Journal of Information Display, Vol. 10, No. 4, December 2009 (ISSN 1598-0316)

Time Series Evaluation of Visual Fatigue and Depth Sensation Using a Stereoscopic Display

Sanghyun Kim[a], Shinsuke Kishi[a], Takashi Kawai[a], and Toyohiko Hatada[b]

Abstract

Conventional stereoscopic (3D) displays using binocular parallax generate unnatural conflicts between convergence and accommodation. These conflicts can affect the observer's ability to fuse binocular images and may cause visual fatigue. In this study, time series changes in visual fatigue and depth sensation when viewing stereoscopic images with changing parallax were examined. In particular, the physiological changes, including the subjective symptoms of visual fatigue, when viewing five parallax conditions, were examined. Then a comparative analysis of the 2D and 3D conditions was performed based on the visual function. To obtain data regarding the visual function, the time series changes in the spontaneous-blinking rate before and during the viewing of 3D images were measured. The time series change results suggest that 2D and 3D images cause significantly different types of visual fatigue over the range of binocular disparity.

Keywords: 3D display, visual fatigue, depth sensation, time series change

1. Introduction

Conventional stereoscopic (3D) displays can show designs in a 3D space, eliminating the need for the construction of expensive models and thereby greatly reducing development costs. They also serve as simulation and training aids, allowing users to learn in a virtual world rather than in the real world. As such, 3D display systems are currently being developed in many fields, including advertising, scientific research, entertainment, and medicine [1, 2]. Although they are expected to become widely used in the future, however, the current 3D displays have failed to gain acceptance because they can cause visual fatigue and because the 3D contents include erroneous depth information.

Most 3D display technologies use binocular parallax to produce 3D images. As the human eyes are located at different points in the skull, each eye receives a slightly different image of any given object. This is called "binocular disparity." The brain perceives the two retinal images of an object as a 3D image. Binocular parallax is the degree of disparity between the two retinal images, or the difference in the angles at which an object is fixed by the right and left eyes. 3D images with binocular parallax, however, create unnatural conflicts between convergence and accommodation that can affect the ability to fuse binocular images and that may cause visual fatigue, a symptom related to the mechanisms of human visual perception. The mechanism by which unnatural conflicts cause visual fatigue is not fully understood, but unnatural and contradictory visual information clearly relates to the observer's sense of visual fatigue [3-5].

When creating 3D contents, therefore, two aspects must be considered: safety, by preventing visual fatigue; and comfort, by providing appropriate depth sensations. This means that producers and creators have more delicate issues to consider when creating 3D images than when creating 2D images. A content creator with little 3D image experience will have difficulty creating 3D contents that are safe and comfortable to view. Furthermore, a method has yet to be formulated for creating such 3D contents despite the fact that the binocular parallax must be adjusted so that the viewers will see the objects in front of or behind the display. Similarly, to make 3D contents, it is important for

Manuscript Received November 28, 2009; Revised; December 16, 2009 Accepted for publication December 24, 2009.
This research was carried out under a contract awarded by the Mechanical Social Systems Foundation and with support from a grant from the Japan Keirin Association.
Corresponding author : Sanghyun Kim
[a] Graduate School of Global Information and Telecommunication Studies, Waseda University 1011 Okuboyama, Nishi-Tomida, Honjo-shi, Saitama 367-0035, Japan
[b] Tokyo Optometric College 2-15-10 Hyakunin-cho, Shinjuku-ku, Tokyo 169-0073, Japan
E-mail: kim@akane.waseda.jp **Tel:** + 81-495-24-6076 **Fax:** + 81-495-24-6645

the creator to understand the relationship between the many types of parallax information and the time series changes that can occur in various viewing environments.

In this study, the positions of 3D images with binocular parallax and the time series changes in visual fatigue and depth sensation were examined. Both subjective measures (a brief self-rating questionnaire) and objective measures (spontaneous-blinking activity) were used for this purpose. Human blinking has the important function of spreading a film of precorneal tears over the eye to maintain a moist ocular surface. The spontaneous-blinking rate appears to vary intra-individually as a function of the alternation between different psycho-physiological states. Many reports have shown that the blinking rate changes along with the cognitive workload [6, 9-11]. Nevertheless, little research has been conducted on the relation between the blinking rate changes and the visual loads under the conditions of binocular parallax with time series changes. In this study, it was shown that the blinking rate can be a useful marker of visual fatigue when viewing 3D images. As a result, basic knowledge of the safety and comfort aspects of creating and viewing 3D images was obtained.

