Effect of Vergence–Accommodation Conflict and Parallax Difference on Binocular Fusion for Random Dot Stereogram

Donghyun Kim, *Student Member,* Sunghwan Choi, *Student Member, IEEE,* and Kwanghoon Sohn, *Member, IEEE*

***Abstract*—Recently, various studies of human factors have been conducted to reveal stereoscopic characteristics of the human visual system and visual fatigue. In this paper, we investigate the effect of vergence–accommodation conflict and parallax difference on binocular fusion for random dot stereograms. The aim of this paper is to provide a study on visual fatigue induced by the conflict. We measured the time required for fusion under various conditions that include foreground parallax, background parallax, focal distance, aperture size, and corrugation frequency. The results show that foreground parallax and parallax difference between foreground parallax and background parallax have significant influences on fusion time. In addition, we verify the relationship between fusion time and visual fatigue by conducting a subjective evaluation of stereoscopic images.**

***Index Terms*—Random dot stereogram, stereoscopic image, visual fatigue.**

I. Introduction

A NUMBER of electronic manufacturers have launched high-definition stereoscopic 3DTVs into the market since 2010. Regardless of whether their display type uses shutter glasses or polarized glasses, current 3-D display systems tend to cause visual fatigue, which is induced by watching stereoscopic images or videos [1]. Symptoms of visual fatigue can be measured subjectively by assessing eyestrain, difficulty in focusing or blurred vision, stiff shoulders, and headaches, etc. [2]. The International Telecommunications Union has developed recommendations for stereoscopic television pictures that include evaluation methods, shooting conditions, and viewing conditions, which can be used to measure visual fatigue [3]. In addition, objective measurements of visual fatigue, including accommodation, visual acuity, pupil diameter, critical fusion frequency, and task performance, were compared in [4].

In [5] and [6], visual fatigue induced by the conflict between accommodation and vergence is reviewed. Akeley, Hoffman, and Banks developed a volumetric display and investigated the effect of vergence–accommodation conflicts by measuring the time required to identify a stereoscopic stimulus [5], [6]. They assumed that demanding stereoscopic tasks will require less time when the stimuli for accommodation and vergence are consistent than when they are not, since the physiological link between accommodation and vergence increases the speed of accommodation and vergence [6], [7]. They stated that the decoupling of vergence and accommodation required by 3-D displays frequently reduces the ability to fuse the binocular stimulus and causes visual fatigue [6]. This phenomenon is also observed in other studies [8]. When a visual target is presented in front of the screen, vergence is evoked and accommodation is accompanied. Then accommodation returns to the screen surface, and both accommodation and vergence result in instability and oscillation, which disturbs fusion of binocular images [9]. In addition, even if a user is able to perceive a consistent 3-D view, the effort required to resolve visual conflicts may lead to serious fatigue, eyestrain, and headache [9].

Visual fatigue is also caused by a number of other factors that include camera configuration, viewing conditions, and image characteristics: magnitude of parallax, parallax distribution, parallax variation, vertical parallax, crosstalk, and asymmetries [9], [10]. The issue of visual fatigue induced by excessive parallax over the fusional range has been studied in several publications [9], [11]–[13]. Excessive parallax often occurs because of the content creator's desire to provide a more powerful 3-D impact. Horizontal parallax directly affects perceived depth and visual fatigue with respect to several shooting parameters (baseline, focal length shooting distance, resolution) and several viewing parameters (viewing distance, resolution, display size). Moreover, excessive parallax occurs when the viewing circumstances or the target display are changed. The 3-D Consortium established safety guidelines for creating comfortable 3-D content [11]. They recommended a limit of 2 degrees and recommended that disparity be maintained at less than 60 arcmin. Disparity is the difference between the converging angles of the 3-D object and the display screen [11]. In addition, they recommended minimizing the time spent using large disparity. Kooi and Toet measured comfort from a wide range of distortions, including spatial distortion, asymmetries, and disparities [9]. They suggested that disparity should not exceed 30 arcmin while Pastoor proposed a rule of thumb that a 35 arcmin is acceptable and 70 arcmin is too large to watch comfortably [9],

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[12]. Shibata *et al.* examined the effect of viewing distance and the effect of the sign of the vergence–accommodation conflict on discomfort [13].

