ELSEVIER

Displays 23 (2002) 57–64

DISPLAYS

www.elsevier.com/locate/displa

Head mounted display

Takashi Shibata

Graduate School of Global Information and Telecommunication Studies, Waseda University, 29-7 Building, 1-3-10, Nishi-Waseda, Shinjuku-ku, Tokyo 169-0051, Japan

Abstract

This chapter describes head mounted displays (HMDs) from the viewpoint of the human factors. Because it has two separate display systems, HMDs are especially effective in displaying stereoscopic images. To develop better stereoscopic three-dimensional display technologies, it is important to investigate visual functions such as accommodation and convergence. From the results of the experiments, it is now possible to establish the proper settings for HMD devices to reduce the visual load. An example of the industrial application of an HMD is illustrated. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Head mounted displays; Accommodation; Convergence; Stereoscopic images; Simulation system

1. Features of HMD

Head mounted displays (HMDs) are image display units that are mounted on the head. A unit consists of a helmet and small CRTs or liquid-crystal displays (LCDs) in a pair of goggles. The field vision on the display screens is expanded by the optical system producing an imaginary screen that appears to be positioned several meters in front of the viewer. Some types are mounted on the face in the form of glasses. Development and improvement of the technical aspects of these systems have been recently carried out.

HMDs have the following features: (1) large, wide-ranging screens are possible for vision; (2) miniaturization and weight reduction are possible for usability; (3) utility is fundamentally depending on individual preference; (4) it is possible to present interactive spatial information; and (5) it is possible to superimpose the image on an external scene by means of see-through function. The uses of HMDs include image display for virtual reality, games for the amusement industry, and a personal theater system. HMDs are effectively used in simulation systems for virtual experience to improve the users concentration on images. For instance, the risk and accidents simulation system in Japan Advanced Information center of Safety and Health uses any simulation techniques (Fig. 1).

This system aims to give a user serious experience of risks and accidents that are unable to encounter in daily life. Fig. 2 illustrates the above system consisting of an HMD, data glove, data acquisition system of user's motion and a graphics workstation. The user observes stereoscopic three-dimensional images by an HMD, which are generated according to the user's position and motion acquired.

From the viewpoint of mounting the unit on the human head the development of an image presentation method that matches the head's motion [4], and the development of equipment for measuring and recording eye movement [11] are also being carried out, and utilization is expanding into new fields.

The points of the development are the ways to miniaturize and reduce the weight of the equipment, improve resolution, create wide fields of view, etc. An example of miniaturization and weight reduction is the Eye-Trek (OLYMPUS OPTICAL CO., LTD). This consists of a display and a control system. The weight of the head mounted display unit is about 85 g [2]. The Datavisor (n-vision, inc.) is an example of an HMD with high resolution and a wide viewing field. It is capable of 1280×1024 (SXGA) resolution and produces a wide, 120-degree field of view.

Though 640×480(VGA) and 800×600(SVGA) resolutions have recently become mainstream, it is difficult to simultaneously achieve miniaturization, high resolution, and a wide field of view. Optical systems and display devices must be developed according the intended application.

2. Stereoscopic image display using HMDs

HMDs are especially good at displaying stereoscopic images because they have two separate display systems. They can display one image for the right eye and one image for the left eye, a necessary condition for displaying binocular stereoscopic images like this. They are also nice

PII: S0141-9382(02)00010-0

Fig. 1. Views in the risk and accidents simulation system (Japan Advanced Information center of Safety and Health).

because they restrict the user's visual field by blocking the user's peripheral vision, thereby increasing the reality of the images. With HMDs, we can easily create interactive stereoscopic images that change in accordance with the user's head motion. The use of HMDs to display stereoscopic images should increase in this way.