2. Experiments

The study subjects were made to view visual stimuli on a 3D display while wearing polarized glasses (Hyundai IT, E465S). The experiment was performed under an average illuminance of 150 lux based on the Japanese industrial standards. The temperature and humidity were 26°C and 45%, respectively. The subjects were seated in comfortable, high-back chairs placed in front of the display and were asked to direct their respective heads towards the display. To restrict head movement, the subjects' heads were placed on chin rests at a viewing distance of 171 cm, which were three times the height of the display. The chair and chin rest height were adjusted to make viewing comfortable, and the display height was such that the center of the screen would be level with the subjects' eye positions. The stimuli were stereo images of a 50% gray square, circle, and triangle on black backgrounds. The series was viewed for 15 min. Each stimulus had a viewing angle of 2° on a side or diameter, as shown in Fig. 1.

As the distance between the human right and left eyes ranges from approximately 5 to 7 cm, the image seen from one eye differs from that seen from the other. By showing

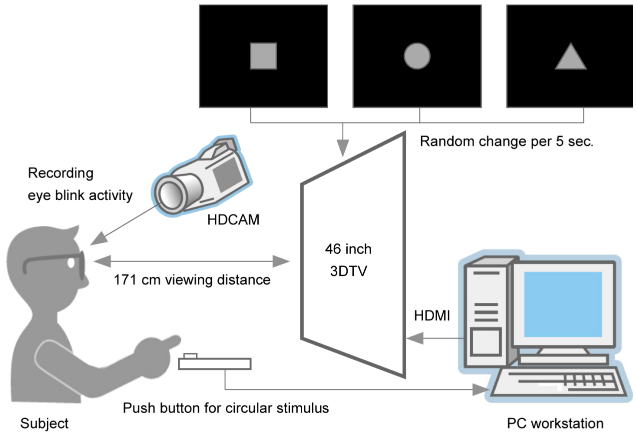

Fig. 1. The experiment arrangement for the measurement of the time series changes in visual fatigue and depth sensation.

images corresponding to the right and left eyes to each eye, respectively, it is possible to induce a sense of depth. 3D conditions using binocular parallax, with the help of a polarized filter and glasses, have made it possible to show independent images to the right and left eyes. The difference between the convergence angle and the convergence upon seeing a 3D image that is determined by the binocular parallax is known as the "parallactic angle." The parallactic angle is the convergence-angle-to-display-surface minus the convergence-angle-to-3D-images. For example, if a display using this principle shows separate images for the left and right eyes, as shown in Fig. 2, the image can appear in front of and behind the display, as a 3D image. An image feature that appears in front of the display is called "crossed disparity" (θ 1, θ 2) while an image feature that appears behind the display is called "uncrossed disparity" (θ 3). When an image feature appears in the same place in both the left and right images on the surface of a display, the viewer perceives them to be equidistant from the display screen as 2D images. This is called "zero disparity" (θ 0). Based on the results of previous studies, stimuli were presented using one of the following four parallactic angles: 1° (uncrossed disparity), 0° (zero disparity), -1° (crossed disparity), and -2° (crossed disparity) [3, 7-8]. Fig. 2 shows the arrangement of the depth conditions using a parallactic angle.