The effects of parallax variation can be found in [14]–[16]. Ijsselsteijn *et al.* [14] utilized a continuous assessment methodology to rate presence, depth, and naturalness. The results indicated that presence ratings were subject to considerable temporal variation. Yano *et al.* [15] investigated the factors of visual fatigue and reported that even if the image was displayed within a corresponding range of depth of focus, visual fatigue was induced if the objects in the image moved with depth. Emoto *et al.* [16] assessed whether visual comfort was affected by the range of parallax distribution and temporal parallax change.

When stereoscopic videos contain visual fatigue factors, there are several possible approaches for increasing visual comfort by adjusting the depth range via view synthesis [17]. These approaches increase comfort by reducing excessive parallax using interview rendering techniques. In the previous work, we proposed a visual fatigue prediction metric for stereoscopic images in [18] and proposed depth-scaling method based on the results of the metric [19]. The level of visual fatigue was predicted by examining the horizontal and vertical disparity characteristics of 3-D images. However, our previous studies on visual fatigue prediction and depth scaling were performed under fixed subjective evaluation conditions that imply reconfiguration is required when there is a change in display devices or viewing conditions.

In this paper, we investigate the effect of vergence–accommodation conflict and parallax difference on binocular fusion for random dot stereograms. This paper could help establish guidelines for safe stereoscopic imaging and viewing. Conditions were tested that varied foreground parallax, background parallax, focal distance, aperture size, and corrugation frequency. The remainder of this paper is organized as follows. First, we provide background and experimental setup in Sections II and III. Experimental results are presented in Sections IV–VI, followed by the conclusion in Section VII.

II. Binocular Fusion

Binocular vision enables stereopsis, in which parallax provided by the different positions of the two eyes produces precise depth perception [20]. The differences in the two retinal images are called retinal disparity or binocular parallax. Such binocular vision is usually accompanied by binocular fusion, in which a single image is seen although each eye has its own image of any object [20].

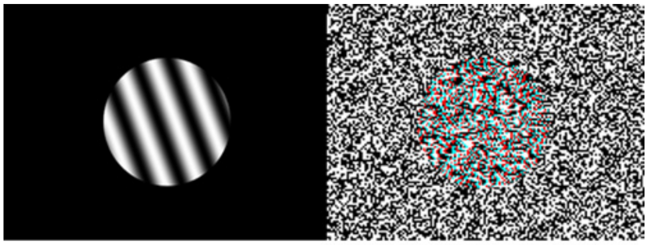
Fusion of images occurs only in a small volume of visual space around the point where the eyes are fixated. The volume is known as Panum's fusional space, and double vision occurs when the object is outside this space, and the image lies outside Panum's fusional area on the retina [21]. In addition, Percival's zone of comfort was studied, which includes vergence and accommodation responses that can be achieved without discomfort [6]. Fusional limit is a measure of the amount of disparity that can be fused in 3-D. Conventional methods of measuring the fusional limit include bar-tests as proposed in ITU-Recommendation BT.1438 [3]. The test uses square bars in the left and right images with disparities. However, crosstalk and double-image problems occur in the image with a large disparity due to the contrast of the background and foreground, and this lowers the reliability of the test. Random dot stereogram can be used, which includes a pair of random dot images that produce a sensation of depth when viewed with a stereoscopic display [22]. This enables binocular disparity to be evaluated while eliminating all other depth cues such as perspective, shadow, and cognitive effects. Since random dot stereograms also induce crosstalk and double-image, we need a pattern that can be recognized only if the binocular fusion is properly performed. One study investigated the fusional limits of retinal disparity for a large random dot stereogram [23]. In addition, fusional limits increase in proportion to the angular field of view and the size of the viewing target [24].

Researches measuring the time for binocular fusion to occur when a stereoscopic stimulus is presented have been conducted in [5], [6], and [10]. Hoffman *et al.* [6] investigated the effects of vergence–accommodation conflicts that reduce the ability to fuse binocular stimuli and cause visual fatigue. Previously, we proposed an experiment that assesses the fusional response curve to measure visual fatigue induced by stereoscopic videos [10]. A random dot stereogram was utilized to determine reliable fusional limits and a response curve. The subjects' task was to determine the direction of the stimulus. The results can be modeled by the exponential curve, and the modeling parameters show susceptibility to visual fatigue.

