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The Effects of Proximity Cues on Visual Comfort When Viewing Stereoscopic Content

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Abstract. *Proximity cues including perspective, motion parallax, etc., are important depth cues besides disparity cue and blur (defocus) cue. Disparity and blur are now known to have important effects on visual comfort when viewing stereoscopic content. However, the effects of proximity cues are still unknown. In order to explore this question, the authors conducted two experiments. In the first one, the instant effects of proximity cues on the visual comfort of 3D stimuli were assessed using relative comparison. There were, in total, three sessions in this experiment, in which all 3D stimuli were compared with different baselines. The results showed that proximity cues also have significant effects on visual comfort when viewing stereoscopic content. Such effects do not vary significantly with disparity cue, blur cue and the selection of baseline stimuli. In the second experiment, the authors further tested the stimuli with proximity cues, and the results were in accordance with many existing literature results when the stimuli were viewed consecutively. Their results suggest that the perspective information and radial optic flow in the proximity cues may increase vergence–accommodation conflict and therefore reduce visual comfort. However, the effects seem to be limited during consecutive viewing.* © *2017 Society for Imaging Science and Technology.*

INTRODUCTION

Modern life, and especially professional work like aviation, aerospace, traffic, health and education, etc., is often accompanied with intensive use of eyesight, which could potentially cause visual discomfort. The negative effect and potential harm have attracted academic attention in related disciplines, and much research has been devoted to the related issues, e.g., visual discomfort, vergence or accommodation response, depth cues and blurred visual content. However, visual discomfort is still prevalent in many professions related to visual tasks,[1] and may make observers tend to prefer a 2D presentation over a 3D one.[2] Usually, people believe that viewing stereoscopic content may cause visual discomfort more seriously than viewing real world scenes,[3] and also more seriously than viewing planar content.[4,5] One of the most important reasons is believed to be that there is vergence–accommodation conflict when viewing stereoscopic content.[6] Binocular disparity and blur are treated as the main depth cues.[7] They have important influences on vergence and accommodation response, either directly or through vergence–accommodation interaction.[8] Besides disparity and blur, there are some other cues called "proximity cues." These are combinations of dynamic cues such as looming, motion parallax and motion in depth, as well as static cues such as relative size, overlap, perspective, shading and texture gradients, and perceived position in space.[9,10] Proximity cues also have some effect on vergence and accommodation response.[7] In certain conditions, looming as a depth cue is even stronger than disparity when they are in conflict.[11] Some existing research has shown that disparity and blur in the content have important effects on visual comfort.[12] However, the effect of proximity cues is still not clear.

Visual Discomfort

In recent decades, the safety and health issues related to the use of VDTs (visual display terminals), especially stereoscopic displays, have been extensively investigated. The problem of visual discomfort is a highlighted topic in this research. In recent studies, researchers have intended to distinguish the term visual discomfort from the term visual fatigue, although in usual contexts they are often interchangeable. Lambooij et al. treat visual fatigue as decrease in performance of the human vision system, which can be objectively measured, while treating visual discomfort as the subjective counterpart of visual fatigue.[5] Urvoy et al. believe that visual discomfort is perceived instantaneously, while visual fatigue is induced after a given duration of effort.[2] The different definitions provide interesting reference for further research.

With the existing understanding of visual problems, some methods have been proposed accordingly to relieve visual discomfort. For example, Leroy et al. proposed an algorithm for removing the high-frequency information in high-disparity zones, and quantified the positive effect of the algorithm.[13] 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.[14] In the method proposed by Yong et al., the disparity

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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.[15]

Vergence or Accommodation Response

Hoffman et al. find that vergence–accommodation conflicts not only hinder visual performance, but also cause visual fatigue. They develop a novel 3D display which presents focus cues that are correct or nearly correct for the depicted scene, and then use the display to evaluate the influence of focus cues on perceptual distortions, fusion failures and visual fatigue. Their results show that viewer fatigue and discomfort are reduced when focus cues are correct or nearly correct.[16] Besides vergence–accommodation conflict, some other factors also cause visual discomfort on viewing stereoscopic content. For example, Collier et al. find that a slightly reduced vergence response increases subject comfort during the task.[17]

On the other hand, there is interaction between vergence and accommodation.[18] 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 blur. The experiment was conducted under conditions of both relatively low and high conflict between accommodation and convergence stimuli. The results showed that under the low-conflict conditions, accommodation was stable, but convergence-driven accommodation was dominant when the target was extremely blurred. Under the high-conflict conditions, the role of convergence-driven accommodation increased systematically with the degree of target blur. Therefore, they proposed that defocus-driven accommodation became weak when the target comprised low-spatial-frequency components.[19]

Depth Cue

A series of studies have been devoted to depth cues such as blur (defocus), binocular disparity and proximity cues. Mather et al. investigated the interactions between image blur and stereoscopic disparity, and proposed that cue combination between blur and disparity cues was weighted very heavily in favor of the latter. In addition, the visual system was most likely to make use of blur cues over distances beyond the range of disparity mechanisms since the two cues were effective over different distances.[20] Held et al. also believe that blur and disparity are complementary cues to depth. Furthermore, disparity is more precise near fixation and blur is more precise away from fixation. When both cues are available, observers rely on the more informative one.[21] However, Langer et al. drew a different conclusion on a different condition.[22] In the study conducted by Horwood et al., blur, disparity and looming cues were presented in combination or separately to evaluate their contributions to the total near response. The results showed that response gain for both vergence and accommodation reduced markedly whenever disparity was excluded, but with much smaller effects when blur and proximity were excluded. Therefore, they proposed that in mature, nonclinical, populations, the relative contribution of blur and proximity was weaker than disparity when driving vergence and accommodation to naturalistic targets.[7]