When we develop a new display unit or display technique, we need to consider its effect on the human visual function. A display system that does not match the characteristics of human vision may cause visual overload, and possibly it may damage the user's vision [8]. To develop effective stereoscopic display units using HMDs, research

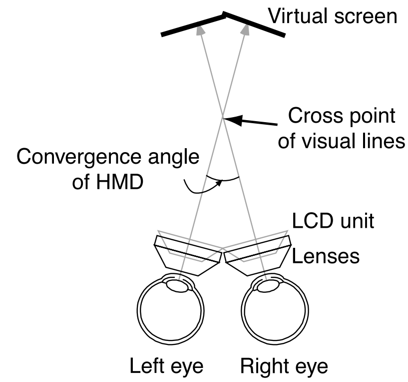

Fig. 3. Relationship between virtual screen, crossing point of visual lines, and convergence angle of an HMD. In this case, the cross point of the visual lines is not on the virtual screen.

whether these displays affect human visual function will become increasingly important or not.

From the viewpoint of the characteristics of human visual functions, HMDs have features that differ from those of conventional displays [9]. One is that someone using an HMD sees virtual images of displayed pictures through optical devices located in front of his or her eyes. The location of the images depends on the power of the lenses used in the optical system of the HMD and is related to the focus of the eyes. Another feature is that an HMD has two display units containing optical devices one for each eye. This means we need to adjust the distance and angle between the right and left optical devices [10]. The convergence angle of an HMD, which is the angle between the two display units affects the fixation point of the eyes. When we look at a picture on a conventional display, such as a CRT display the left visual line to the picture crosses the right visual line at the plane of the display. However, when using an HMD with the setup illustrated in Fig. 3, the left visual line crosses the right visual line at a point distant

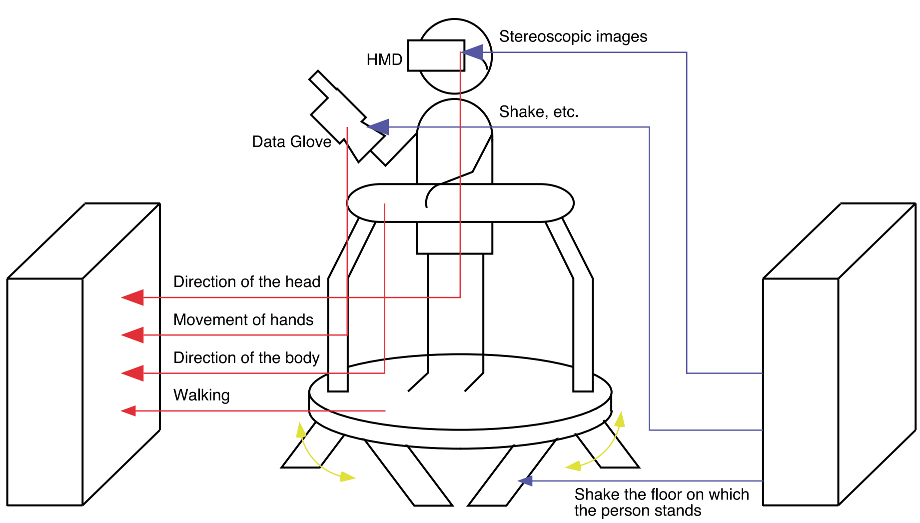

Fig. 2. System (Fig. 1) consisting of an HMD, data glove, data acquisition system of user's motion and a graphics workstation.

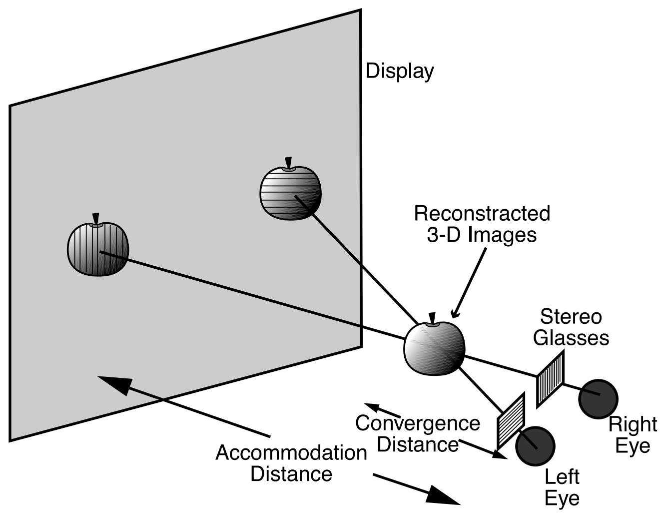

Fig. 4. Stereoscopic 3D display and the mismatch of distance between accommodation and convergence of the human eyes.

from the plane of the display. The crossing point provides distance information to the convergence function of the human eyes. Therefore, under the conditions illustrated in Fig. 3 the distance information given by the accommodation differs from that given by the convergence of the eyes. These visual conditions place a significant visual load on the eyes.