The stimuli were presented in random order at 5 sec intervals. The subjects were asked to concentrate on the center of each stimulus and to push a button when the circle was presented. In experiment conditions 1-4, the subjects observed a stimulus with a parallactic angle of -1° for 10

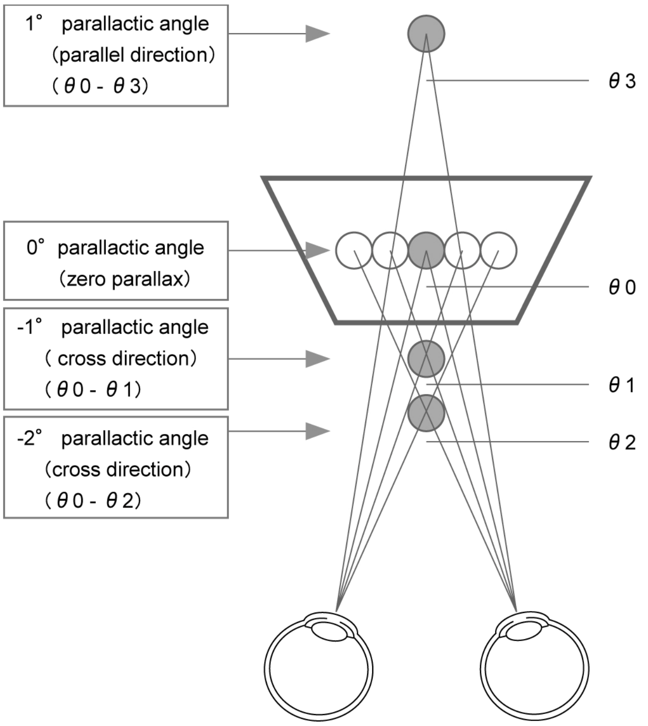

Fig. 2. The arrangement of depth information for the experiment conditions.

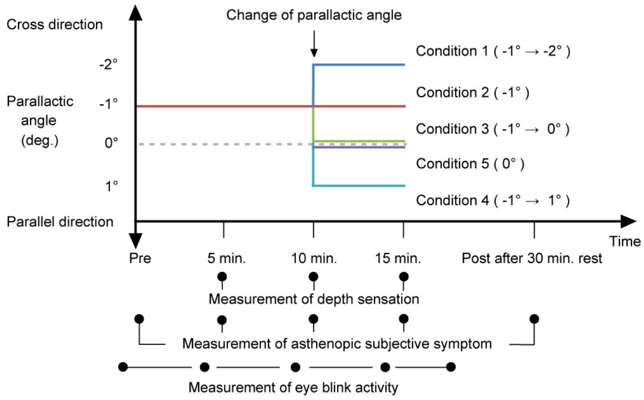

Fig. 3. The experiment conditions with the variety of parallax information and time series changes in a stereoscopic-viewing environment.

min then viewed each stimulus at different parallactic angles (1, 0, -1, and -2°) for 5 min. In condition 1, the subjects observed a stimulus with a parallactic angle of -2° for 5 min after stimulus presentation with a parallactic angle of -1° for 10 min. In condition 2, a stimulus with a parallactic angle of -1° was presented for 15 min. In condition 3, the subjects observed a stimulus with a parallactic angle of 0° for 5 min after stimulus presentation with a parallactic angle of -1° for 10 min. In condition 4, the subjects observed a stimulus with a parallactic angle of 1° for 5 min after viewing with a parallactic angle of -1° for 10 min. In condition 5, the subjects observed a stimulus with a parallactic angle of 0° for 15 min. Fig. 3 shows the experiment conditions.

The subjects' subjective experiences of visual fatigue and depth sensation were evaluated according to a five-point self-rating method, using a simple oral questionnaire consisting of two questions: (1) How tired are your eyes? and (2) What was your impression of the sense of depth? The subjects reported their symptoms and perceptions every 5 min. The five stages of visual fatigue were (a) no symptoms; (b) mild; (c) fair; (d) strong; and (e) severe. The five stages of depth sensation, on the other hand, were (a) no depth; (b) mild; (c) fair; (d) good; and (e) excellent.

The blinking activity was measured every 5 min, using a high-resolution CCD video camera (Sony HDR-FX1; 30 frames/sec, standard NTSC signal). The video camera was located at head height but away from the subjects and at an angle at which it would not directly interfere with the simple visual stimuli presented to the subjects. The camera was started with the examiner seated beside the subjects from 3 min before the stimulus was presented until 3 min thereafter. The spontaneous-blinking rate was examined for 1 min prior to the administration of the oral questionnaire. In this study, the blinking rate was measured for 1 min every 5 min pre-experiment, for 3-4 min, for 8-9 min, for 13-14 min, and post-experiment).

