (67 cm). The value of the amplitude was reduced to 75 % of the visual target. The delay was about 0.2 seconds against the movement of the visual target.

Generally, people in their 40's suffer from presbyopia and need to use glasses. Therefore, almost all the subjects of this group were considered to be affected by presbyopia.

4) Eldery Subjects (Age 65 or More)

Figures 19 (10 seconds period) and 20 (2.5 seconds period) show the typical accommodation and pupil diameter results for sine curve real object movement in the elderly subjects. The accommodation and pupil diameter values for 4 out of 34 subjects were superimposed and averaged, as shown in Figure 21 (10 seconds period).

Figure 19 shows a typical subject (72 years old, female) who viewed the visual target for a period of 10 seconds. The values for accommodation were almost unchanged for the real object movement. The values for accommodation showed a very weak back and forth movement between 0.47 D (2.13 m) and 0.90 D (1.11 m). The pupil diameter showed typical synchronization with the distance of the visual target. When the target was close to the subject, the pupil diameter was about 2.8 mm. When the target moved away, the pupil diameter was about 3.8 mm. The elderly subjects seemed to compensate for their poor accommodative power by using extreme pupil constriction to capture close targets clearly.

Figure 20 shows a typical subject (72 years old, female) who viewed the visual target for the period 2.5 seconds. The values of lens accommodation were almost unchanged with the movement of the visual target. The mean of the lens focus (accommodation) showed a back and forth movement from 0.59 D (1.69 m) to 0.82 D (1.22 m). The delay was about 0.9 seconds. The pupil diameter showed typical synchronization with the distance of the visual target. When the target was close to the subject, the pupil diameter was about 2.8 mm. When the target was far away from the subject, the pupil diameter was about 3.6 mm. These subjects also used extreme pupil contraction to compensate for the reduction in their lens accommodation ability.

Figure 21 shows the fitting results of the elderly subjects for the period of 10 seconds. We superimposed data of the 4 cases that were successfully measured among the 34 subjects. The calculated values of the sine curve fitting showed a back and forth movement between 0.61 D (1.64 m) and 0.83 D (1.20 cm).

The value of the amplitude was reduced to 22 % of the visual target. The value of accommodation was reduced approximately 1.17 D on the near-point side. The delay was about 0.9 seconds against the movement of the visual target.

IV. Discussion

This section presents a discussion of experiments I and II (simultaneous measurement of accommodation and convergence) followed by a summation of experiment III (fitting to a sine curve).

A. *Experiments I and II: Comparison of Simultaneous Measurement Results of Lens Accommodation and Convergence*

Hoffman et al. stated that there is an inconsistency between accommodation and convergence, and they said that lens accommodation in viewing 3D images should be fixed at the position of the display [6]. 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 [23]. Their experimental stimuli were random dot stereograms depicting sinusoidal depth corrugations. . They used a unique test with a spatial-frequency modulated depth stimulus of small amplitude.

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. However, these two studies did not actually measure accommodation and convergence in their subjects simultaneously. In contrast, we used the Power 3D™ (Olympus Memory Works, Corp.) for the stimulus in this experiment. This technique involves the use of two cameras showing a background image, and two cameras showing an object in motion, so that the views are superimposed. It is able to show multiple focal planes corresponding to different focal lengths and convergence angles. It presents a very natural dynamic in the movement of the image in consideration of the natural human eye. Therefore, in our experiment, accommodation for the artificial 3D image 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-convergence discrepancy can create problems such as eyestrain and visual discomfort [8][9][24][25].

However, in this experiment, we found no mismatch in accommodation and convergence, at least in the younger subjects participating in the study.

According to our previous studies, accommodation does not agree strictly with a real object (or with a virtual image) but does agree with a position slightly behind the object [4][26]. Our past studies have shown that the accommodation gap behind the object in younger 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 the 3D video clips.

Experiment III: Amplitude of Accommodation According to Age with Real Object, and Average Delay

The data from the subjects were classified into four groups. For the 10 seconds period, the groups were young: 15/40, young middle-aged: 10/23, middle-aged: 9/37, and elderly: 4/34. For the 2.5 seconds period, they were young: 20/40, young middle-aged: 10/23, middle-aged: 9/37, and elderly: 3/34. Figures 9,10,13,14 and 21 show the fitting of the data to the sine curve for each subject, and the average of each amplitude and delay. In general, the amplitude for accommodation becomes smaller with age and the delay of accommodative response becomes longer [27][28]. The amplitude changes and becomes significantly smaller beginning in middle age. However, the delay for accommodative response was nearly the same at 0.3 seconds for all groups except the elderly group. The elderly group showed a notable delay of 0.9 seconds in accommodative response.

