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Experimental investigation of the effect of binocular disparity on the visibility threshold of asymmetric noise in stereoscopic viewing

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Abstract: Stereoscopic images could have asymmetric distortions caused by image processing in capture, synthesis, and compression of them. In 3D perception in stereoscopic display, the visibility threshold of the asymmetric distortions in the left and right images is important, which is tolerable to the human visual system. In this paper, we investigate the effect of the binocular disparity on the visibility threshold of asymmetric noises in stereoscopic images via subjective assessments. Existing just-noticeable-difference (JND) models for stereoscopic images have not taken into account the effect of the disparity in stereoscopic viewing. In this paper, we subjectively assessed the visibility threshold of asymmetric noises in stereoscopic images according to the disparity. Subjective evaluations showed that large disparity magnitudes could make more tolerable to perceive the asymmetric noises in the stereoscopic viewing.

OCIS codes: (330.0330) Vision, color, and visual optics; (330.1400) Vision - binocular and stereopsis.

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1. Introduction

Stereoscopic three-dimensional (S3D) display systems provide viewers with a unique viewing experience by presenting binocular disparity into the left and right eyes. By fusing the binocular disparity, human visual system (HVS) perceives the relative depth of the presented scene; this is called as stereopsis [1]. The left and right images presented in S3D displays could have undesirable differences (e.g., different intensities and appearances in the left and right images) due to the asymmetric capture, synthesis, compression, and streaming of stereoscopic images. To properly address the perceptual issue of stereoscopic images, the visibility threshold of the asymmetric noises in the left and right images is important, which is tolerable to the HVS.

To determine the visibility threshold of the HVS, just-noticeable-difference (JND) models have been studied and extensively exploited in many image and video processing applications [2–6]. The visibility threshold could be affected by the features of stimulus such as the average background luminance behind pixels and the spatial non-uniformity of background luminance [6–10]. The conventional JND models for 2-D images would be not applicable for stereoscopic images because they did not consider the properties of stereoscopic viewing (e.g., binocular fusion of asymmetric noises). For S3D contents, Zhao *et al*. constructed a binocular JND (BJND) model [11]. They conducted psychophysical experiments to measure the visibility threshold of asymmetric noises according to the luminance and the contrast masking effects and binocular combinations of noise. However, their BJND model did not include the effect of disparity of visual stimuli on the visibility threshold.

In fact, many previous studies indicated that an amount of binocular disparity could have significant influences on the visual performance of human eyes [12,13]. Hoffman *et al*. showed that a conflict between accommodation and vergence coming from screen disparities (i.e., it is related to converging angles of the two eyes, and the distance to the screen [14].) degraded visual performance and increased binocular fusion time [12]. Zaroff *et al*. reported that the ability to perceive disparity difference (i.e., stereoacuity) could increase as the disparity decreased [13]. In an objective quality metric for synthesized stereoscopic images

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[15], the perceptual quality degradations induced by left and right mismatches could be accurately predicted by taking into account the disparity. Given the above previous studies, we speculate that the visibility threshold of asymmetric noise could be affected by the disparities of visual stimuli. To the best of our knowledge, there have been no attempts to investigate the relationship between binocular disparity and the visibility threshold of asymmetric noise.

The purpose of this paper is to investigate the effect of disparity magnitude (i.e., the amount of binocular disparity) on the visibility threshold of asymmetric noise. Subjective assessment has been conducted with stereoscopic square targets, which have a disparity varying from −1.00 to + 1.00 degree and a background luminance varying from 1 to 90 cd/m^2. The square targets on the left and right images have asymmetric noises. Our subjective assessment experiment aims to measure the perceptible asymmetric noise amplitudes at varying disparities in stereoscopic viewing.

The experimental results showed that disparity magnitude could significantly affect the visibility threshold of the asymmetric noise in stereoscopic viewing. In particular, the threshold for detecting asymmetric noise increased as stimulus binocular disparity increased.

The remainder of this paper is organized as follows. In Section 2, we describe the experimental method used in our subjective measurement of the visibility threshold of asymmetric noise. Section 3 presents the experimental results and discussion. Finally, conclusions are drawn in Section 4.

2. Method

2.1 Subject

Fifteen subjects were participated in the experiment to measure the visibility threshold of asymmetric noise. The subject's ages ranged from 22 to 31 with an average age of 25.53 years. All subjects had normal or corrected-to-normal vision with a minimum stereoacuity of 50 arcsec (measured by the Randot stereotest®). The subjects were recruited under the approval of the KAIST institutional review board (IRB).