Other than the above 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. They further investigated and proposed that flow-induced vergence is just one of a family of rapid ocular reflexes, mediated by the medial superior temporal cortex, compensating for translational disturbance of the observer.[23] The study conducted by Iijima further demonstrated that vergence serves as a reliable marker signifying 3D depth perception when viewing 2D movies. Specifically, the pictorial gaze-area depth information affects vergence mainly in the virtual far space, while optic flow robustly affects vergence irrespective of the nearness.[24]

Visual Comfort and the Characteristics of Stimuli

It has been demonstrated that the contrast and spatial frequency of stimuli have important effects on visual comfort. O'Hare et al. found that visual noise with a $1/f$ amplitude spectrum (typical of natural images) was judged to be more comfortable than images with a relative increase in contrast energy within a narrow spatial frequency band. In addition, a peak centered on 0.375–1.5 cycles/degree of spatial frequency was more uncomfortable than a peak at a higher spatial frequency.[25] Their later study showed 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. They proposed that one potential reason for the results could be that blurring the image degrades the feedback for the accommodation response, and therefore leads to increased micro-fluctuation.[26]

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.[27] Several methods based on DOF have also been proposed to relieve visual discomfort.[28,29] The result demonstrated the positive effect of blur on visual comfort. In addition, Schor et al. found that binocular sensory fusion is at least 600% larger when stimulated by low-spatial-frequency (coarse) detail.[30]

Binocular disparity and motion in stimuli also have effects on visual comfort. Sumio Yano et al. found that a local low subjective evaluation appeared for both high degree of disparity and amount of 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 rarely very low.[12] On the other hand, 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.[31]

When the blur and disparity of the viewed area remain constant and there is no motion in that area, do the proximity cues produced by the surrounding area still have effects on visual comfort? Given that the effects of DOF and normal blur are quite different from each other, the answer for the above question may not be obvious and therefore needs investigation.

Current Study

The aim of this study is to assess the relationship between the proximity cues in stimuli and the visual comfort when viewing them. There are two aspects in this relationship, one of which is the instant effect of proximity cues on visual comfort, and the other of which is the accumulative effect.

The instant effect was assessed using a relative comparison to judge the relative visual comfort of 3D stimuli (stereoscopic stimuli) with different characteristics, to determine whether the presence of proximity cues has a significant influence on the judgment of visual comfort.

In order to assess the accumulative effect, the study was then extended to a consecutive viewing process. The observers were required to view both 2D and 3D stimuli for a period of time, and rate the visual comfort at any time. Moreover, eye movements and responses to questionnaires were collected to see if such stimuli cause obvious visual discomfort after viewing.

GENERAL METHODS

Apparatus

Stimuli were presented at a distance of 1.8 m, on an LG 47GB7800-CC television with polarized stereoscopic mode. The size of the screen is 1.05 m × 0.59 m, and the resolution is 1920 x 1080. The distance was about three times the screen height, which is recommended by ITU-R BT.2021-1.[32] An infrared HD camera (Sony HDR-PJ790E, 850 nm infrared camera lens) was used to capture the eye movements of the subjects, and an infrared light (850 nm) was used for illumination. A desktop PC was used to record subjective scores, questionnaire answers and present stimuli. A desk and a chair were set properly so that subjects could easily keep correct position relative to the screen.

Observers

We performed two experiments in total. 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 years. Efforts were made to ensure that the same observers participated in all sessions. However, only fourteen observers (7 male and 7 female) participated in the second and third sessions. Then, the same fourteen naïve observers took part in experiment 2.

All participants in all experiments in this study were paid for their participation measured by time period, and they all had normal or corrected-to-normal vision. The entire study was approved in accordance with the Declaration of Helsinki, and informed consent was obtained for experimentation with the observers.

Stimuli

All stimuli were 1920 × 1080 pixel videos. Each of the videos had a main target (pattern) at the center and some other patterns surrounding it. Observers were strictly required to gaze at the main target during observation in any stage of this study. The videos were synthesized using computer software and programs because this type of stimuli was difficult to find among natural ones. The videos show ovals over a black background, and the ovals have various patterns and movements. The ovals may be clear or blurred to different levels. The arrangement of ovals varies, either all in a plane, or at different distances from the observer. When they have different distances, some of the ovals move from near to far, or from far to near. Viewing on 3D TV, the observer will find that the distance of the scene changes from video to video.

