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The Effects of Disparity Cue and Blur Cue on the Relative Visual Comfort of Stereoscopic Content

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Abstract. *The human visual system produces the sensation of stereopsis with the help of depth cues. Disparity and blur (defocus) are widely accepted as the most important depth cues. The two cues are also known to have important effects on the visual discomfort caused by viewing stereoscopic content. However, the relationship between the combination of the two cues and visual comfort has rarely been investigated, especially when considering the effects of proximity cues, e.g., looming and motion parallax. In this study, various stereoscopic videos were compared with the planar videos corresponding to them. Each of the stereoscopic videos contained a set of depth cues, and the levels of the cues varied from video to video. The subjects were required to judge the relative visual comfort (RVC) for each pair, where RVC means the level of visual comfort of the first stimulus in the pair relative to the second one. The results showed that both disparity and blur have significant effects on RVC. The effects of disparity did not vary significantly with blur and proximity cues, and the effects of blur did not vary significantly with disparity and proximity cues. Based on these findings, the authors further built a regression model for the estimation of RVC from depth cues.* © *2016 Society for Imaging Science and Technology.*
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INTRODUCTION

Many daily or professional activities are often accompanied by intensive use of eyesight, and may cause visual discomfort. It is believed that viewing stereoscopic content causes extra visual discomfort,[1–3] and one of the most important reasons is the vergence–accommodation conflict caused by stereoscopic content.[4] For example, Hoffman et al. find that vergence–accommodation conflicts not only hinder visual performance, but also cause visual fatigue.[5] Besides, there are interactions between vergence and accommodation.[6] Yuuki Okada et al. measured the accommodation and convergence of subjects continuously when they were viewing a high-contrast Maltese Cross target at three levels of Gaussian filter target blur. They proposed that defocus-driven accommodation became weak when the target comprised low-spatial-frequency components.[7]

Based on the findings, some methods were proposed to relieve visual discomfort. For example, Leroy et al. proposed an algorithm for removing the high-frequency information in high-disparity zones, and then quantified the beneficial effect of the algorithm.[8] MacKenzie et al. examined the minimum image-plane spacing needed for accurate accommodation to binocular depth-filtered images, and concluded that depth filtering could be used for precisely matching accommodation and vergence demand in a practical stereoscopic display.[9] In the method proposed by Yong et al., the disparity of a scene was adjusted under the guidance of an objective metric of visual comfort. The metric took into account various discomfort factors in stereoscopic viewing.[10] Woods et al. also proposed a method based on disparity remapping to ameliorate visual comfort of stereoscopic video.[11]

Disparity and blur are treated as the main depth cues,[12] which have important influences on vergence and accommodation responses. A series of studies have been devoted to depth cues such as blur (defocus), binocular disparity and proximity cues.[12–15] Other than these cues, optic flow has also been proved to be a type of depth cue. Busettini et al. found that radial optic flow can elicit horizontal vergence eye movements with ultra-short latencies in human subjects.[16]

Disparity, which indicates the difference between the retinal images in different eyes, has been proved to have effects on visual comfort when viewing stereoscopic videos.[17] Yano et al. found that a local low subjective evaluation appeared for both high degree of disparity and amount of

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Table I. The possible values of the three factors. Disparity cue was actually represented using the apparent depth of the main targets, which could be measured by distance or diopter.

Factor (depth cue)	Abbreviation	Value	Unit
Blur cue	B	0, 16, 32	Minute of arc
Disparity cue	D	10, 5, 1	Meter
(Apparent depth of main target)		0.1, 0.2, 1	D (Diopter)
Proximity cues	P	0, 1	

motion in the test stereoscopic images. In their study, when the amount of disparity was large but motion components were very small, the subjective evaluation value was on average higher.[18] Nojiri et al. found that the features of disparity distribution in a frame are strongly related to visual comfort, and large disparity causes discomfort even if the motion is small.[19]

Researchers have also reported the effects of blur on visual comfort. O'Hare et al. found that a relative reduction in high-spatial-frequency contrast results in both increased discomfort and perceived blur, no matter whether in artificial or natural stimuli.[20] However, O'Hare also found that DOF (Depth-Of-Field) can be used as a cue to depth without inducing visual discomfort, even when cue conflicts are large. For DOF, the fixation point is in focus despite the majority of the image being blurred.[21] In addition, Schor et al. found that binocular sensory fusion is at least 600% larger when stimulated by low-spatial-frequency (coarse) detail.[22]

Although the two cues are known to have effects on visual comfort, it is not very clear whether there are interactions between these effects. The aim of this study is to investigate the existence of interactions, and then further build a model for estimation of visual comfort based on the cues. By doing this, deeper insight may be gained into the relationship between depth cues and visual comfort.