2.2 Apparatus

The subjective assessment was conducted in a dark room (room illumination was 9.34 lux as measured by Minolta T-10®) with a stereoscopic display (Redrover SDM-400®). The display consisted of a half mirror and two 40-inch liquid crystal displays (LCDs). The spatial resolution of each LCD was 1920 × 1080 pixels. The bit depth of the display was 8-bit. For the calibration of LCDs in the left and right displays, we calibrated the physical luminance values on the left and right displays from pixel intensity values with spectroradiometer (Minolta CS-1000®). Based on the definition of crosstalk [16,17], the crosstalk levels of the left and right displays were measured as 0.75% and 0.27%, which were lower than the visibility threshold of crosstalk [16]. The crosstalk levels were measured by the spectroradiometer (Minolta CS-1000®) as well. The viewing distance between a subject and the stereoscopic display was 1.5 meters, which was about three times the height of the display [18]. The horizontal and vertical viewing angles were 32.91 degrees and 18.85 degrees, respectively. The viewing environment was set up based on the recommendations of the ITU-R BT. 500-11 [18] and BT. 1438 [19].

2.3 Visual stimulus

As shown in Fig. 1(a), visual stimulus consisted of a square (5° × 5° of visual angle; corresponding to parafovea [20]), a fixation cross (0.8° × 0.8° of visual angle [21]), and a uniform background (chromaticity: D65, illumination: 28.87 cd/m^2). The fixation cross had a zero disparity to signal the screen plane. As shown in Fig. 1(b), the 5° × 5° square was

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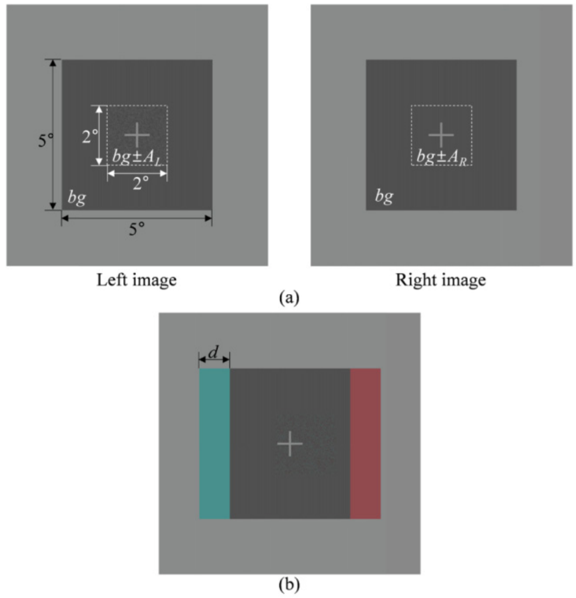

Fig. 1. (a) Illustration of the visual stimulus of the left and right eye images. (b) Anaglyph view of the visual stimulus. Note that *bg* denotes the background luminance (cd/m^2), *d* denotes the disparity (degree), A_L and A_R denote the noise amplitude (cd/m^2) injected in the left and right images, respectively. The bipolar noise was randomly injected in the 2° × 2° central area (i.e., dashed region) in (a).

Table 1. Visual stimulus attributes.

Parameters	Conditions
Background luminance (*bg*)	1, 9, 38, 90 (unit: cd/m^2)
Noise amplitude injected in the left view (A_L)	0, 0.002, 0.010, 0.050 (unit: cd/m^2)
Disparity (*d*)	−1, −0.75, −0.5, −0.25, 0, 0.25, 0.5, 0.75, 1 (unit: degree)

Note that negative disparity values represent the crossed disparity (i.e., squares in front of the screen) and positive disparity values represent the uncrossed disparity (i.e., squares behind the screen). The noise amplitudes {0, 0.002, 0.01, 0.05} in physical luminance value correspond to {0, 2, 4, 8} in pixel intensity values, used in [11].