The contrast of stimuli is believed to have effects on visual comfort. Therefore, in some studies, the contrast was matched before the comparison of stimuli so as to focus on other factors.[6] In this study, we did not investigate the quantitative relationship between proximity cues and visual comfort, but investigated whether the visual comfort of each stimulus might be affected by the presence of proximity cues. Therefore, it was required that factors other than proximity cues should have the same amounts in both a pair of stimuli without proximity cues and the similar pair of stimuli with proximity cues. For example, there were two pairs of stimuli (Depth10_Blur26_Prox0, Depth10_Blur26_Prox0_2D) and (Depth10_Blur26_Prox1, Depth10_Blur26_Prox1_2D) in this study (for detailed definition of depth, blur and proximity cues, please refer to experiment 1). Depth10_Blur26_Prox0 represented a stimulus with an apparent depth of 10 m, a blur level of 26 arc minutes, and without proximity cues. Depth10_Blur26_Prox0_2D represented the 2D stimulus corresponding to Depth10_Blur26_Prox0. Similarly, Depth10_Blur26_Prox1 represented a stimulus with an apparent depth of 10 m, a blur level of 26 arc minutes, and with proximity cues. Depth10_Blur26_Prox1_2D represented the 2D stimulus corresponding to Depth10_Blur26_Prox1. It was then required that there were the same amounts of disparity, blur and contrast in the two pairs. Actually, the disparity levels and blur levels in both pairs were exactly the same, i.e., the apparent depths were both 10 m, and the blur levels were both 26 arc minutes. For the contrast, we calculated the average contrast of each video. The definition of contrast used by Peli was adopted for each frame in the videos.[33] The results showed that there were no significant differences between 3D and 2D stimuli ($F < 0.001$, $p = 0.995$), and there were no significant differences between 3D stimuli with and without proximity cues ($F = 0.069$, $p = 0.796$) either. Therefore, it was reasonable to believe that there was the same amount of contrast in the two pairs.

Procedures

Every subject was required to take a vision test. Only those who had normal stereo vision took part in the formal experiment (experiment 1 and experiment 2).

Table I. The possible values of the three factors.

Factors (depth cues)	Abbreviation	Value	Unit
Blur cue	B	0, 16, 32	Minute of arc
Disparity cue (apparent depth of main target was employed here)	D	10, 5, 1	Meter
		0.1, 0.2, 1	D (Diopter)
Proximity cues	P	True, False	

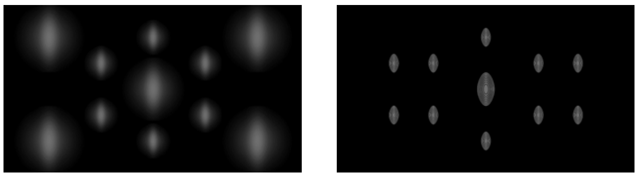

Figure 1. Examples of the 3D stimuli used in this study, each of which comprised a left view and a right view. (a) One example frame of a stimulus with high blur level and far target, which contained proximity cues. (b) One example frame of a stimulus with low blur level and near target, which did not contain proximity cues.

EXPERIMENT 1: RELATIVE COMPARISON

Method

Stimuli

The stimuli were all 10 s videos, which were used in relative comparison. As shown by Figure 1, each stimulus had a main target (an oval) displayed at the center, and also several other patterns (other ovals) around it. The main targets in different stimuli have similar apparent sizes although their disparities might be quite different. The surrounding patterns might have different sizes, positions and disparities so that depth cues can be included.

We were interested in the effect of the three important cues on visual comfort. Therefore, the combinations of three cues shown in Table I were taken into account when designing the stimuli.[7]

In order to provide different blur cues, two types of main targets were adopted. One was a sharp pattern with much high-frequency spatial information. The other was a blurred pattern with little high-frequency spatial information. For the latter, the corresponding stimuli were blurred using a Gaussian filter. The amount of blur was defined as the radius of half width at half height of the Gaussian form. Three blur levels were used: 0 (no blur), 16 and 32 arc minutes.[19]

The disparity of the main target was changed so as to get three different apparent distances: 10 m, 5 m and 1 m; namely, 0.1 D, 0.2 D and 1 D. In the former two conditions, the main target was farther than the screen plane from the viewer. In the latter condition, the main target was nearer than the screen plane. No matter which condition, the main target kept the same apparent size.

"Proximity cues are a combination of dynamic cues such as looming, motion parallax and motion in depth, as well as static cues such as relative size, overlap, perspective, shading and texture gradients, and perceived position in space."[9] In this study, a stimulus might or might not have proximity cues. When there were proximity cues, several patterns were arranged around the main target from near to far positions. The apparent depths of these patterns were between the maximal and minimal depths of the main target. There were also several other patterns moving repeatedly from near to far (when the main target appeared far) or from far to near (when the main target appeared near). When there were no proximity cues, several patterns were arranged around the main target. The apparent depth of these patterns was a fixed value which was between the maximal and minimal depths of the main target. In that case, there were no moving patterns.

Therefore, there were, in total, 18 combinations of the above three cues. Each combination corresponded to one 3D stimulus. Each 3D stimulus corresponded to one 2D stimulus, and the latter was almost the same as the former expect that it had no disparity. Examples of 3D stimuli and 2D stimuli are given in Fig. 1.

Procedures

The procedure of experiment 1 was designed similarly to the "paired comparison" regulation in ITU-R BT.2021-1,[32] but the stimuli were compared with certain baselines. There were, in total, three sessions in experiment 1, each of which focused on a certain aspect, as follows.

- **Session 1:** Each 3D stimulus was compared with the corresponding 2D stimulus. The only difference between the 3D and 2D stimuli was that 2D stimulus had no disparity.
- **Session 2:** Each 3D stimulus was compared with the 2D baseline, i.e., one of the 2D stimuli used in session 1.
- **Session 3:** Each 3D stimulus was compared with the 3D baseline, i.e., one of the 3D stimuli used in session 1.

This study is an extension of our previous research,[34] and session 1 actually includes the previous experiment. However, this is just a small part, and the previous research was focused on the relationship between disparity cue and blur cue, while the purpose of this study is to find out the effects of proximity cues on visual comfort. Considering the essential difference and the integrity of this study, we still describe it briefly here.