Furthermore, binocular stereoscopic 3D displays have problems related to the human visual functions [6]. A major problem with stereoscopic 3D displays is that they can produce a mismatch between the focus (accommodation distance) and the fixation (convergence distance) of human eyes. That is, stereoscopic 3D images may give different depth information to the accommodation and convergence functions [7].

Although an observer's convergence changes when the observer looks at reconstructed 3D images set at varying distances in a 3D display the required accommodation remains constant because the distance between the observer and the display screen is fixed (Fig. 4). This causes a mismatch in distance between accommodation and convergence. Such viewing conditions are significantly different from normal viewing conditions under which the planes of convergence and accommodation almost coincide. In addition, there is interaction between accommodation and convergence, and these mechanisms cannot be altered independently [5,12,14]. Therefore, the mismatch of accommodation and convergence in stereoscopic 3D displays might be one of the causes of visual fatigue related to viewing 3D images.

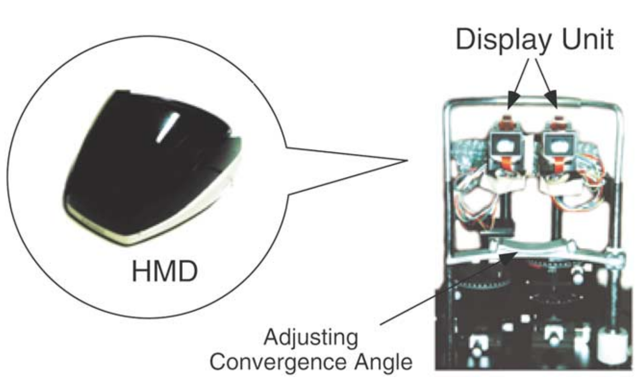

Fig. 5. An HMD used in the experiments consisted of two display units, each incorporating a liquid-crystal monitor and optical devices. The distance and angle of the two display units were adjustable.

The imbalance in visual information may be one of the reasons for the visual overload and visual fatigue associated with stereoscopic images. Studies on visual functions such as accommodation and convergence are needed before we can develop better stereoscopic 3D display technologies. Our previous studies, in which we used a stereoscopic display system showed significant changes in the responses of eye movements and accommodation after subjects viewed stereoscopic images [1,3,13].

This problem will also occur if we use an HMD for stereoscopic display because the problem is common to stereoscopic display systems. However, HMDs have features different from those of conventional stereoscopic displays. For example, images produced by HMDs are virtual images and HMDs cover an observer's visual field. Therefore, experimental studies are required to evaluate the visual load induced by viewing stereoscopic images through an HMD. Such studies would be of interest from the viewpoint of the visual sciences and would lead to the development of better stereoscopic display units.

3. Effects of HMDs on the visual function

We conducted two experiments to investigate the visual load induced when viewing stereoscopic images through an