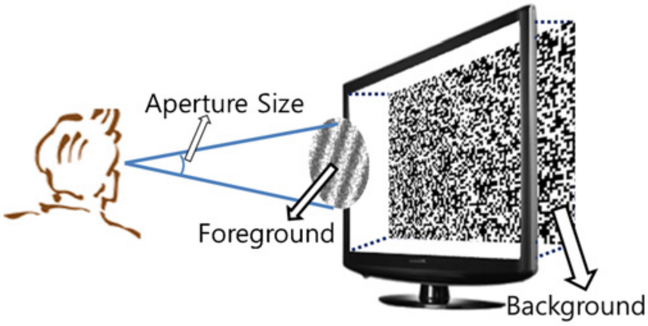
III. Experimental Setup Using Random Dot Stereogram

An experiment was designed to investigate the characteristics of binocular fusion by watching a conventional stereoscopic display. Similar experiments have measured the time for binocular fusion of stereoscopic stimulus [6], [10], but they only presented vergence–accommodation conflicts by varying the parallax of the foreground object while the background was not considered. These studies were based on the assumption that binocular fusion often fails when the conflict is large. However, it is common to place main objects near the display plane and to provide a 3-D impression from the perspective of the background scene when filming stereoscopic videos. In addition, an excessive parallax difference often induces visual fatigue since even parallax of the foreground object is suppressed.

In this paper, we conducted an experiment to explore the effect of vergence–accommodation conflicts in conventional stereoscopic displays. This experiment measured the time for binocular fusion under various conditions, which can be observed in stereoscopic images or videos. We generated conflict between vergence and accommodation by varying the foreground parallax and focal distance, and for each combination, we varied background parallax, aperture size, and corrugation frequency of the pattern. Foreground and background parallax is the parallax of the pattern and the parallax of the remainder region, respectively. While the conflict implies a discrepancy between the focal plane and



(a)



(b)

Fig. 1. Fusion test using random dot stereogram. (a) Depth map and anaglyph of the corrugation pattern [6]. (b) Stimulus for binocular fusion with random dot stereogram.

binocular stimulus, the absolute amount of accommodation is controlled by focal distance (viewing distance). Finally, we verified the relationship between the fusion time and visual fatigue, by comparing the subjective evaluation of stereoscopic images from [18].

The pattern used in the previous experiment was a "Landolt C," which contains a gap that can be in one of two positions, left and right [10]. The task of the subject was to decide on which side the gap was [10]. However, the direction of the pattern can be recognized even when binocular fusion fails due to double images. Therefore, we decided to utilize an oriented corrugation pattern from [6] as a foreground pattern and to have the subject determine the orientation of the pattern. The time to reach each decision was recorded.

Fig. 1 shows the fusion test using a random dot stereogram with the corrugation pattern. The depth map and anaglyph of the corrugation pattern are shown in Fig. 1(a), and the overall figure of the stimulus, which includes foreground pattern, background, and aperture size is shown in Fig. 1(b). Table I shows the parameters of the pattern. We tested the eight levels of foreground parallax and five levels of background parallax, which were all between −1 and 1 degree. Positive parallax implies that the content is shown in front of the screen. In addition, each of the three conditions was tested for aperture size, corrugation frequency, and focal distance as shown in Table I.

We utilized degrees for the unit of parallax instead of diopters. In addition, the dot density of the stereograms was 50 dots/deg^2 that enables fine representation of parallax. Peak-to-trough parallax was 15 arcmin at all focal distances. The orientation of the pattern was tilted ±15 deg from vertical. Between each trial, a fixation target was presented on the display plane. It appeared at random intervals for 1500 to 1800 ms, which discouraged anticipation by the observer. The experiment presented all combinations in random order so that the observer could not anticipate the pattern. A session included 360 trials and took about 25 min for one focal distance.

TABLE I
TEST CONDITIONS OF THE PATTERN

Parameters	Test Conditions
Foreground parallax	1.05, 0.75, 0.45, 0.15, −0.15, −0.45, −0.75, −1.05 (degree)
Background parallax	1, 0.5, 0, −0.5, −1 (degree)
Aperture size	8, 6, 4 (degree)
Corrugation frequency	1, 0.5, 0.25 (cycles/degree)
Focal distance	0.5, 1, 2 (diopter)