Figure 2 shows the procedure of the relative comparison in each session. First, a hint was initially shown to the observer for 3 s, indicating the beginning of the session. After that, (1) one stimulus was shown for 10 s, (2) a mid-gray

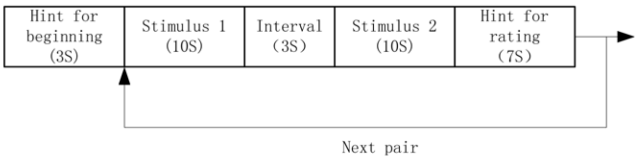

Figure 2. The procedure of relative comparison. In session 1, stimulus 1 and stimulus 2 were one 3D stimulus and the 2D stimulus corresponding to it. In session 2, stimulus 1 and stimulus 2 were one 3D stimulus and the 2D baseline. In session 3, stimulus 1 and stimulus 2 were one 3D stimulus and the 3D baseline.

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

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 presentation time of the stimulus was determined referring to ITU-R BT.2021-1[32] and existing literature.[26] The value of relative comfort could be one of the following Table II.[32]

Steps (1)–(4) were repeated until all of the pairs in the session had been compared.

The count of pairs in each session was 18, i.e., equal to the count of the 3D stimuli. As each pair was compared twice (in different orders), the total number of comparisons in each session was 36.

RESULTS

The data of the three sessions were analyzed using repeated measure MANOVA.[35]

The 3D Stimuli Compared with the Corresponding 2D Stimuli

In this session, the 3D stimuli were very similar to the corresponding 2D stimuli in content. In fact, the 3D stimuli were rendered from the left and right views, while the corresponding 2D stimuli were rendered from the center view (between the left and right ones). The results of repeated measure MANOVA are listed in Table III. Here, we are mainly concerned with the result of *Pr*. It indicates whether the effect of the corresponding factor is significant. The value of *Pr* is shown in the last row in Table III. The symbol "***" means that *Pr* is greater than 0 but smaller than 0.001. The symbol "**" means that *Pr* is greater than 0.001 but smaller than 0.01. The symbol "*" means that *Pr* is greater than 0.01 but smaller than 0.05, and so on. In this case, it means that there is a significant effect when *Pr* is "**" or "***".

As shown by Table III, proximity cues have significant effects on the relative visual comfort of the 3D stimuli over the corresponding 2D stimuli. Disparity cue and blur cue also have significant effects. However, there were neither two-way nor three-way interactions between the cues. The TukeyHSD

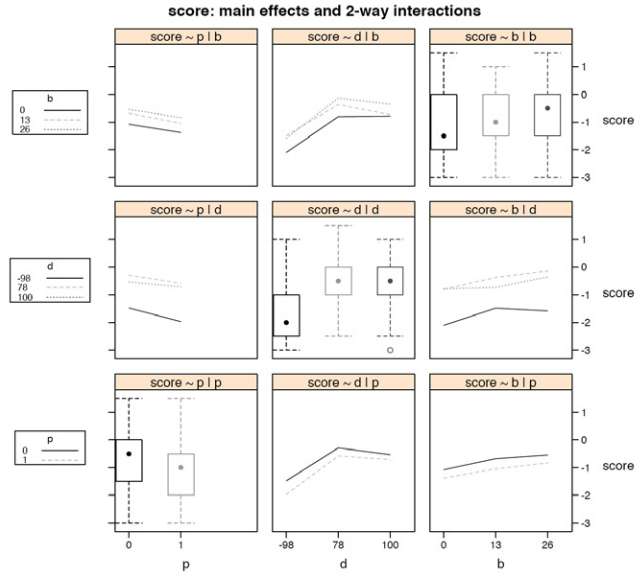

Figure 3. The main effects and two-way interactions for the factors. The first column shows the effect of proximity cues (denoted as "p") with the interaction of blur cue (denoted as "b") and disparity cue (denoted as "d"). The second column shows the effect of disparity cue with the interaction of blur cue and proximity cues. The third column shows the effect of blur cue with the interaction of disparity cue and proximity cues. The values −98, 78 and 100 are screen disparities, which correspond to 1 m, 5 m and 10m of apparent depth, respectively.

Table III. The results of MANOVA for session 1. The second row to the fourth row show the main effects of proximity cues, disparity cue and blur cue, respectively. The fifth row to the seventh row show the two-way interaction of the three factors. The eighth row shows the three-way interaction of the three factors. The significance for each situation is marked with asterisks in the last column.

	Df	Sum	Sq	Mean Sq	*F* value	*Pr*(> *F*)
Proximity	1	6.85	6.85	7.784	0.005674	**
Disparity	2	87.21	43.60	49.563	<2e-16	***
Blur	2	13.64	6.82	7.749	0.000542	***
Proximity : disparity	2	1.12	0.56	0.636	0.530415	
Proximity : blur	2	0.08	0.04	0.045	0.955760	
Disparity : blur	4	3.18	0.79	0.902	0.463053	
Proximity : disparity : blur	4	2.25	0.56	0.640	0.634126	
Residuals	252	221.70	0.88			

(Signif. codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 "" 1)

test was then conducted, and the result verified the above analysis.