displaced in a depth with a certain amount of disparity. Depth information of the square was generated by shifting squares to opposite direction in left and right views. Note the fixation cross always had a zero disparity. For asymmetric noise, the bipolar noise patterns with the independent amplitude, A_L and A_R were added into the central area (2° × 2° of visual angle; corresponding to the fovea [22]) in the left and right images, respectively [11]. The bipolar noise patterns (+ or -) were randomly generated. So, the noise patterns presented to the left and right eye were identical but independent amplitude. Table 1 shows the attributes of visual stimuli. As seen in Table 1, four different background luminance values (*bg*), four different noise amplitudes injected in the left image (A_L), and nine different disparity values (*d*) were examined in this study. Note that the disparity values of visual stimuli were carefully selected to avoid visual discomfort effect in subjective assessment. Disparity values examined in this study were within the so-called comfort zone, which is generally considered to be about 1 degree of screen disparity [23]. As a result, a total number of 144 visual stimuli were generated for the subjective assessment (i.e., 144 = 4 background luminance values × 4 noise amplitude levels × 9 disparity values).

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2.4 Procedure

A visual stimulus was randomly chosen from 144 visual stimuli and was presented to the subjects. Let A_L denote the noise amplitude of the left image and $A_R(n)$ denote the noise amplitude in the right images assessed by the n-th subject. Given the noise amplitude in the left view (A_L) at different disparities (d) and background luminance (bg), a subject (e.g., n-th subject) adjusted the noise amplitude in the right view ($A_R(n)$) with the staircase method (reversal 3) [24] for detecting the just noticeable noises pair $\{A_L, A_R(n)\}$. Note that the noise amplitude in the right view started from the same amplitude in the left view. The noise amplitude in the right view indicates the visibility threshold which can evoke perceptible asymmetric noise in the stereoscopic viewing for the n-th subject. From all 15 subjects, we gathered the perceivable asymmetric noise pairs $\{A_L, A_R(n)\}$ under 9 disparities and 4 background luminance levels. Then, the measured right noise amplitude A_R (i.e., visibility threshold) that makes asymmetric noise perceptible was obtained by averaging individual thresholds ($A_R(n)$). Note that for each trial, the subjects were instructed to hold their visual fixation on the fixation cross. In addition, the subjects were also instructed to maintain the binocular fusion state when the central square was perceived as a single vision (not double vision) [25].

The exposure time of a visual stimulus was not limited to provide sufficient time to judge the visibility threshold of asymmetric noise [26]. To avoid visual fatigue which could be induced in the assessment process for all visual stimuli, the test was paused after every 30 minutes and the subjects were instructed to relax their eyes [27]. Even within 30 minutes of testing, the test was stopped immediately when the subjects sensed any visual fatigue.