IV. FUSION TIME FOR EACH PARAMETER

A 55-in 240 Hz stereoscopic display from Samsung was used that offered a resolution of 1920×1080. A signal emitter generated a synchronization signal for the shutter glasses and controlled the shutter for each eye to ensure that the correct left and right views were presented to the correct eye. The experiment was conducted using three subjects who were familiar with 3-D display devices, because naïve viewers usually exhibit large variance in fusion time. Furthermore, naïve viewers may fail to fuse a stimulus that they were able to fuse in a previous trial. We trained the 3-D-familiar viewers for two weeks in order to acquire stabilized results for our experiment, which utilizes keypad pressing. The subjects, aged 25, 29, and 30, were screened for color vision, visual acuity, and stereo acuity. Then, we conducted additional experiments with ten subjects who were not familiar with 3-D display. Aperture size and corrugation frequency of the test for 3-D-unfamiliar group was fixed to 6 degree and 0.5 cycle/degree, respectively. The subjects were screened with color vision test [25] and had corrected visual acuity of 20/20 or better. In addition, stereo acuity was tested with our corrugation pattern image, which has a minimum 0.15 degree of binocular parallax.

Fig. 2 shows 1-D analyses per parameter: foreground parallax, background parallax, and foreground parallax minus background parallax. The bar graphs present average fusion time on each parameter and include 95% confidence intervals. Analysis of variance (ANOVA) showed significant differences across all parameters ($p < 0.01$). In Fig. 2(a), foreground parallax was highly correlated with fusion time, and 3-D-unfamiliar subjects had longer fusion times than 3-D-familiar subjects. In Fig. 2(b), moderate background parallaxes led to similar fusion times, while larger parallaxes led to longer times. Fig. 2(c) compares the averaged fusion time of parallax difference between foreground parallax and background parallax. Two-dimensional analyses of the parameters will be shown in the next section.

V. EFFECTS OF FOREGROUND PARALLAX AND OTHER PARAMETERS ON FUSION TIME

A. *Effects of Foreground Parallax and Parallax Difference*

Since the results show that foreground parallax is highly correlated with fusion time, we compared the effects of

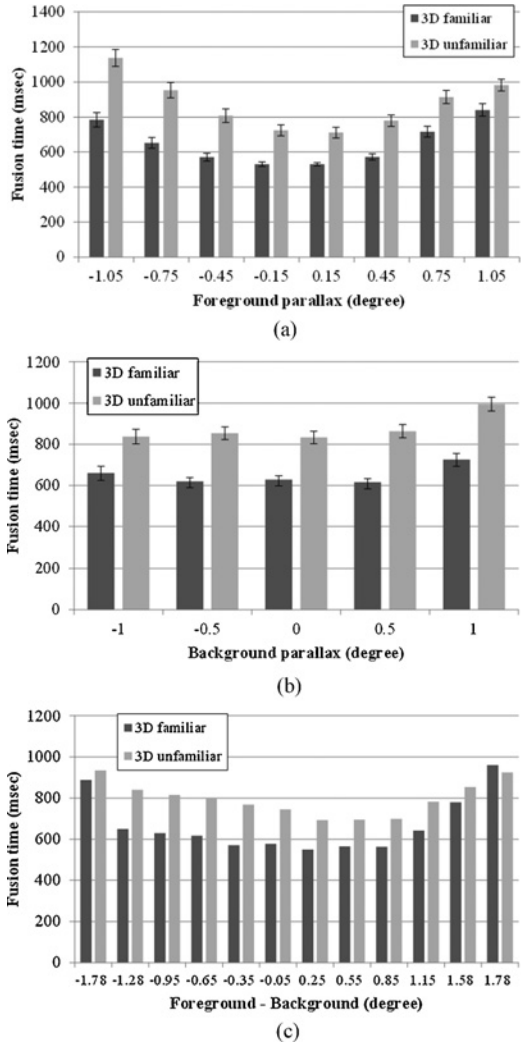


Fig. 2. Fusion test using random dot stereogram. (a) Foreground parallax. (b) Background parallax. (c) Parallax difference.