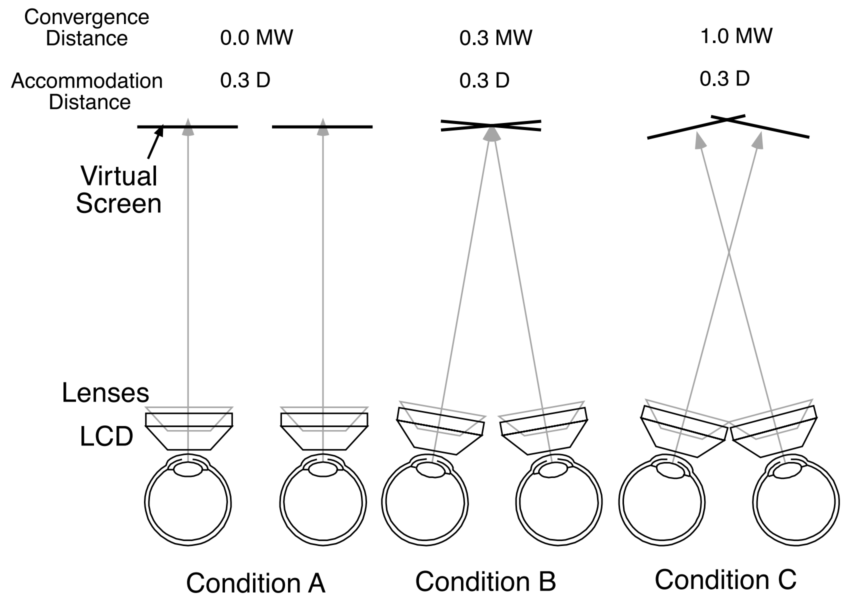

Fig. 6. The three settings of the two displays in Experiment 1. Under the conditions A and C the convergence distance differed from the accommodation distance. (MW: meter angle, D: diopter).

HMD. In the first experiment, we measured the visual load induced at three different convergence angles. In the second experiment, we investigated the changes in the visual load when the binocular disparities of the stereoscopic images were changed. The results of these experiments demonstrate the need to develop HMDs that is appropriate for human visual functions.

3.1. Display and stimulus images

An HMD used in our experiments is illustrated in Fig. 5. The distance between the two displays and their convergence angle were adjustable. Each display unit consisted of a LCD and optical lenses. The LCDs were 0.7 inches diagonally. The lenses were set between the LCD and the eye and had a power that established the perceived viewing distance of the display plane 3 m in front of the eye. The size of the virtual screen the virtual image of the LCD was about 97 inches diagonally and the horizontal viewing angle of the screen was 37 degrees.

The stimuli were binocular stereoscopic images generated and controlled by a personal computer (NEC PC9801NS/E) that had a 640×480 video-frame memory (Canopus CIM-1104). The video signals for the generated images were sent to the LCDs. The stimulus images were cubes and the stereoscopic distance of the images through the lenses distance from the subject was 3 m.

The subjects watched each stimulus image for 15 min. The color (red, green, blue) of the images changed randomly. To monitor the subject's attention, they were told to push a button when the color changed to red and their response time was recorded.

Table 1
Binocular disparity conditions in Experiment 2

Condition	Disparity between image and virtual screen of HMD (deg)
B2	1.0 (rear screen)
B1	0.5 (rear of screen)
N	0.0 (on screen)
F1	1.0 (front screen)
F2	2.5 (front screen)

3.2. Stimulus conditions

In the first experiment, three conditions for the convergence angle between the two display units were examined while the binocular disparity of the stimulus image and the power of the lenses were kept constant. The three conditions are illustrated in Fig. 6.

The setting of the optical devices under the condition A is used in many types of HMDs. The two displays are set parallel, and the power of the lenses is adjusted to place the virtual images several meters from the eyes. With this setting, the convergence distance (fixation distance) is theoretically different from the accommodation distance (focus distance) of human eyes. With the setting under the condition B the convergence distance is almost the same as the accommodation distance. The convergence distance is shorter than the accommodation distance under the condition C. The difference in the two distances is larger under the condition C than under the condition A, so the stereoscopic images perceived under the condition C are remarkably distorted. The distances of the two display units were adjusted in accordance with the measured distance between the eyes of each subject.