The video tapes were analyzed in slow motion and frame by frame using a video-editing program (Adobe, Premiere Pro 2.0). The criterion for blinks employed the following definition of spontaneous blinking: "the simultaneous closure of the upper and lower eyelids of both eyes" [6]. The statistical correlation between the blinking parameters and the experiment conditions were evaluated using the statistical software packages Sigma Plot and Sigma Stat for Windows SPSS. The $p<0.05$ level was considered statistically significant.

In the post-experiment interviews, the subjects were asked about their viewing impressions. The subjects were 13 graduate student volunteers between the ages of 23 and 30, with emmetropia and normal binocular stereoscopic vision.

3. Results

3.1 Visual fatigue

The subjective symptoms of visual fatigue showed an upward tendency for 10 min after the stimuli were presented in all the experiment conditions. Significant differences were noted among the conditions following a change in the parallactic angle. In condition 1, the average rate of visual fatigue was 1.00, as it was in all the other conditions before the stimuli were presented. The rate gradually increased to 2.23 after 10 min and soared to 3.08 after 15 min. In condition 2, it gradually increased to 1.92 after 10 min and to 2.38 after 15 min. In conditions 3 and 4, it increased to the same extent as in condition 1 after 10 min and then after 15 min decreased to 2.00 in condition 3 and 2.62 in condition 4. In condition 5, it gradually increased to 1.85 after 10 min and then slightly increased to 1.92 after 15 min. A primary efficacy analysis of visual fatigue was performed using two-way analysis of variance (ANOVA) with the Bonferroni test according to the measurement time (pre-experiment; 5, 10, and 15 min; and post-experiment), the five experiment conditions, and the time-by-condition interaction. The measurement time ($F=39.385$; $p<.01$) and time-by-condition interaction ($F=2.760$; $p<.01$) differed significantly. For the examination at 15 min, conditions 3 and 5 had significantly lower values than condition 1 ($p<.05$). Fig. 4 shows the average rate of visual fatigue for the five experiment conditions.

3.2 Depth sensation

The subjects felt a depth sensation associated with the changing parallactic angle for all the experiment conditions. In condition 1, the average rate of depth sensation was 2.77 after 5 min, which slightly increased to 2.85 after 10 min and soared to 3.85 after 15 min. In condition 2, it remained at 3.00 up to the 10-min mark then slightly decreased to 2.92 after 15 min. In condition 3, it remained at 3.31 up to the 5-min mark then increased to 3.15 after 10 min and plunged to 1.00 after 15 min. In condition 4, it stood at 3.15 after 5 min then increased to 3.54 after 10 min and then to 3.69 after 15 min. In condition 5, it remained at 1.08 up to the 10-min mark and then increased slightly to 1.15 after 15 min. The two-way ANOVA also showed significant differences in depth sensation for the time-by-condition interaction ($F=27.563$; $p<.01$). Compared with the 15-min data, significant differences were seen between: (a) condition 1 and conditions 3 and 5; (b) conditions 2 and 5; (c) condition 3 and conditions 1, 4, and 5; (d) condition 4 and conditions 3 and 5; and (e) condition 5 and conditions 1, 2, 3, and 4 ($p<.05$). Fig. 5 also shows the average rate of depth sensation under the five experiment conditions.

3.3 Blinks and post-experiment interviews

The number of blinks (blinks/min) was measured over a 1-min period at five points during the experiment, for all the conditions. Before the presentation of the stimuli, the mean number of blinks in condition 1 was 37.00±8.67 (blinks/min ± SD), 35.69±18.27 in condition 2, 30.62±12.80 in condition 3, 34.15±11.23 in condition 4, and 35.69±15.57 in condition 5. Between 3 and 4 min, the mean number of blinks decreased for all the experiment conditions: 24.31±10.32 in condition 1, 26.85±13.90 in condition 2, 24.77±14.13 in condition 3, 24.92±14.38 in condition 4, and 30.08±11.56 in condition 5. Between 8 and 9 min, the