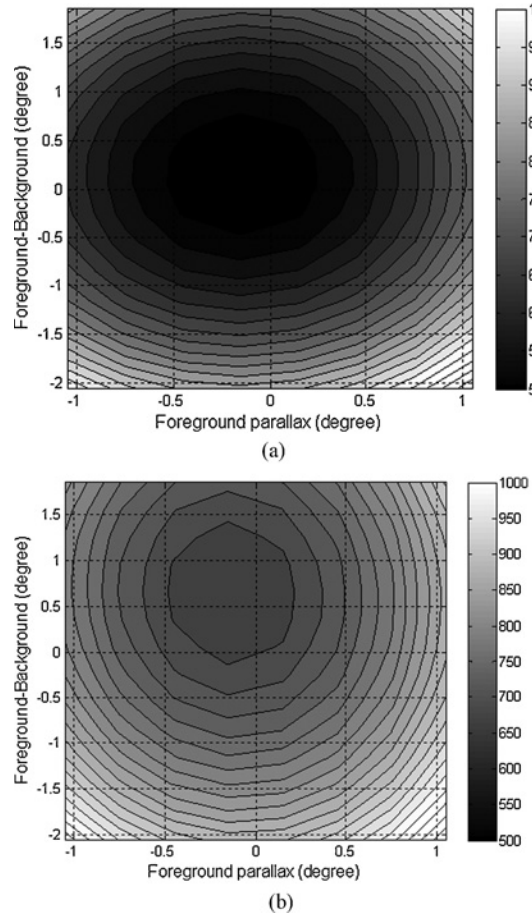


Fig. 3. Fusion time for foreground parallax and parallax difference. (a) 3-D-familiar subjects. (b) 3-D-unfamiliar subjects.

foreground parallax and parallax difference. Fig. 3 shows the fusion time, in which the *x*-axis and *y*-axis represent foreground parallax and parallax difference, respectively. The graph is modeled by polynomial surface fitting and is bell-shaped with a gradient increase in fusion time according to the increase in foreground parallax and parallax difference. This reveals that parallax difference also has a significant influence on fusion time and might affect visual fatigue, while conventional guidelines or studies only focus on the amount of foreground parallax. Fusion times from 3-D-unfamiliar subjects were slower and more biased than times from 3-D-familiar subjects as shown in Fig. 3(a) and (b). The bias occurred because 3-D-unfamiliar subjects showed a slight delay in discriminating the orientation of the pattern when the pattern and background were on the same depth plane.

B. Effects of Aperture Size, Corrugation Frequency, and Focal Distance

Fig. 4 shows the fusion times for foreground parallax with aperture size, corrugation frequency, and focal distance. In Fig. 4(a), the majority of the influence was driven by foreground parallax. In Fig. 4(b), higher fusion time occurred with higher corrugation frequency. Fig. 4(c) shows the fusion time for foreground parallax and focal distance. Focal distance is a fixed value when the viewing distance is constant. Fusion time is only affected by foreground parallax for long focal distances, while it is slowed at relatively short focal distances.

VI. Relationship Between Fusion Time and Visual Fatigue from Subjective Evaluation

We verified the relationship between the fusion time and visual fatigue by comparing subjective evaluations of 40 stereoscopic images. The images were selected to have a wide range of visual fatigue levels because they were chosen from scenes filmed under various shooting conditions, and thus have different characteristics for horizontal parallax. We utilized the results of subjective evaluation, foreground parallax, and parallax difference from our previous work [18]. Five-level grades were used to rate the subjective visual fatigue, and foreground parallax and parallax difference were calculated by feature matching from the left and right images [18].

Fusion times for foreground parallax and parallax difference were calculated as shown in Fig. 3 with the same focal distance as in previous subjective evaluations. Then, fusion times for every image were estimated by inserting foreground parallax and parallax difference into the surface model. The scatter