It can be further seen from Figure 3 how the relative visual comfort varied with different kinds of cue. As shown by the first column, the relative visual comfort was greater when there were no proximity cues than the case with proximity cues. As there were no two-way interactions, similar patterns were observed for all the levels of disparity cue and blur cue. As shown by the second column, the relative visual comfort was the smallest when the apparent depth was 1 m. The relative visual comfort levels were similar to each other when the apparent depth was 5 m or 10 m. In most cases, it was

Table IV. The results of MANOVA for session 2. The meanings of parameters are the same as in Table III.

	Df	Sum	Sq	Mean Sq	*F* value	*Pr*(> *F*)
Proximity	1	4.86	4.861	5.538	0.0194	*
Disparity	2	48.78	24.388	27.785	1.49e-11	***
Blur	2	20.69	10.346	11.787	1.33e-05	***
Proximity : disparity	2	1.09	0.543	0.618	0.5398	
Proximity : blur	2	0.91	0.453	0.517	0.5973	
Disparity : blur	4	6.19	1.549	1.764	0.1368	
Proximity : disparity : blur	4	1.40	0.349	0.398	0.8101	
Residuals	252	221.70	0.88			

(Signif. codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 "" 1)

slightly larger when the apparent depth was 5 m. Similar patterns were observed no matter how the proximity cues and blur cue were changed. As shown by the third column, the relative visual comfort gradually increased with the level of blur cue. Similar patterns were observed no matter how the proximity cues and disparity cue were changed. Except when the apparent depth was 1 m, the relative visual comfort was slightly greater with blur level 26 than with blur level 13.

The 3D Stimuli Compared with the 2D Baseline Stimulus

In this session, each of the 3D stimuli was compared with an identical 2D baseline stimulus. The latter was one of the 2D stimuli corresponding to the 3D stimuli.

As shown by Table IV, proximity cues have significant effects on the relative visual comfort of the 3D stimuli over the 2D baseline stimulus. Disparity cue and blur cue also have significant effects. However, there were neither two-way nor three-way interactions between the cues. The TukeyHSD test verified the above analysis.

As shown by Figure 4, the change of relative visual comfort with proximity cues and disparity cue showed similar patterns to the results in session 1. However, the relative visual comfort gradually fell with the level of blur cue. Similar patterns were observed for all the levels of disparity cue and blur cue.

3. The 3D Stimuli Compared with the 3D Baseline Stimulus

In this session, each of the 3D stimuli was compared with an identical 3D baseline stimulus. The latter was one of the 3D stimuli.

As shown by Table V, proximity cues have significant effects on the relative visual comfort of the 3D stimuli over the 3D baseline stimulus. Disparity cue and blur cue also have significant effects. However, there were neither two-way nor three-way interactions between the cues. The TukeyHSD test verified the above analysis.

As shown by Figure 5, the change of relative visual comfort with all three kinds of cue showed similar patterns to the results in session 2.

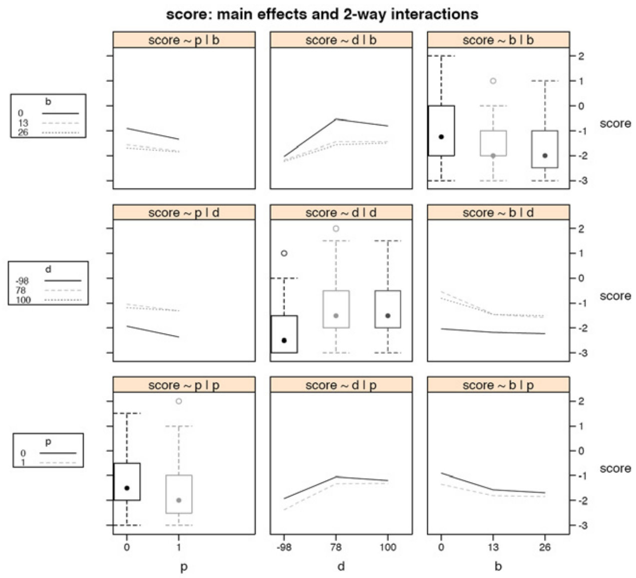

Figure 4. The main effects and two-way interactions for the factors. The symbols are the same as in Fig. 3.

Table V. The results of MANOVA for session 3. The meanings of parameters are the same as in Table III.

	Df	Sum	Sq	Mean Sq	*F* value	*Pr*(> *F*)
Proximity	1	10.5	10.525	6.083	0.0144	*
Disparity	2	38.3	19.134	11.060	2.57e-05	***
Blur	2	39.5	19.771	11.428	1.84e-05	***
Proximity : disparity	2	4.8	2.382	1.377	0.2544	
Proximity : blur	2	3.7	1.846	1.067	0.3457	
Disparity : blur	4	2.8	0.690	0.399	0.8092	
Proximity : disparity : blur	4	1.1	0.284	0.164	0.9564	
Residuals	234	404.8	1.730			

(Signif. codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 "" 1)

DISCUSSION

Since the effects of disparity cue and blur cue on visual comfort had already been investigated by previous laboratory studies, we mainly focused on the effects of proximity cues. As shown by the results, proximity cues had significant effects on visual comfort. More specifically, the presence of proximity cues reduced the visual comfort. Furthermore, the effects of proximity cues had no significant interaction with other cues. On the one hand, similar patterns were observed no matter how the disparity cue and blur cue were changed. On the other hand, the presence of proximity cues did not change the effects of disparity cue and blur cue on visual comfort significantly. When different baselines were selected, the results showed only slight differences. Although the effects of proximity cues and disparity cue were relatively stable, the effects of blur cue on visual comfort varied with the selection of baselines. When the baseline varied with the 3D stimuli, i.e., in the first session, the effects also varied. However, when the baseline was a fixed one, i.e., in the second and third sessions, the effects did not vary.

