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3D visual comfort assessment by measuring the vertical disparity tolerance ☆

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Misalignment in stereo images leads to 3D discomfort, but the visual tolerance for disparities varies with viewing environment and stimulus. The aim of the study was twofold: first, to assess if vertical disparity tolerance (VDT) could be a reliable indicator of 3D visual comfort under certain restrained condition when vertical disparity is induced; second, to be able to predict how viewing conditions can affect visual comfort using an analytical model. Two viewing condition parameters were considered: luminance and stimulus angular size. The study was carried out in two experiments involving 17 subjects. In Experiment 1, visual comfort and vertical disparity tolerance were measured by a series of psychophysical tests for different stimulus angular sizes and luminance. Based on a regression analysis of this data, a model was proposed to estimate VDT as a function of luminance and stimulus angular size. In Experiment 2, a validation test was carried out to assess the quality of the model. Results confirm that for given viewing conditions (luminance, angular size, induced vertical disparity), the visual comfort measured is in agreement with the one predicted ($\rho = 1.0008$, $p = 0.0026$). VDT is a recognized reliable indicator of visual comfort due to vertical disparity and the model can be used to predict visual comfort for given viewing conditions.

1. Introduction

The growing use of 3D display in recent years has led to numerous studies on 3D visual comfort, highlighting the importance of various parameters on the viewer's experience such as the display type [1,2], 3D contents [3,4] and physiological parameters (e.g. vergence-accommodation conflict [5–8]). To assess 3D viewing experience, both subjective and objective methods have been proposed. Observers may be instructed to fill in questionnaires to rate their visual fatigue after watching 3D videos. Alternatively, several physiological indicators can be measured. Visual fatigue can cause a decrease in the pupil diameter size, eye motion speed reduction [9,10]. Oculomotor fatigue leads to accommodation/vergence amplitude reduction, and eye blinking rate decreases with visual fatigue when watching 3D stimuli [11]. Electroencephalograms (EEG) and electrocardiograms (ECG) can also be used as a reliable indicator to report visual fatigue; e.g. Chen et al. used the energy changes of the EEG's four waveband (alpha, beta, theta, delta) to compare the visual fatigue generated by 2D/3D display (the four wavebands representing the stimulation of different regions of the brain [12]).

When assessing the 3D viewing experience, it is necessary to assess the importance of parameters such as luminance and stimulus angular size (according to the configurations of screen size and viewing distance, etc.), which are involved in all types of 3D displays. In previous work we have shown that the stereoscopic perception is affected by the 3D viewing environment configuration, such as the size of the screen, the viewing distance and the room lighting [13]. Regarding the effect of luminance on visual performance, it has been extensively investigated [14–16]. It is reported that the ability to read and recognize is greater under high luminance sources and room lighting, even if visual fatigue is not statistically significantly affected by luminance [15]. The fusion capability of binocular vision is also affected by luminance [17], accommodation and vergence are closely related as well [18], making luminance a critical factor for 3D perception.

Regarding the stimulus angular size, its importance is related to the size of the vision field it occupies. The vision field is made up of

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central and peripheral vision. Interaction between central and peripheral perception has been investigated in previous studies [19,20]. The interaction intensity is related as how much central and peripheral vision is stimulated (itself determined by the screen size, the peripheral area and the viewing distance [5]). Different vertical fusion amplitudes have been reported in previous studies. Devis reported that the normal vertical disparity fusion amplitude is 3Δ (Δ stands for prism diopter) [21]. In the study of Rutstein, the fusion amplitude of vertical disparity measured by prism bar is 6.6 ± 1.6Δ [22]. Such inconsistencies might be caused by distinct measuring methods, target sizes and viewing distances [23]. Stimulus angle size is a combined expression of target size and viewing distance. We demonstrated in previous work it is a critical parameter affecting 3D perception [2]. Experimental results indicate that the vertical disparity tolerance is better when the stimulus angle size is larger, thus impacting on 3D perception.