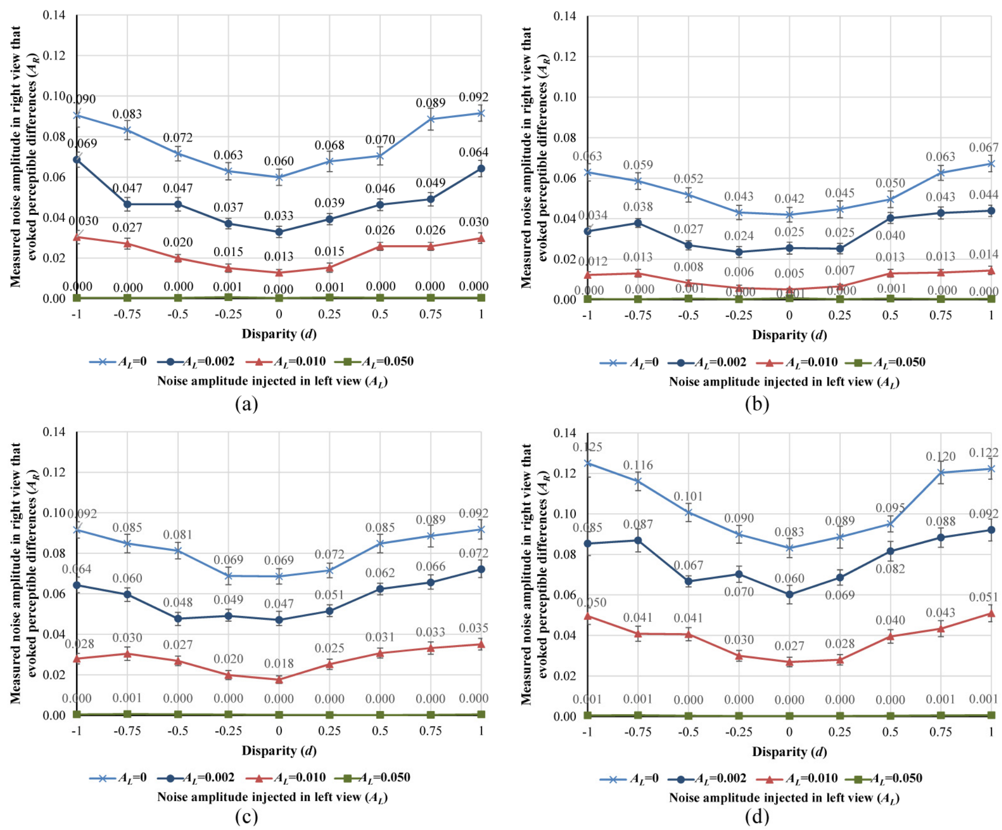

Fig. 2. Measured noise amplitudes in the right image that evoked perceptible difference (i.e., *visibility threshold of asymmetric noise*) along the disparity. (a) Visibility threshold for 1cd/m^2

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of background luminance, (b) for 9cd/m^2 of background luminance, (c) for 38cd/m^2 of background luminance, and (d) for 90cd/m^2 of background luminance. The abscissa represents the disparity (in degree). The ordinate represents the measured visibility threshold (A_R). In figures, different markers represent the different noise amplitudes injected in the left image (A_L). The error bars represent the standard error of the mean. Note that subjects were instructed to hold their fixation on the fixation cross with a zero disparity in order to induce viewers' vergence on the screen plane.

Table 2. Statistical analysis results using the two-way repeated-measures ANOVA

Background luminance	Factors	Mauchly's test of sphericity (p-value)	F statistics	p-value
1 cd/m^2	d	$p = 0.549$	$F(8,112) = 9.577$	$p<0.001$
	A_L	$p = 0.259$	$F(3,42) = 2529.660$	$p<0.001$
	dxA_L	.	$F(24,336) = 3.642$	$p<0.001$
9 cd/m^2	d	$p = 0.435$	$F(8,112) = 21.253$	$p<0.001$
	A_L	$p = 0.061$	$F(3,42) = 1188.760$	$p<0.001$
	dxA_L	.	$F(24,336) = 3.057$	$p<0.001$
38 cd/m^2	d	$p = 0.218$	$F(8,112) = 11.840$	$p<0.001$
	A_L	$p = 0.209$	$F(3,42) = 3182.144$	$p<0.001$
	dxA_L	.	$F(24,336) = 1.980$	$p = 0.005$
90 cd/m^2	d	$p = 0.627$	$F(8,112) = 25.003$	$p<0.001$
	A_L	$p = 0.074$	$F(3,42) = 2393.674$	$p<0.001$
	dxA_L	.	$F(24,336) = 2.183$	$p = 0.001$

Note that d denotes disparity, A_L denotes noise amplitude injected in left image, and dxA_L denotes the interaction between the disparity and the noise amplitude injected in the left image.

3. Results and discussions

Figure 2 shows the measured noise amplitudes in the right image which evoked perceptible difference (i.e., visibility threshold of asymmetric noise) in different disparities. In the Fig. 2, different markers represent different noise amplitudes injected in the left image (A_L). As seen in the Fig. 2, the visibility threshold of the asymmetric noise increased as disparity magnitude (i.e., absolute disparity values) increased for all background luminance. For instance, for a case of no noise in the left image (A_L = 0), the visibility threshold increased from 0.060 to 0.092 cd/m^2 for 1cd/m^2 of background luminance, from 0.042 to 0.067 cd/m^2 for 9cd/m^2 of background luminance, from 0.069 to 0.092 cd/m^2 for 38cd/m^2 of background luminance, and from 0.083 to 0.125 cd/m^2 for 90cd/m^2 of background luminance as the disparity magnitude increased from 0 to 1 degree, respectively. In addition, the visibility threshold of the asymmetric noise decreased as the noise amplitude injected in left image increased. For the large noise amplitude (A_L = 0.05) in the left image, subjects perceived asymmetric noise in most of the disparity magnitudes. As seen in Figs. 2(a)-2(d), the visibility threshold of the asymmetric noise varied at different background luminance values [11].