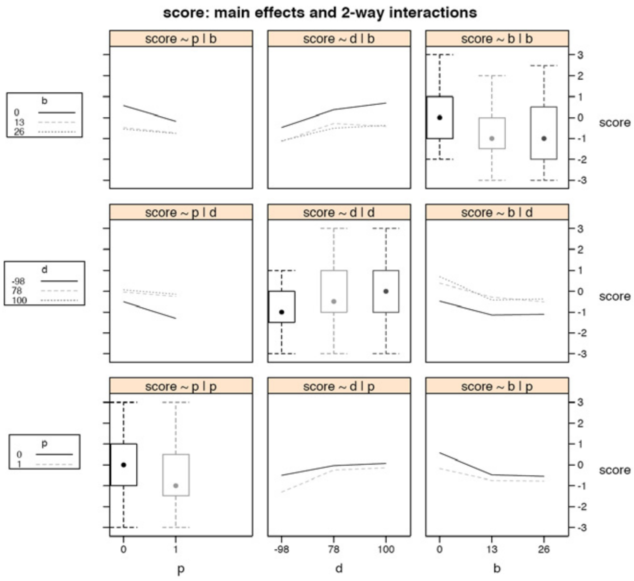

Figure 5. The main effects and two-way interactions for the factors. The symbols are the same as in Fig. 3.

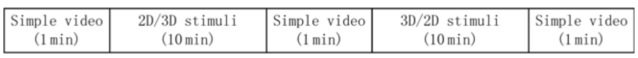

Figure 6. The structure of the stimuli used in experiment 2. The 2D or 3D stimuli comprised several shorter videos which appeared repeatedly in random order. If the first 10 min were 2D stimuli, the second 10 min would be 3D stimuli, and vice versa.

EXPERIMENT 2: CONSECUTIVE VIEWING

Experiment 1 demonstrated that the stimuli with proximity cues had lower instant visual comfort than similar stimuli without proximity cues. However, the accumulative effects of proximity cues on visual comfort were still not clear. The aim of experiment 2 was to check the visual comfort caused by the stimuli with proximity cues when viewed consecutively.

Method

Stimulus

As shown by Figure 6, the stimulus was a 23 min video, which comprised many short videos. There was a base video at both the beginning and the end of the stimulus. This was a simple 1 min video showing a black circle at the center of a gray background. The simple video provided a uniform visual load for the observers when capturing eye movements. Between the beginning and the end, there were a 2D video and a 3D video separated by another base video. The 2D video might appear before or after the 3D one, and their order was determined randomly for each observer. Both the 2D and 3D videos were 10 min each and comprised several shorter videos. The shorter videos were selected from the stimuli used in experiment 1, and were arranged consecutively and randomly for each observer. These shorter videos were repeated several times so as to constitute 10 min of 2D or 3D video.

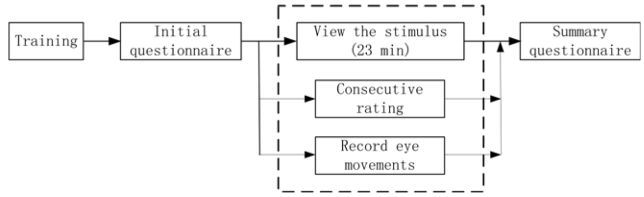

Figure 7. The procedure of experiment 2. Ideally, the three operations "view the stimulus," "consecutive rating" and "record eye movements" should begin and end at the same time. In practice, they began one after another, and were then synchronized (trimmed) along the axis of time before analysis.

Procedures

The procedure of experiment 2 was designed according to the Single Stimulus Continuous Quality Evaluation (SSCQE) regulation in ITU-R BT.2021-1.[32] As shown by Figure 7, the observers were initially asked to practice consecutive rating. They had 5 min to practice rating their visual comfort at any time when they were viewing a training video. The rating was conducted without breaking the viewing process. The scores were defined according to the SSCQE regulation, as shown in Table VI.

The observer was then asked to fill in a questionnaire which collected the personal information of the observer and the current symptoms of visual comfort.

After that, the formal stimulus was shown to the observer, and the observer was required to rate their visual comfort when viewing. At the same time, the eye movements of the observer were captured using an infrared camera. The captured video was used to extract blink rate through manual counting. When the observer finished viewing the stimuli, another questionnaire was used to collect the visual comfort at that time, and also how the observer felt about the stimulus.

RESULTS

Experiment 1 focused on the instant effects of proximity cues, while the accumulative effects were revealed by experiment 2. The stimuli differed from each other mainly in the positions of patterns, but were similar in both brightness and contrast. From the experiment, three types of results could be obtained, namely, sequence of rating score, blink rate and response to questionnaire.

Sequence of Rating Scores

In the experiment, a sequence of rating scores was produced by each observer when viewing the 2D and 3D stimuli. The averages of all of the sequences for all of the observers are shown in Figure 8.

As shown by Fig. 8, the average waveforms of both 2D and 3D stimuli were stable and fluctuated in similar ranges. The patterns of their fluctuations were also similar. Repeated measured ANOVA showed that there were no significant differences before and after viewing for either 2D stimuli ($F = 0.48$, $p = 0.49$) or 3D stimuli ($F = 0.13$, $p = 0.72$). The mean values for the 2D and 3D sequences were 2.66 and 2.51, respectively, and repeated measured ANOVA showed that

Table VI. The possible values of subjective score.