In the second experiment, five conditions for the binocular disparity of the displayed stereoscopic images were

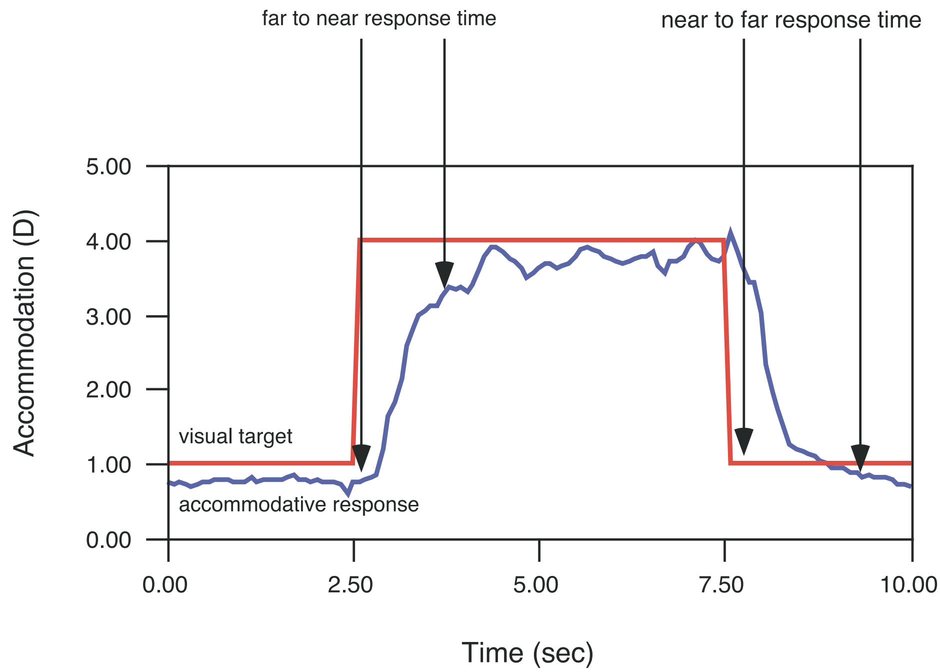

Fig. 7. Accommodation responses to step displacement of stimulus. Two accommodation response times were measured: far-to-near response time and near-to-far response time.

examined by using the setting under the condition B of Experiment 1. Condition A difference in binocular disparity means a difference in the location of the stereoscopic images (stereoscopic distance). The five conditions for the binocular disparity between the reconstructed 3D image and the virtual screen are listed in Table 1.

To avoid subject fatigue, we divided the five conditions into two groups and did the testing on different days. The two groups were as follows

Experiment 2-1: Conditions B1, N, F2.
Experiment 2-2: Conditions B2, N, F1.

3.3. Measurements for evaluation

To estimate the visual load induced on the subjects we compared the accommodation response time to the target step displacement before and after viewing stereoscopic images. We also investigated the subjective symptoms of visual fatigue.

The accommodation response times were measured with an infrared optometer (NIDEK AR2000), which objectively records the dynamic response time. The target in the optometer was used as the stimulus for accommodation. The target position was changed between the far point and near point of each subjects five times at 5 s intervals and the results of the five trials were averaged. The response time was measured after the target was displaced. Two response times were measured: far-to-near response time and near-to-far response time (Fig. 7). The subjective symptoms of visual fatigue were evaluated based on the responses of the subjects to 37 items on a questionnaire administered immediately after viewing each session.

3.4. Procedure of the experiments

Each viewing session proceeded as follows.

(a) Evaluation of subjective symptoms before viewing stereoscopic images.
(b) Measurement of accommodation response times to step displacement of target before viewing stereoscopic images.
(c) Viewing of stereoscopic images for 15 min.
(d) Measurement of accommodation response times to step displacement of target immediately after viewing stereoscopic images.
(e) Evaluation of subjective symptoms immediately after viewing stereoscopic images.
(f) Measurement of accommodation response times to step displacement target 15 min after viewing stereoscopic images.
(g) Evaluation of subjective symptoms 15 min after viewing stereoscopic images.

Three sessions with different stimulus conditions were held for each subject in a day. Nine subjects participated in Experiment 1 and eight participated in Experiment 2. Subjects younger than 20 years old were emmetropic, and had normal stereovision.