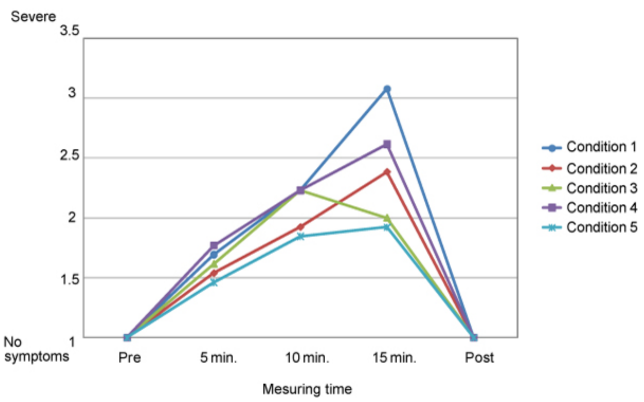

Fig. 4. Average rate of visual fatigue with time series changes under the five experiment conditions.

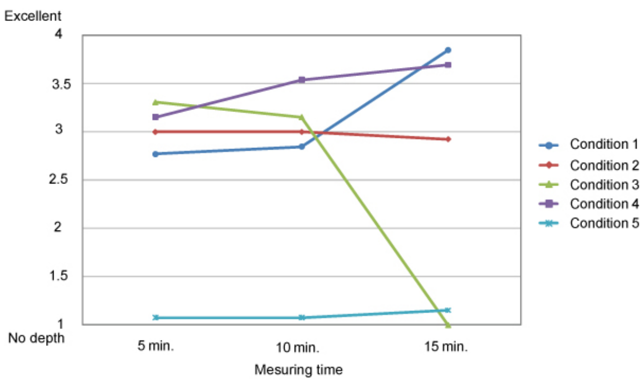

Fig. 5. Average rate of depth sensation with time series changes under the five experiment conditions.

Table 1. Changes in the blinking rate under the five experiment conditions. The change in the blinking rate is specified as the geometric mean and 95% CI.

Condition		Pre	3-4 min	8-9 min	13-14 min	Post
Condition 1	Mean±SD	37.00±8.67	24.31±10.32	29.08±12.43	33.92±14.34	42.38±15.24
	95% CI	31.76-42.24	18.07-30.55	21.57-36.59	25.26-42.59	33.18-51.59
Condition 2	Mean±SD	35.69±18.27	26.85±13.90	31.38±13.78	34.08±15.81	41.85±13.72
	95% CI	24.65-46.73	18.44-35.25	23.06-39.71	24.52-43.63	33.55-50.14
Condition 3	Mean±SD	30.62±12.80	24.77±14.13	27.92±13.45	26.23±10.96	37.08±9.90
	95% CI	22.88-38.35	14.44-33.25	19.8-36.05	19.61-32.85	31.09-43.06
Condition 4	Mean±SD	34.15±11.23	24.92±14.38	25.38±15.01	29.15±17.15	45.08±17.15
	95% CI	27.32-40.94	16.23-33.61	16.32-34.45	18.79-39.51	37.62-52.54
Condition 5	Mean±SD	35.69±15.57	30.08±11.56	29.31±15.76	30.00±11.45	38.31±14.82
	95% CI	26.28-45.10	23.09-37.07	19.78-38.83	23.08-36.92	29.35-47.27

mean number of blinks increased for four conditions: 29.08±12.43 in condition 1, 31.38±13.78 in condition 2, 27.92±13.45 in condition 3, and 25.38±15.01 in condition 4. In condition 5, the mean number of blinks slightly decreased to 29.31±15.76, unlike in the other conditions. Between 13 and 14 min, the mean number of blinks increased for three conditions: 33.92±14.34 in condition 1, 34.08±15.81 in condition 2, and 29.15±17.15 in condition 4. In condition 3, the mean number of blinks decreased to 26.23±10.96. For condition 5, the number of blinks remained steady at 30.00±11.45. During the 30-min post-experiment rest, the mean number of blinks showed a tendency to increase for all the conditions: 42.38±15.24 in condition 1, 41.85±13.72 in condition 2, 37.08±9.90 in condition 3, 45.08±17.15 in condition 4, and 38.31±14.82 in condition 5. The two-way ANOVA also showed statistical significance in the mean blinking rate for the time-by-condition interaction (F=1.633; p=.064). Compared with the data between 13 and 14 min, significant differences were seen between (a) condition 1 and conditions 2 and 5; (b)