METHOD

Apparatus

Stimuli were presented at a distance of 1.8 m, on an LG television with a size of 1.05 m × 0.59 m and a screen resolution of 1920 × 1080. The distance was about three times the screen height, which is recommended by ITU-R BT.2021-1.[23] A desktop PC was used to present stimuli and record the response of the observers. A desk and chair were set properly so that subjects could easily keep the correct position relative to the screen.

Observers

Fifteen naïve observers (8 male and 7 female) took part in experiment 1. They ranged in age from 21 to 34 years; the mean age was 25.5. All participants in this study were paid for their participation measured by time period, and they all had normal (no need to wear glasses) or corrected-to-normal (wear glasses) vision. The entire study was approved in accordance with the Declaration of Helsinki.

Stimuli

All stimuli were 10 s and 1920 × 1080 pixels, which were used in paired comparison. Each stimulus had a main target displayed at the center, and also several other patterns around it. The main target might have different disparities but similar apparent sizes in different stimuli. The surrounding patterns might have different sizes, positions and disparities so that proximity cues could be included. Besides, the contrast of stimuli is believed to have effects on visual comfort. Therefore, we calculated the average contrast of each video, and the results showed that there was no significant difference between 3D and 2D stimuli. As shown by Table I, several combinations of three depth cues were taken into account when designing the stimuli.[12]

Two types of main target were adopted. One was a clear pattern which contained a lot of high-frequency spatial information. The other was a blurred pattern with little high-frequency spatial information. For the latter, the corresponding stimuli were further blurred using a Gaussian filter. Three blur levels were used according to Okada: 0 (no blur), 16 and 32 arcmin, which corresponding to the values of 0, 13 and 26 (unit: pixel) used in our program, respectively.[7]

The disparity of the main target was changed so as to get three different apparent distances: 10 m, 5 m and 1 m; namely, 0.1D, 0.2D and 1D. However, the main target was kept at the same apparent size.

A stimulus might have or not have proximity cues. When there were proximity cues, several patterns were arranged from near to far around the main target. There were also several other patterns moving in and out repeatedly. When there were no proximity cues, several patterns were arranged at the same depth around the main target, and there were no moving patterns.

Each combination of the above three cues corresponded to one 3D stimulus, and each 3D stimulus corresponded to one 2D stimulus. The only difference between the 3D and 2D stimuli was that the 2D stimulus had no disparity.

Procedures

Every subject was required to take a vision test. Only those who had normal stereovision took part in the formal experiment.

The procedure of experiment 1 was designed according to the "paired comparison" regulation in ITU-R BT.2021-1.[23] Each 3D stimulus was compared with the corresponding 2D stimulus.

Figure 1 shows the procedure of the paired comparison in the experiment. First, a hint was initially shown to the observer for 3 s, indicating the beginning of the experiment. After that (1) one stimulus was shown for 10 s, (2) a mid-gray field was shown for 3 s, (3) the other stimulus was shown for 10 s, (4) another hint was shown for 7 s, and the observer was required to rate the relative comfort of the first stimulus over the second. The value of relative comfort could be one of the values shown in Table II.

Steps (1)–(4) were repeated until all the pairs were compared. As each pair was compared twice (in a different

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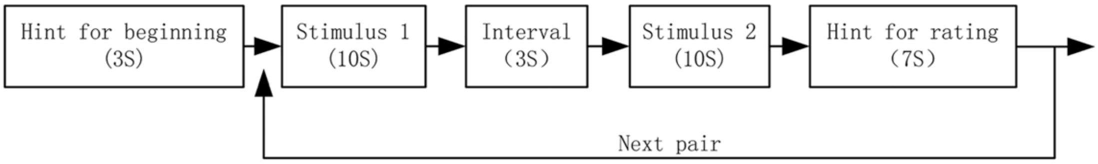

Figure 1. The procedure of the paired comparison. Stimulus 1 and stimulus 2 were one 3D stimulus and the 2D stimulus corresponding to it.