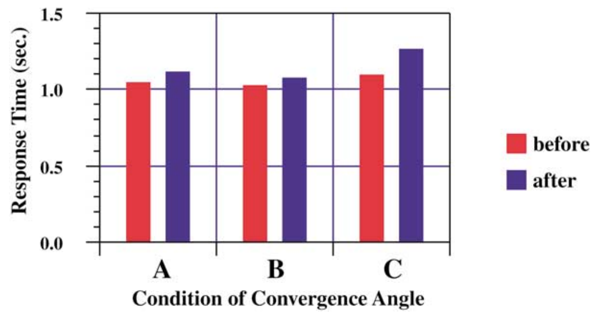

Fig. 8. Average change in far-to-near response time after subjects viewed images. The change was larger under the condition C.

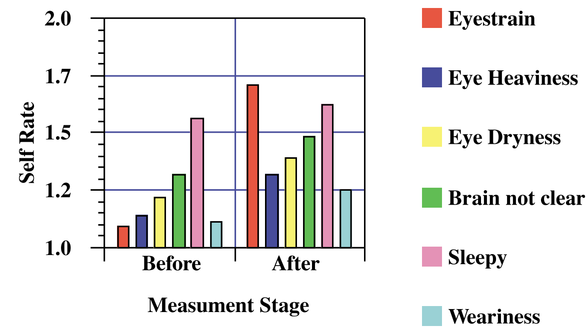

Fig. 10. Average change in self-evaluated rate for subjective symptoms. The change was largest for eyestrain.

3.5. Experiment results

In Experiment 1 on the convergence angle the average accommodation response time to the step stimulus was longer after viewing the stereoscopic images than that before viewing the images. This was true under all conditions. As shown in Fig. 8 only under the condition C was the far-to-near response time significantly longer after the subjects viewed the images than before. We analyzed the variance in response time for two factors: the measurement time (before and after viewing) and the kind of response time (far-to-near and near-to-far). The first factor was significant ($F = 15.206$, $p < 0.01$) while the second factor was not significant. We also compared the change in the accommodation response time among the stimulus conditions. The changes for far-to-near and near-to-far were significantly larger under the condition C, while they were small under the condition B (Figs. 8 and 9).

Under all conditions the results of evaluating the subjective symptoms showed increases in six symptoms: (a) eyestrain, (b) eye heaviness, (c) eye dryness, (d) brain clarity, (e) sleepiness and (f) body weariness (Fig. 10). The change was the largest for 'eyestrain'. The changes in the rates for these symptoms were small under the condition B and a significant difference in the changes between conditions was not found.

In Experiment 2 on the binocular disparity the average accommodation response time to the step stimulus was

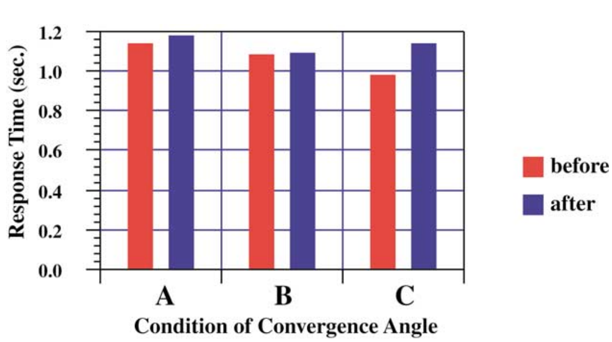

Fig. 9. Average change in near-to-far response time after subjects viewed images. The change was larger under the condition C.

again longer after viewing the images than that before viewing the images. Analysis of the variance in response time for the same two factors showed that the first factor was significant (Exp. 2-1: $F = 26.482$, $p < 0.01$; Exp. 2-2: $F = 26.482$, $p < 0.01$). The changes in both response times were significantly large under the conditions F1 and F2 and were small under the condition N in both Experiments 2-1 and 2-2 (Figs. 11 and 12).

Evaluation of the subjective symptoms after viewing the images showed significant increases in two symptoms: eyestrain and eye heaviness (Fig. 13). The increase for both symptoms was significant under the conditions F1 and F2 and small under the condition N.