1	2	3	4	5
Very uncomfortable	Uncomfortable	Slightly uncomfortable	Comfortable	Very comfortable

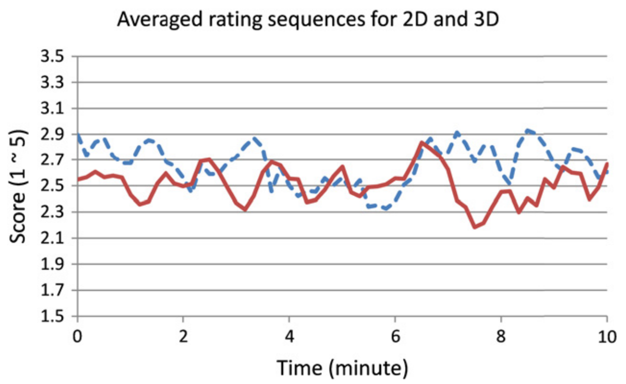

Figure 8. Averaged rating sequences of all of the subjects for 2D and 3D. The dashed line shows the 2D result, and the solid line shows the 3D result. The duration was 10 min, and the score was between 1 and 5.

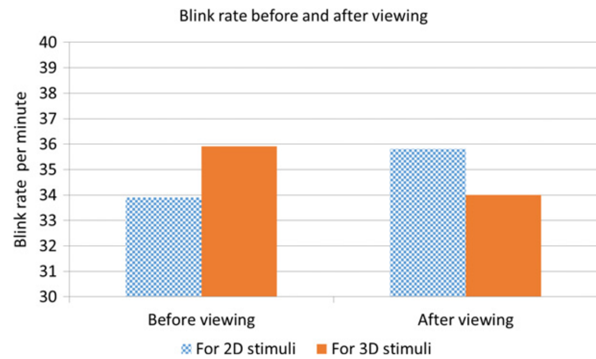

Figure 9. Blink rate before and after viewing. The two bars on the left side represent the blink rates before viewing 2D or 3D stimuli, and those on the right side represent the blink rates after viewing 2D or 3D stimuli. Each blink rate was calculated within 1 min.

the difference between them was significant ($F = 31.545$, $p < 0.001$).

As shown by the results, 10 min of viewing did not cause obvious increase or decrease of the scores for either 2D or 3D stimuli. The tendency was in accordance with the experimental results reported by Lambooij.[36] However, as is widely accepted, normal 3D stimuli are usually less comfortable to view than similar 2D stimuli.[6] Similarly, the average comfort of the 3D stimuli was also less than for the 2D stimuli in this study.

Blink Rate

Eleven valid sets of data were collected. Five of the observers viewed the 2D stimuli before the 3D ones. Six of them viewed the 3D stimuli before the 2D ones. As shown by Figure 9, the blink frequencies of the observers were collected during 1 min both before and after the 2D and 3D stimuli. ANOVA showed that the blink rate did not change significantly before and after no matter whether the stimuli were 2D ($F = 0.08$, $p = 0.78$) or 3D ($F = 0.07$, $p = 0.8$).

Blink rate can indicate accumulation of visual discomfort (or fatigue) after undertaking the same visual task for a period of time.[37] Therefore, the above results suggested that viewing these types of 2D or 3D stimuli for 10 min did not cause obvious visual discomfort.

Response to Questionnaire

The scores of visual fatigue symptoms were collected using questionnaires before and after viewing. The symptoms were numbered as shown in Table VII.

The medians of all of the symptoms for all of the observers are shown in Figure 10. It can be seen that most of the medians did not change after viewing. Wilcoxon signed-rank test showed that there were significant differences in

Table VII. Symptoms of visual fatigue.

1	Overall discomfort	6	Dizziness	11	Gritty eyes
2	Photophobia	7	Blurred vision	12	Nausea
3	Eye dry	8	Itchy eyelids	13	Difficulty focusing
4	Eye pain	9	Teary eyes	14	Double vision
5	Headache	10	Burning eyelids		

none of the symptoms; for example, $p = 0.329$ for "overall discomfort" and $p = 0.493$ for "blurred vision."

The sensation of stereopsis for the 3D stimuli was also surveyed using the questionnaires. The medians for the stimuli with and without blur were 3 and 4, respectively. Wilcoxon signed-rank test showed that there were significant differences between the two types of 3D stimuli ($p = 0.002$).

DISCUSSION

Subjective rating has been widely accepted as a reliable tool for the evaluation of visual comfort.[5] Blink rate is also treated as a useful indicator for the objective assessment of visual comfort or visual fatigue.[37]

Both of the results of rating score and blink rate in experiment 2 suggested that 10 min of viewing the 2D and 3D stimuli did not cause obvious visual discomfort.

Actually, the results of the questionnaire suggested that the observers did not feel obvious visual discomfort even after viewing 20 min of video that contained both the 2D and 3D stimuli. When these findings were compared with existing literature,[6,36] it seemed that the visual comfort caused by the stimuli had similar characteristics to common ones when viewed consecutively.