To check the statistical significance of the effect of the disparity on the visibility threshold of the asymmetric noise, two-way repeated-measures ANOVA test [28] was conducted. In the statistical analysis, the disparity (d) and the noise amplitude injected in the left image (A_L) were considered as within-subjects variables. In general, for a within-subjects design, within-subjects variables were manipulated by testing each subject at each level of the variables. Table 2 shows results of the statistical significance test. As seen in the table, the effect of the disparity and the noise amplitude injected in the left image on the visibility threshold of the asymmetric noise was significant for each background luminance of a visual stimulus (p<0.001). In addition, the interaction between the disparity and the noise amplitude injected in the left image was significant at 95% confidence level (p<0.005). This result indicates that

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the effect of the disparity on the visibility threshold of an asymmetric noise varies with the noise amplitude injected in the left image.

In sum, the observations from the above subjective assessment results are as follows: 1) the visibility threshold of the asymmetric noise increased as the disparity magnitude increased for each background luminance value, and 2) the visibility threshold of the asymmetric noise decreased as the noise amplitude injected in the left image increased. Based on these observations in this study and the previous studies on binocular vision [11,29,30], a visibility threshold of the asymmetric noise for a background luminance, which includes both effects of the disparity and the noise amplitude in one eye image, can be modeled as

Table 3. Estimated parameter values and the goodness-of-fit statistics of visibility threshold models

Background luminance (bg)	Estimated parameters				R-square
	λ	α	β	γ	
1 cd/m^2	1.2577	1.2514	0.0622	5.9082	0.9903
9 cd/m^2	1.3184	1.1775	0.0800	4.9094	0.9815
38 cd/m^2	1.3245	0.8773	0.0533	6.2863	0.9921
90 cd/m^2	1.2552	1.4026	−0.0222	6.9267	0.9913

$$Thr_{bg}(d, A_L) = A_{\text{limit},bg}(d)\left(1-\left(\frac{A_1}{A_{\text{limit},bg}(d)}\right)^{\lambda}\right)^{\frac{1}{\lambda}}, \text{for } -1 \le d \le 1, \text{and } 0 \le A_1 \le 0.050. \quad (1)$$

where A_1 denotes the noise amplitude in one eye image (e.g. A_1 is A_L in Fig. 2), and Thr_{bg} denotes the visibility threshold of the asymmetric noise (the minimum noise amplitude in the other eye image that evokes the perceptible difference for a given background luminance). λ is a regression parameter, which was obtained by minimizing the sum of square errors between the model-calculated visibility thresholds and the subjectively measured visibility thresholds. $A_{\text{limit},bg}$ is the upper limit of Thr_{bg} (i.e., $A_1 = 0$) for given background luminance.

Based on the observation that subjectively measured visibility thresholds increased along the disparity magnitude in a convex form, we define $A_{\text{limit},bg}(d)$ as a quadratic polynomial function of d, which can be written as

$$A_{\text{limit},bg}(d) = \alpha d^2 + \beta d + \gamma. \quad (2)$$

where α, β, and γ are regression parameters. Table 3 summarizes the estimated parameter values and the goodness-of-fit statistics of the visibility threshold models.

Figure 3 represents the modeled visibility threshold of the asymmetric noise along the disparity change for background luminance. The abscissa represents the disparity (in degree) and the ordinate represents the visibility threshold of the asymmetric noise. As shown in Fig. 3, the model captures the disparity effect on the visibility threshold of the asymmetric noise.

We examined whether the modeled visibility threshold of the asymmetric noise is also valid for other subjects. To this end, an additional subjective assessment was conducted with newly recruited ten subjects [31,32]. To obtain the visibility threshold of the asymmetric noise for the new subjects, we used the same experimental setup, visual stimuli, and procedures as described in Section 2. Then, the visibility thresholds of the asymmetric noise were obtained for the new subjects, which were compared in the models in Fig. 3. The mean absolute difference (MAD) between the predicted visibility thresholds of the asymmetric noise and the measured visibility thresholds was as small as 0.0022 ± 0.0012 (mean ± std). In addition, the difference between the predicted visibility thresholds of the asymmetric noise and the measured visibility thresholds was not statistically significant (pairwise *t*-test [28];

$t(143) = 1.582$, $p = 0.141$). These results suggest that the modeled visibility threshold of the asymmetric noise could be valid for other subjects.

There are various potential sources of binocular mismatches [33]. Many stereoscopic image processing related to the binocular mismatch (e.g., objective quality assessment [15,34]) could achieve better performances by considering the BJND model, which took into account purely noise amplitude deviation [11]. In [34], the BJND was used as the weight of the quality score for binocular mismatched regions. A high BJND value at a pixel indicated that the pixel was less important. It could improve the performances of the quality assessment for stereo images including various noises (e.g., JPEG, Gaussian blur, white noise, etc.). In [15], the BJND model was used to detect the most important errors between the left and right images (LR critical areas). By determining the threshold based on the model, more accurate LR critical areas could be detected for quality assessment of the synthesized stereo images.