Disparity processing is one of the main mechanisms for 3D perception, and fusion-range measurement of disparity is an important indicator of changes in the visual system caused by short-term stereoscopic viewing [24]. Due to the eye physical structure, our vision system fuses relatively large horizontal disparity (20–30Δ), and the tolerance to horizontal disparity changes with 3D viewing conditions (eccentricity, spatial frequency, etc.) [25]. The relationship between visual comfort and horizontal disparity fusion range has been explored extensively and metrics predicting visual comfort from horizontal disparity values have been proposed [5,13,26]. Vertical disparities encountered are very small in real viewing environments (much less than horizontal disparity) and the induction of vertical disparity leads rapidly to diplopia. However, when watching 3D displays, there is the potential acceptance for vertical disparities when the head is not aligned vertically with the display [27]. The visual tolerance to vertical disparity has been explored in several studies. In the Kertesz experiments, the VDT is larger with complex stereo images when compared with simple ones [28]. Bharadwaj reported that the ability to fuse vertical disparity varies with convergence [29]. Kooi et al. reported in their study that large binocular asymmetric vertical disparity should not exceed 1Δ for normal perception [5]. They observed that visual fatigue appeared when vertical disparity was induced, whereas Speranza et al. reported that the human eyes had relatively high tolerance for vertical disparity [30]. The reason for such opposite conclusions could be that VDT changes with different viewing condition (screen size, viewing distance, room lighting etc.) and 3D display platforms [2,31]. To assess our visual response to 3D stimulus and environment variation, a fast and precise response could be obtained by measuring VDT, since our vision system is sensitive to vertical disparity with much less tolerance (3–5Δ) [2,19,29].

In this study, we used VDT as an indicator to assess visual comfort, with respect to different stimulus conditions (luminance and stimulus angular size). Visual comfort in this study stands for the eyestrain experienced by the subjects when they are required to watch 3D contents under given viewing conditions (viewing distance, screen size, room lighting, etc.) and when no particular A/C conflict is created (we remain here in the Perceval comfort zone [32]). A score is given by subjects to express their visual comfort level from 1 to 5 (1 for severe uncomfortable and 5 for very comfortable), the visual discomfort is caused by eye strain, diplopia and blur. VDT here means the maximum vertical disparity that could be fused by the visual system. In Section 2, we describe the psychophysical experiments used to collect the data and propose a model to predict VDT as a function of stimulus angler size and luminance. In Section 3, a second experiment is described to confirm the accuracy of the proposed function and model. Results are then discussed in Section 4 and conclusions given in Section 5.

2. Experiment 1: Psychophysical measurement for VDT

2.1. Subject selection

17 naive observers (13 males, 4 females, 24.58 ± 4.36 years old) participated in the experiment. They were all students from Telecom Bretagne and received financial compensation for participating to the experiments. Inclusion vision criteria were as follows: monocular visual acuity (evaluated using a decimal scale chart) better than 10/10; all with good binocular stereo vision; no history of functional or organic ocular pathology. Approval for the publication of subject data is obtained from Brest University Hospital institutional review board, according to the tenets of the Declaration of Helsinki.

2.2. Stimuli

In this experiment, we used two images: one with a single horizontal line (Fig. 1a) and one with several lines (Fig. 1b), following the method used by Kertesz [26]. In both cases, lines are not straight but made of dots randomly located in a limited zone (the vertical distribution range is 40 pixels for each line). Paired stereo images were displayed by a 3D projector (NEC-U310W) and subjects watched the images through 3D active glasses. Liquid crystal shutters were specially customized to prevent ghosting by having very dark blocking states (with a contrast ratio in the normally black case better than 1/1000). The custom-programmed software was written using VS2010C# and DirectX 11.0.

2.3. Measurements

Measurements were carried out in two sessions. The first one investigated the VDT under different conditions. The second one assessed the relationship between induced vertical disparity and visual comfort. In all experiments there was no horizontal disparity induced, only vertical disparity.

In session 1, the VDT was measured under varying levels of luminance and stimulus' angular size. The unit to calculate VDT is prism diopter (Δ). As demonstrated in Fig. 1c, when subject looks at the screen through 3D glasses, the right eye image and left eye image are delivered separately to the eyes. When small vertical disparity is induced to the stereo paired images, this difference can be fused by the brain and the observer perceives a single image. When the disparity continues to increase, the binocular fusion will be interrupted and the observer will perceive diplopia. The vertical separation between each image of the stereo pair is recorded as VDT according to the viewing distance.

Two parameters are considered in the experiment: luminance and stimulus angular size. Luminance is the amount of luminous flux per unit area at a given viewing position. Stimulus angular size is the vertical angle of the 3D content according to the viewing distance (cf. Fig. 1d). By changing the viewing distance and using different stimulus images, we have obtained 4 levels of stimulus angular size (0.8, 1.5, 12 and 23 degrees). 4 levels of luminance are induced (20, 75, 110, 150 cd/m^2). We used a luminance meter to measure the light received by the subjects when wearing 3D glasses (the luminance behind the 3D glasses is recorded).

In each trial, subjects were instructed to look at the center of the image (black point). The vertical disparity at the beginning was 0, then, slight disparity was induced at the speed of 0.2Δ/s. Subjects used a joystick to control the vertical disparity induction, the induction should be stopped as soon as they perceive diplopia, or one of the square near the fixation point disappeared. The vertical separation of the stereo images was recorded as VDT. The square above or below the fixation point serves as a binocular rivalry mar-