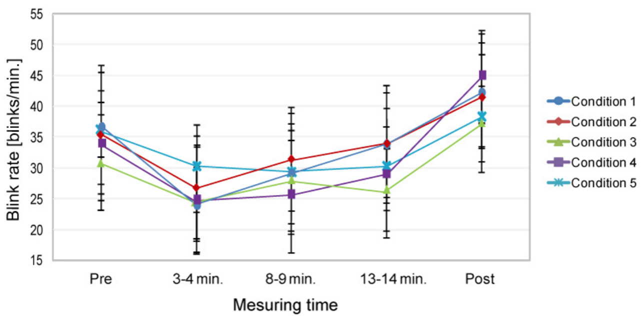

Fig. 6. Mean blinking rate with time series changes during the viewing of the stereoscopic images under the five experiment conditions.

condition 2 and conditions 1, 4, and 5; (c) conditions 3 and 5; (d) condition 4 and conditions 2 and 5; and (e) condition 5 and conditions 1, 2, 3, and 4 ($p<.05$). For all the conditions, the mean number of blinks was higher than the stimulus presentation value. Table 1 and Fig. 5 also show the average blinking rate for the five experiment conditions.

The post-experiment interviews suggested that the subjects felt different visual-fatigue symptoms under different parallax conditions. In conditions 1, 2, and 4, the subjects perceived visual fatigue as the binocular parallax changed. In condition 3, however, the subjects stated that their visual fatigue was reduced by the poor sense of depth. The subjects also felt visual comfort when the binocular parallax was changed to 0°.

4. Discussion

In this study, the time series changes in visual fatigue and depth sensation were analyzed to elucidate the safety and comfort of viewing 3D images. The physiological changes, including the subjective symptoms of visual fatigue, were examined under five viewing conditions, with various stimuli and parallax conditions.

In all the conditions, the subjective symptoms of visual fatigue showed an upward tendency for 10 min after the viewing of the stimulus at a parallactic angle of -1 or 0°. Moreover, significant differences were seen among conditions 1, 3, and 5 after the parallactic angle was changed at 15 min. In condition 1, the average rate of visual fatigue increased over the range of parallactic angles. In condition 3, it decreased when the parallactic angle was changed to 0°. In condition 5 (2D condition), it increased slightly at 15 min. These results mean that the degree of visual fatigue for the 3D and 2D images differed significantly with the time series changes over the range of binocular parallax. The time series changes in visual fatigue may thus have been influenced by the frequency at which the parallactic angle of the related images became 0°. There seemed to have been no significant difference between condition 2 and conditions 4 and 5. These results coincide with those of other studies on the ocular accommodation function [7-8]. In particular, in condition 4, with accommodation at a point beyond the display, the visual fatigue gradually increased to almost the same level as in condition 2, in which the accommodation was in front of the display (-1°). Thus, the visual fatigue from viewing 3D images may have been influenced by the absolute value of the parallactic angle, which changed over time.

The subjects' blinking rate differed significantly between the 2D and 3D conditions with the time series changes. The blinking rate between 13 and 14 min increased after the subjects viewed the stimulus with a parallactic angle in conditions 1, 2, and 4. In condition 1, the blinking rate rose to 14.29% according to the change in the largest binocular parallax angle (-2°). In condition 2, the blinking rate showed an increase of 7.90% when the binocular parallax angle (-1°) was maintained. These data show that the large binocular disparity was able to create a significant increase in the blinking rate. In addition, although 3D images appeared behind the display in condition 4, the blinking rate showed a significant increase (12.93%) according to the change in the binocular parallax angle (1°). This means that other factors, such as depth sensation for 3D images in front of or behind the display, may affect the change in the blinking rate. On the contrary, the blinking rate slightly decreased to 6.45% when the parallactic angle -1° (3D condition) was changed to 0° (2D condition) in condition 3. This data also differed from that in condition 5, where the 2D condition was maintained for 15 min, in which the blinking rate slightly increased to 2.31%. This suggests that the change in the blinking rate may be influenced by both the changing parallax and the time series changes in 3D images.