B. *Relation between Depth of Field and Blurring*

Patterson [29] reported that the accommodation convergence 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 [30].

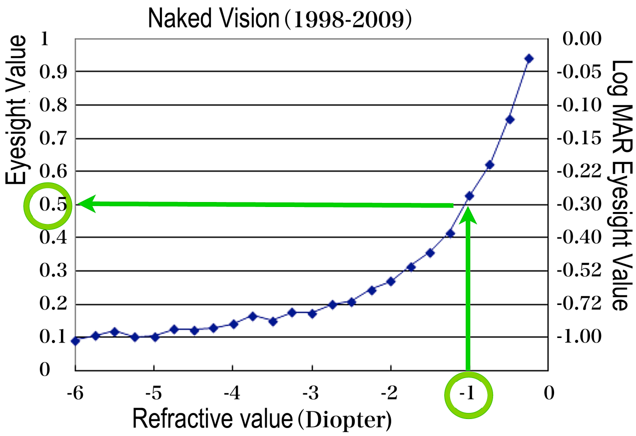

Figure 22. Acuity of fifth grade elementary school student without astigmatism

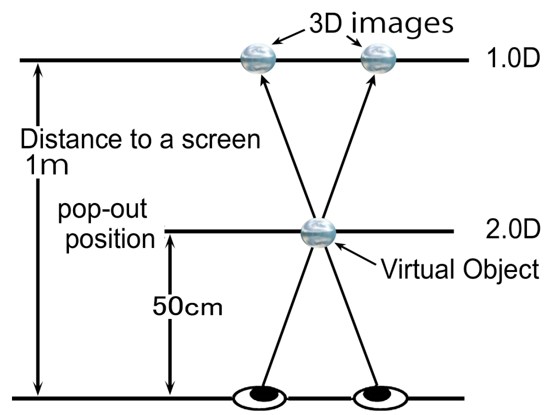

Figure 23. Lens accommodation focused at the pop-out position (50 cm apart from the display)

Two factors that affect a person's perception of depth of field are pupil size and resolution. A person's depth of field changes as the pupil diameter decreases linearly with an increase in luminance [31][32]. The 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 D [33][29]. The depth of field is also affected by the spatial resolution. Ogle and Schwartz [34] found that the total depth of focus increased by approximately 0.35 D per 0.25 as the arcmin increased in the angular target size. They showed that the total depth of focus was an average of 0.66 D for a 1.0-arcmin target and 2.0 D for a 2-arcmin target. In our experiment, the screen was set at 1.0 D (1 m) from the subject and the object emerged to the point of 2.0 D. Most of our subjects accommodated at 0.4 D behind the object at 1.6 D (93 cm). Typically, a perfect match for accommodation and convergence in such a case would be at 2.0 D (50 cm); however, most individuals would show lens accommodation at 0.4 D, which is the boundary point of the depth of field. The usual TV screen has a brightness of 300 cd/m^2. If the illumination occurs on an indoor screen, the diameter of a pupil will be about 2.0 mm, and the depth of field will be about ±0.5 D. None of the subjects in this study commented on any blurring.

C. *Relation between Refractive Power and Blurring*

When lens accommodation moves forward to the position of a virtual object when viewing a 3D image, the object displayed on the screen appears the same as the image, as if the person had myopia. Therefore, if the character is not too small it can be viewed satisfactorily [34]. For example, it is considered that if you focus the lens accommodation to a virtual object "popping out" 50 cm from the display at a viewing distance of 1 m, the image shown on the screen can be seen the same as an image viewed with a decimal visual acuity of 0.5 (refer to Figures 22 and 23).

Patterson [29] stated that the interval of the depth of field was on the order of 1.0 D on average.

Therefore, when a subject's 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 visual point. For a fixed distance of 2.0 m, the interval range 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. [35] also showed that the depth of field increased with age because of the constriction in pupil diameter. According to these authors, the typical depth of field values for young observers was approximately 0.8 D to 1.2 D. In our present study, none of the subjects reported blurred images. This might be because the target was set in the depth of field range when subjects were viewing 3D images.

V. CONCLUSION

In younger subjects, the real object and 3D image were interlocked with the movement of the object, without large deviation between accommodation and convergence, and the focus position changed.

Since the elasticity of the crystalline lens is lost with age and accommodative power decreases, there is a discrepancy between accommodation and convergence in the middle-aged and the elderly, even if it is a natural vision state. 3D images on a screen can be seen without much blurring even if the accommodation focus moves to the position of the virtual object when the 3D image visual target is popping out. Subjects can recognize an object with little or no blurring despite the separation of accommodation from the screen because the position of their focus is within the depth of field. Patterson [29] and Patterson and Silzars [36] proposed that the eyestrain and viewing discomfort that accompany the viewing of stereo displays comes 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.

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