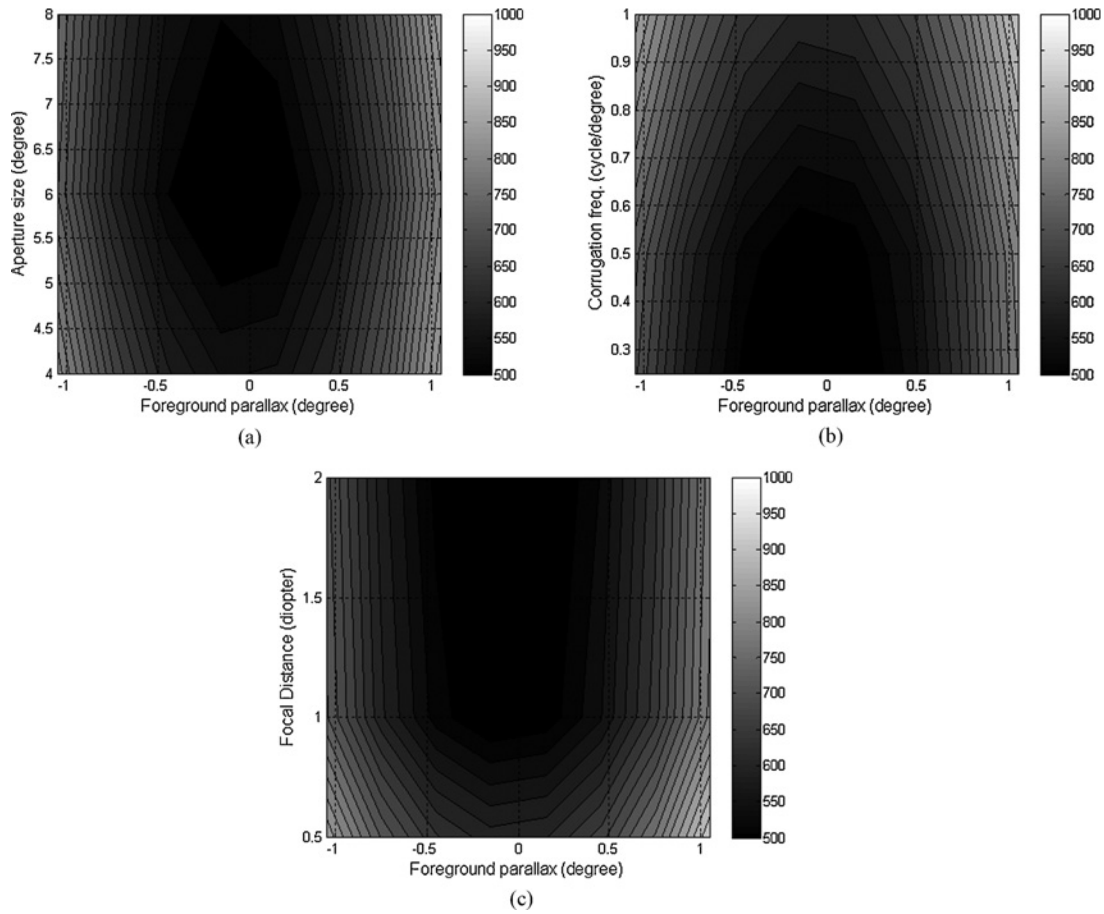


Fig. 4. Fusion time for (a) aperture size, (b) corrugation frequency, and (c) focal distance.

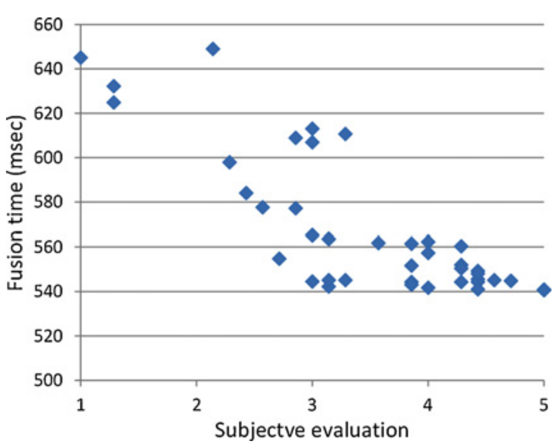


Fig. 5. Scatter plot of subjective evaluation and fusion time.

plot of subjective evaluation and fusion time for stereoscopic images is shown in Fig. 5; Pearson's correlation coefficient was 80.76%, which indicates that fusion time for the random dot stereograms and visual fatigue from real stereoscopic images are highly correlated.

VII. Conclusion

Although various studies of human factors have been conducted, it is clear that more studies should be performed on stereoscopic characteristics of the human visual system and visual fatigue. In this paper, we conducted an experiment to investigate the effect of vergence–accommodation conflicts that occur from conventional stereoscopic displays. We tested various conditions by varying foreground parallax, background parallax, focal distance, aperture size, and corrugation frequency. The results showed that foreground parallax and parallax difference have a significant influence on fusion time. In addition, the fusion times of random dot stereograms are highly correlated with visual fatigue from stereoscopic images. In future work, we will extend our research to establish guidelines for stereoscopic videos based on the study of random dot stereogram videos, since guidelines for safe stereoscopic imaging and viewing are necessary for the success of 3DTV.

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