The interpretation of the significant relationship between eye fatigue and blinking is more complex because many factors are known to affect these factors. A notable difference between 2D and 3D images was designed to appear according to the usage of images with binocular parallax. In this experiment, the changes in the blinking rate closely matched the subjective symptoms of visual fatigue. Moreover, the blinking rate changed during the viewing of conventional 3D displays, whether or not unnatural conflicts between convergence and accommodation were generated. Several studies have shown that the blinking rate changed after the viewing of an unnatural visual load. As has been shown by Stern and Boyer, blinking rate changes are related to the time spent on a task [9]. In other experiments on video display terminal (VDT) fatigue, an increased blinking rate was assumed to be associated with a higher degree of visual fatigue [10, 11]. Similarly, the blinking rate increased after the viewing of a visual load with binocular parallax and time series changes. Accordingly, the blinking rate may also reflect the time on task and visual fatigue when viewing 3D images. Thus, measuring the blinking rate can be a useful marker of visual fatigue during the viewing of conventional 3D displays.

5. Conclusions

In this study, the time series changes in visual fatigue and depth sensation during the viewing of 3D images with changing parallax were demonstrated. The physiological changes, including the subjective symptoms of visual fatigue, during the viewing of five parallax conditions were examined, and a comparative analysis of 2D and 3D conditions was performed, based on the visual function. To obtain data regarding the visual function, the time series changes in the spontaneous-blinking rate during the viewing of 3D images were measured.

In summary, the following conclusions were arrived at:

(1) 3D and 2D images produce significantly different levels of visual fatigue over time.
(2) The time series changes in visual fatigue may be influenced by the frequency at which the parallactic angle of the related images becomes 0°.
(3) Visual fatigue from viewing 3D images is influenced by the absolute value of the parallactic angle, which changes over time.
(4) The blinking rate is affected by the time series changes in the parallactic angle.

Further study is needed to clarify the complex interactions between visual fatigue and the blinking rate during the viewing of 3D images with various types of depth information. The next step is to conduct evaluations under 3D visual stimuli containing motion components, which may provide content creators with a better understanding not only of the visual function during the viewing of 3D images but also of the relation between the variety of parallax information and the time series changes.

References

[1] T. Kawai, T. Shibata, Y. Shimizu, M. Kawata, M. Suto, *SPIE*, **5291**, 1 (2004).

[2] J. Ilgner, T. Kawai, T. Shibata, T. Yamazoe, M. Westhofen, *SPIE*, **6055**, 46 (2006).

[3] S. Kishi, T. Yamazoe, T. Shibata, T. Kawai, T. Inoue, Y. Sakaguchi, K. Okabe, Y. Kuno, *J of the Institute of Image Information and Television Engineers*, **60**, No.6, 96 (2006). (in Japanese)

[4] S. Yano, M. Emoto, T. Mitsuhashi, *Displays*, **25**, 141 (2004).

[5] M. Emoto, T. Niida, F. Okano, *J of Display Technology*, **1**, 328 (2005).

[6] W. E. MacLean, Jr., a, M. H. Lewisb, W. A. Bryson-Brockmanna, D. N. Ellisa, R. E. Arendta, and A. A. Baumeistera, *Biological Psychiatry*, **20**, 1321 (1985).

[7] T. Inoue, K. Noro, T. Iwasaki, H. Ohzu, *J of the Institute of Image Information and Television Engineers*, **48**, No.10, 1301 (1994). (in Japanese)

[8] T. Iwasaki, T. Kubota, A. Tawara, *Displays*, **30**, 44 (2009).

[9] J. A. Stern, D. Boyer, D. Schroeder, *Human Factors*, **36**, 2, 285 (1994).

[10] R.R. Mourant, R. Lakshmanan, R. Chantadisai, *Human Factors*, **23**, 5, 529 (1981).

[11] E. Lee, K. Park, M. Whang, K. Min, *International Journal of Industrial Ergonomics*, **39**, 798 (2009).