Table II. The possible values of relative comfort.

−3	−2	−1	0	1	2	3
Much worse	Worse	Slightly worse	The same	Slightly better	Better	Much better

Table III. The results of ANOVA for disparity.

	Sum of squares	df	Mean square	F	Sig.
Between groups	87.207	2	43.604	46.791	0.000
Within groups	248.811	267	0.932		
Total	336.019	269			

Table IV. The results of ANOVA for blur.

	Sum of squares	df	Mean square	F	Sig.
Between groups	13.635	2	6.818	5.646	0.004
Within groups	322.383	267	1.207		
Total	336.019	269			

order), the total number of comparisons was twice the number of stimuli.

Results

In this study, the 3D stimuli were very similar to the corresponding 2D stimuli in content. Repeated measures ANOVA was conducted, and the results for disparity are listed in Table III.

As shown by Table III, disparity has significant effects on relative visual comfort ($F = 46.791$, $p < 0.001$). The results for blur are listed in Table IV.

As shown by Table IV, blur also has significant effects on relative visual comfort ($F = 5.646$, $p = 0.004$). Repeated measures MANOVA was also conducted to further reveal the interaction between disparity and blur. The results are listed in Table V.

As shown by Table V, there are neither significant two-way nor significant three-way interactions. Figures 2 and 3 show the plots of relative visual comfort with different cues. It can be seen that relative visual comfort always has similar profiles in different conditions. For disparity, a value of −98 tends to cause the lowest visual comfort. For blur, the lowest visual comfort tends to appear in the condition of no blur.

Table V. The results of MANOVA for the three cues.

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	114.319[a]	17	6.725	7.644	0.000
Intercept	231.481	1	231.481	263.118	0.000
Disparity * blur	3.176	4	0.794	0.902	0.463
Proximity * blur	0.080	2	0.040	0.045	0.956
Proximity * disparity	1.119	2	0.559	0.636	0.530
Proximity * disparity * blur	2.254	4	0.563	0.640	0.634
Error	221.700	252	0.880		
Total	567.500	270			
Corrected total	336.019	269			

Table VI. The multivariate linear regression model.

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.
	B	Std. error	Beta		
1 (constant)	−1.248	0.171		−7.306	0.000
Blur	0.026	0.008	0.408	3.019	0.009
Depth	0.005	0.001	0.683	5.049	0.000
Proximity	−0.444	0.180	−0.333	−2.465	0.027

Based on the above findings, we further built a multivariate linear regression model for estimation of the relative visual comfort using the values of the three cues. The adjusted R^2 is 0.689, the significance of the model is less than 0.05, and the other values of the model are listed in Table VI.

As shown by Table VI, the Sig. values for all of the factors are less than 0.05. It is suggested that the variables have significant effects on relative visual comfort. According to the model, the relative visual comfort can be estimated using the following function:

$$C = -1.248 + 0.026b + 0.005d - 0.444p, \qquad (1)$$

where C represents the score of relative visual comfort, b represents the level of blur, d represents the level of disparity and p represents the level of proximity cues.

In order to verify the proposed model, correlation tests were further conducted for the two factors of most concern in this study, i.e., depth cue and blur cue. Pearson correlation and Spearman rank–order correlation were adopted, which are often used in the existing literature.[24,25] As shown by

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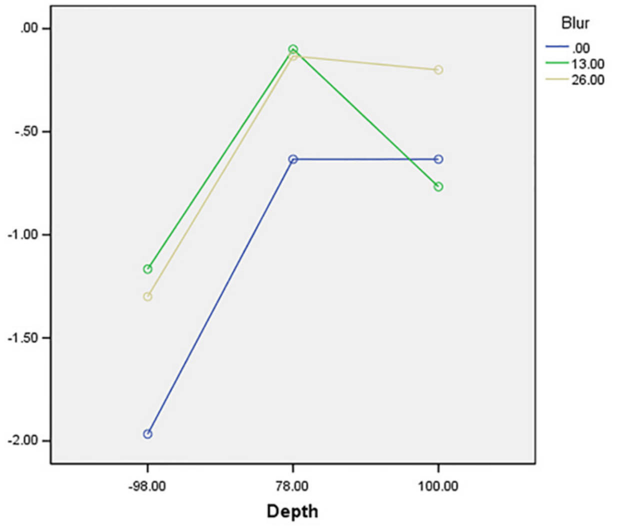

Figure 2. The plots of relative visual comfort with different cues when there are no proximity cues. The blue, green and yellow lines correspond to blur levels of 0, 13 and 26, respectively. The values −98, 78 and 100 are screen disparities, which correspond to 1 m, 5 m and 10 m of apparent depth, respectively.