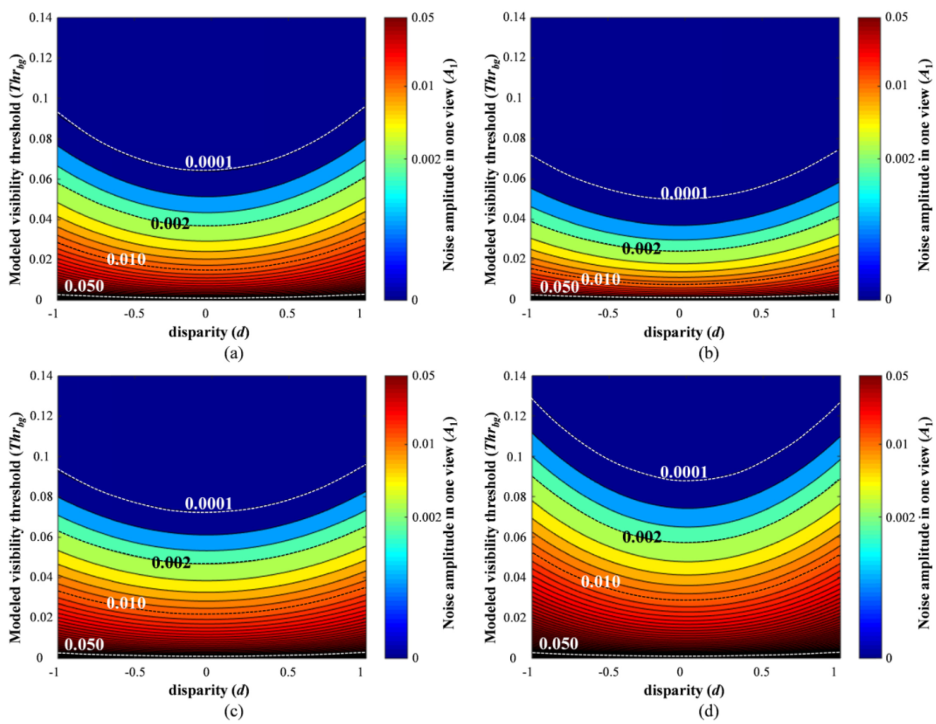

Fig. 3. Modeled visibility threshold of the asymmetric noise along the disparity change. Each value in the dashed-line contour represents given noise amplitude in one eye image (A_1). (a) Modeled visibility threshold for 1cd/m^2 of background luminance, (b) for 9cd/m^2 of background luminance, (c) for 38cd/m^2 of background luminance, and (d) for 90cd/m^2 of background luminance. Note that the colorbar is in log scale for display.

The above previous works indicate that noise amplitude deviation is one of the important factors affecting the binocular asymmetry in the stereoscopic viewing.

The study in this paper is in line with the previous works in terms of the use of BJND model. We can observe the impact of the disparity on the noise amplitude deviations. In addition, we can predict the visibility threshold model considering the effect of binocular disparity on the visibility threshold of asymmetric noises. It is challenging to generalize the effect of binocular disparity on various factors of binocular mismatches. The effect of binocular disparity on the visibility threshold of other binocular mismatches could be good research subject to be investigated as a further work.

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4. Conclusion

In this paper, the effect of binocular disparity on the visibility threshold of the asymmetric noise was investigated. We subjectively assessed the visibility threshold of the asymmetric noise with different disparity values under the various noise levels and background luminance conditions. Experimental results showed that the binocular disparity could affect the visibility threshold of the asymmetric noise in the stereoscopic viewing. From the subjective assessment results shown in Fig. 2, we observed that the visibility threshold to notice the asymmetric noise increased as the disparity increased. The effect of the disparity on the visibility threshold was statistically significant as seen in Table 2. Based on the experiments, we devised the visibility threshold model containing the binocular disparity effect in the stereoscopic viewing. We believe that our observation and quantification of the visibility threshold can be utilized to provide more accurate estimation of stereoscopic perceptual effect. In the quality assessment application [34], the excessive distortions in mismatched regions can be assigned higher weights of quality score based on the visibility threshold, so that the quality of stereoscopic images could be better accessed.