3.6. Discussion

Two experiments revealed physiological and psychological changes in the subjects' visual functions after they viewed stereoscopic images through an HMD. The accommodation response times, far-to-near and near-to-far, were significantly longer after viewing the images than before. Evaluation of the subjective symptoms of visual fatigue showed a significant increase in several symptoms especially eyestrain.

In Experiment 1, the difference in the convergence angle of the HMD caused differences in the accommodation response time and changes in the rate of subjective symptoms after viewing stereoscopic images. The changes in the accommodation response time were the smallest under the condition B (convergence distance nearly identical to accommodation distance). The changes in the rate of subjective symptoms were also the smallest under the condition B. The largest changes in the accommodation response time occurred after viewing stereoscopic images under the condition C (convergence distance of the HMD greatly different from accommodation distance of the HMD). These results indicate that the convergence angle of the HMD should be adjusted to make the difference in the distances small so as to reduce the effect on the viewer's visual functions of viewing stereoscopic images through an HMD.

In Experiment 2, the results showed that the larger the disparities, the longer the changes in the accommodation response time after stereoscopic images were viewed. The

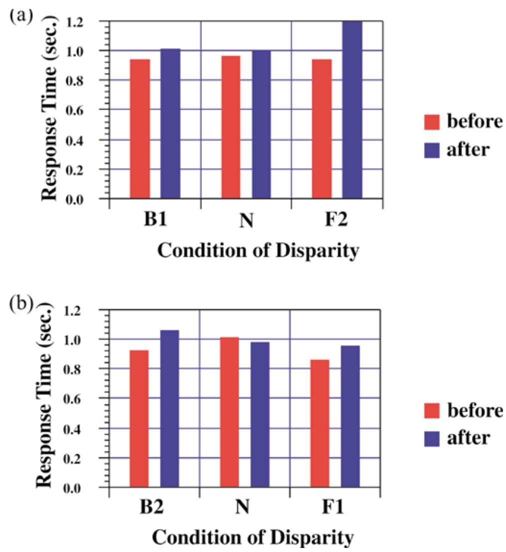

Fig. 11. Average change in far-to-near response time after subjects viewed images in Experiment 2. The data of (a) and (b) were acquired on different days. The change was significant under the condition F2. It was small under the condition N.

changes after viewing images with small disparity (Conditions B1, B2 and F1) were much no difference from those after viewing images with no disparity (Condition N). The results were similar to those obtained in previous studies in which a CRT display and liquid-crystal shutter glasses were used as a stereoscopic display unit [1]. The results of those studies showed that the larger the disparity the larger the changes in eye movement and accommodation response. However, there was no significant difference between the changes after viewing 2D images (zero disparity) and after viewing stereoscopic images with a small disparity (less than 1 degree).

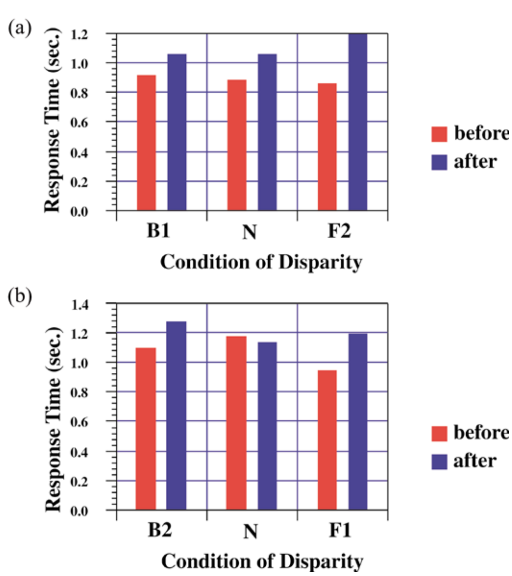

Fig. 12. Average change in near-to-far response time after subjects viewed images in Experiment 2. The data of (a) and (b) were acquired on different days. The change was significant under the condition F2.