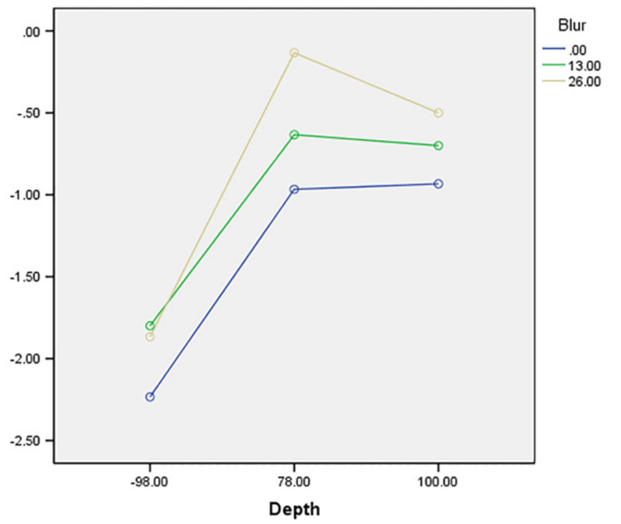

Figure 3. The plots of relative visual comfort with different cues when there are proximity cues. The blue, green and yellow lines correspond to blur levels of 0, 13 and 26, respectively. The values −98, 78 and 100 are screen disparities, which correspond to 1 m, 5 m and 10 m of apparent depth, respectively.

the result of Pearson correlation, depth cue and relative visual comfort were correlated, $r(16) = 0.68, p = 0.002$; blur cue and relative visual comfort were also correlated, $r(16) = 0.41, p < 0.1$. As shown by the result of Spearman rank–order correlation, depth cue and relative visual comfort were correlated, $r(16) = 0.51, p = 0.3$; blur cue and relative visual comfort were also correlated, $r(16) = 0.41, p < 0.1$. All of the results verify and support the proposed regression model.

DISCUSSION

As shown by the above results, both blur and disparity have significant effects on the relative visual comfort of stereoscopic videos. However, the effects of disparity did not vary significantly with blur and proximity cues, and the effects of blur did not vary significantly with disparity and proximity cues. Here, we attempt to give an explanation for the above findings.

On the one hand, the addition of different levels of blur seems to have a similar influence on the relative visual comfort of various disparities. It is already proven that increasing the level of blur enlarges binocular sensory fusion.[22] In this study, all of the selected disparities are within the normal limit of sensory fusion. Therefore, the improvement of visual comfort caused by blur might also be similar for different disparities. Proximity cues provide extra information for sensation of depth so that the vergence gets a stronger drive. As the accommodation is originally different from the vergence, the extra drive may enhance the vergence–accommodation conflict, and thus reduce the visual comfort. For different disparities, such an enhancement of conflict might be similar. Therefore, the change of visual comfort caused by proximity cues might also be similar across disparities.

On the other hand, the addition of different levels of disparity also seems to have a similar influence on the relative visual comfort of various levels of blur. Generally speaking, the visual comfort of stereoscopic videos increases with the level of blur. As such an increase is mainly due to the enlargement of binocular sensory fusion,[22] its contribution to visual comfort might not change with the level of disparity. Similarly, this may also be the reason why the effects of blur did not vary significantly with proximity cues.

CONCLUSIONS

The effects of disparity and blur on the relative visual comfort of stereoscopic videos were evaluated using paired comparison. The results demonstrated that both disparity and blur have significant effects on relative visual comfort in our conditions. However, when the interactions of disparity, blur and proximity cues are investigated, there are neither significant two-way nor significant three-way interactions of the depth cues. Specifically, the effects of disparity did not vary significantly with blur and proximity cues, and the effects of blur did not vary significantly with disparity and proximity cues. Based on these findings, a regression model was further built for the estimation of relative visual comfort from depth cues. The above findings could provide helpful guidance for the production of stereoscopic displays and the design of stereoscopic content.

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