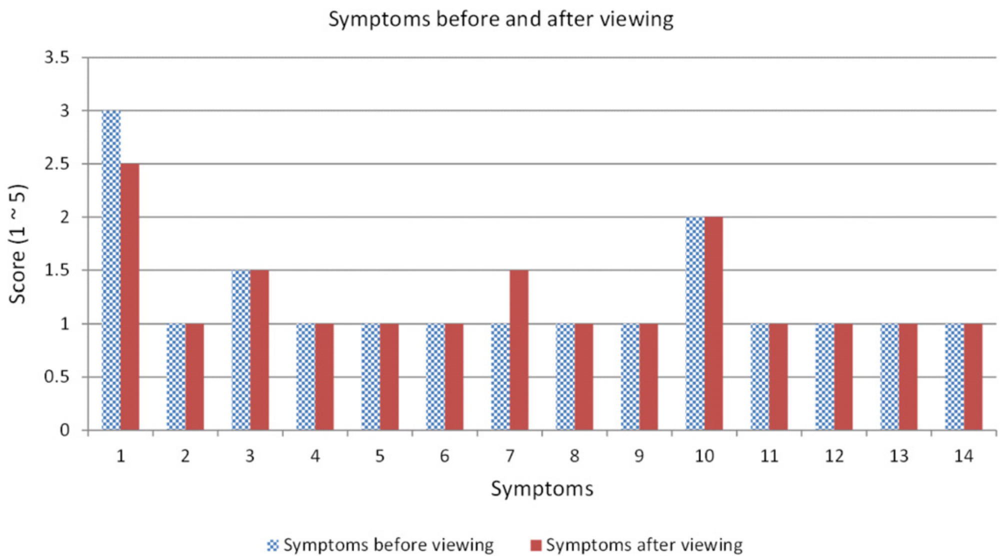

Figure 10. Symptoms before and after viewing. The 14 pairs of bars correspond to 14 symptoms. The chequered bars represent the symptoms before viewing stimuli and the solid bars represent the symptoms after viewing.

GENERAL DISCUSSION

The aim of this study was to investigate the effects of proximity cues on visual comfort. The first experiment investigated the relative visual comfort using relative comparison, which revealed the instant effects. The results showed that proximity cues had significant effects on the instant relative comfort of 3D stimuli, and the effects did not vary with the apparent depth and blur level of 3D stimuli. However, the effects of blur cue varied slightly with the selection of the baseline. The second experiment investigated the rating score of visual comfort during consecutive viewing, which revealed the accumulative effects. The results showed that the 3D stimuli did not cause obvious visual discomfort during 10 min of viewing, but the visual discomfort was still greater than that from viewing similar 2D stimuli. One potential reason for the effects could be because of the components contained in proximity cues.

There are two main types of component in the proximity cues used in this study. On the one hand, proximity cues provide perspective information for sensation of depth so that the vergence gets stronger drive. As the accommodation is originally different from the vergence, this extra drive makes the vergence–accommodation conflict more serious. As a result, the visual comfort also decreases. On the other hand, there are also several moving patterns around the main target. These moving patterns actually produce radial optic flow, which also causes stronger sense of depth[38] and may induce extra vergence eye movements[23] and accommodation eye movements.[39]

As the optic flows appear periodically all through the stimuli, i.e., do not look totally smooth all of the time, the induced vergence and accommodation eye movements may also be changing. However, the sign (positive or negative) and amplitude of the two kinds of eye movement are not necessarily the same all of the time, which may introduce extra uncertainty in the relationship of vergence and accommodation. Original conflict between vergence and accommodation existing in 3D stimuli can cause visual discomfort by the dissociation of vergence and accommodation.[16] When the extra vergence and accommodation eye movements induced by optic flow are added, the relationship between vergence and accommodation may become more uncertain and unstable. This may further dissociate vergence and accommodation, and cause more serious discomfort. Although the above components can decrease the relative visual comfort of the stimuli when compared with those without proximity cues, the effects seem to still be within a limited range. Therefore, the characteristics of visual comfort are still similar to common ones when the stimuli are viewed consecutively.

However, there are also other possibilities. The vergence–accommodation conflict may be affected by proximity cues in other ways. For example, different depths of the surrounding patterns provide relative disparities among them. Relative disparity is believed to play an important role in determining the visual discomfort.[40] Differently from the experiment conducted by Jing et al, the stimuli used in this study have several surrounding patterns with various depths, and not a single background plane. However, relative disparity may also play a role in visual comfort, and thus decrease the visual comfort. Besides, there are some factors other than vergence–accommodation conflict, e.g., crosstalk, and they can also contribute to visual discomfort.[5] It is possible that proximity cues also have effects on these factors, and thereby change visual comfort indirectly.

However, this does not mean that the two reasons are competing. Actually, they may account for different aspects. It is worth further investigation to identify the extra reasons and the contributions of each.

CONCLUSIONS

The instant effects of proximity cues on the visual comfort of simple 3D stimuli were assessed using relative comparison. Based on the results, some of the 3D stimuli were selected, and their accumulative effects on visual comfort were further assessed. The results demonstrated that proximity cues have significant effects on the visual comfort of 3D stimuli. Such effects do not vary significantly with disparity cue, blur cue and the selection of baseline stimuli. The visual comfort in a consecutive viewing process was further tested for stimuli with proximity cues, and the results showed similar characteristics to common ones. One possible reason is that the components contained in proximity cues increase vergence–accommodation conflict, and therefore decrease visual comfort. However, the effects seemed to be still within a limited range so that the characteristics of visual comfort were still similar to common ones when the stimuli were viewed consecutively.

As proximity cues are very common in various types of visual content such as pictures and videos, the above findings might provide helpful guidance for the design of stereoscopic content, and might also be beneficial to the production of stereoscopic displays.

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