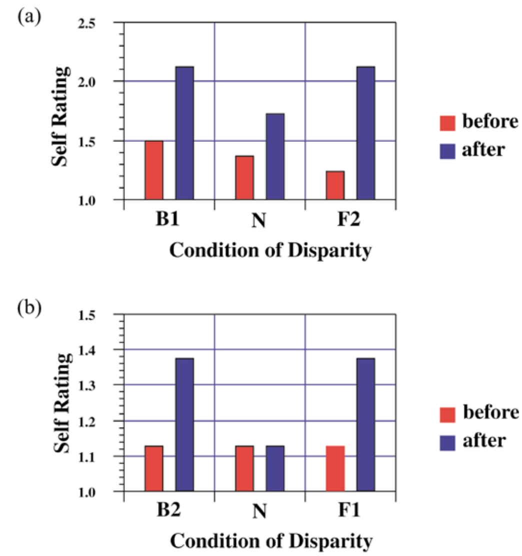

Fig. 13. Average change in self-evaluated rate for eye heaviness. The change was smallest under the condition N.

4. Future investigation for improvement of HMDs

Two experiments were conducted to investigate the visual load induced by viewing stereoscopic images through an HMD. Physiological and psychological changes in visual functions were found after viewing images. The results also suggested that there is a setting that can be applied to an HMD device that reduce the visual load. These investigations indicate that the visual load may be smaller when the image disparities are smaller due to the use of an HMD as the stereoscopic display although the experiments did not clarify the appropriate conditions for viewing stereoscopic images through an HMD. Further investigation is needed to clarify the visual load induced by viewing stereoscopic images through an HMD in order to develop better stereoscopic 3D display.

It is necessary to examine a system using an HMD considering not only visual functions but also other human body information. When visual information and a situation of the circumstance are extremely different, human being is confused. In the future, it would be necessary to also examine a human's posture and a sense of balance about HMD systems.

References

[1] T. Inoue, H. Ohzu, Accommodative responses to three-dimensional display, Appl. Opt. 36 (1997) 4509–4515.

[2] T. Isono, The latest technical trend and the view of HMDs, Inst. Electron., Inform. Commun. Engng 100-436 (2000) 9–14.

[3] T. Iwasaki, S. Akiya, T. Inoue, K. Noro, Viewing distance to accommodation with their after-effects on the pupil, Jpn. J. Ergon. 28-3 (1992) 119–124.

[4] R. Kijima, E. Yamada, T. Ojika, A development of reflex

HMD—head mounted display with vestibular reflex, Trans. Virtual Real. Soc. Jpn 16-2 (2001) 107–114.

[5] M.W. Morgan, Accommodation and vergence, Am. J. Optom. Arch. Am. Acad. Optom. 45 (1968) 417–454.

[6] H. Ohzu, Visual perception mechanism related binocular stereo vision technology, J. Jpn Soc. Precision Engng 54 (1988) 225–258.

[7] H. Ohzu, Artificial 3D display and visual function, Technical Digest of OSA Topical Meeting, vol. 2, 1994.

[8] H. Ohzu, K. Habara, Behind the scenes of virtual reality: vision and motion, Proc. IEEE 84-5 (1996) 782–798.

[9] E. Peli, Visual issues in the use of a head mounted monocular display, Opt. Engng 29 (1990) 883–892.

[10] E. Peli, Safety and Comfort Issues with Binocular Head-Mounted Displays, Proceeding of Hoso-Bunka Foundation Symposium, 1996.

[11] K. Ukai, N. Ishikawa, Use of infrared TV cameras built into head-mouted display to measure torsional eye movements, Jpn. J. Ophthalmol. 45-1 (2001) 5–12.

[12] C.M. Schor, J.C. Kotulak, Dynamic interactions between accommodation and convergence are velocity sensitive, Vision Res. 26-6 (1986) 927–942.

[13] T. Shibata, T. Iwasaki, T. Kawai, K. Noro, A study on the visual function while viewing binocular stereoscopic images, J. Three Dimen. Images 12-2 (1998) 8–12.

[14] T. Yoshida, A. Watanabe, Analysis of interaction between accommodation and vergence feedback control systems of human eyes, Bull. NHK Broadcast Sci. Res. Labs. 3 (1969) 72–80.