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Effect of the accommodation-vergence conflict on vergence eye movements

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ABSTRACT

With the broader use of stereoscopic displays, a flurry of research activity about the accommodation-vergence conflict has emerged to highlight the implications for the human visual system. In stereoscopic displays, the introduction of binocular disparities requires the eyes to make vergence movements. In this study, we examined vergence dynamics with regard to the conflict between the stimulus-to-accommodation and the stimulus-to-vergence. In a first experiment, we evaluated the immediate effect of the conflict on vergence responses by presenting stimuli with conflicting disparity and focus on a stereoscopic display (i.e. increasing the stereoscopic demand) or by presenting stimuli with matched disparity and focus using an arrangement of displays and a beam splitter (i.e. focus and disparity specifying the same locations). We found that the dynamics of vergence responses were slower overall in the first case due to the conflict between accommodation and vergence. In a second experiment, we examined the effect of a prolonged exposure to the accommodation-vergence conflict on vergence responses, in which participants judged whether an oscillating depth pattern was in front or behind the fixation plane. An increase in peak velocity was observed, thereby suggesting that the vergence system has adapted to the stereoscopic demand. A slight increase in vergence latency was also observed, thus indicating a small decline of vergence performance. These findings offer a better understanding and document how the vergence system behaves in stereoscopic displays. We describe what stimuli in stereo-movies might produce these oculomotor effects, and discuss potential applications perspectives.

1. Introduction

The mismatch between accommodation and vergence is considered to be the main difference between stereoscopic and natural viewing conditions. It is also recognized as the predominant factor entailing visual fatigue and discomfort (Hoffman, Girshick, Akeley, & Banks, 2008; Howarth, 2011; Rushton & Riddell, 1999; Shibata, Kim, Hoffman, & Banks, 2011; Ukai & Howarth, 2008; Wann, Rushton & Mon-Williams, 1995). For example, a significant proportion of stereoscopic observers have reported symptoms of eye strain, blurred vision, headache or dizziness symptoms (Hoffman et al., 2008; Shibata et al., 2011). As such, understanding the reason for these oculomotor issues is of major concern for optimal and safe use of stereoscopic systems. Because depth perception is based on vergence, it is crucial to evaluate how the vergence system can be altered by stereoscopic viewing. This study thus examines both the effect and after-effect of the accommodation-vergence conflict on vergence response, using the main sequence analysis (Bahill, Clark & Stark, 1975).

In natural vision, binocular disparity and focus cues provide comparable signals about object distance (Held, Cooper & Banks, 2012), leading to a normal correlation between accommodation distance and vergence distance (Hoffman et al., 2008). These two cues are involved in depth and distance perception (Cutting & Vishton, 1995) and are complementary cues to depth (Held, Cooper & Banks, 2012). In stereoscopic displays, focus cues are, however, inconsistent with the displayed pattern of disparity because they signal a flat object, whose distance tends to be perceived closer to the display as compared to what indicates binocular disparity (Hoffman et al., 2008). Additionally, there is a conflict beyond these stimulations, because accommodation and vergence systems are intrinsically coupled (Schor, 1992). The two oculomotor systems operate together to provide a clear and single view of the world, leading to synkinesis, as the eyes simultaneously

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accommodate and converge to the distance of the target object. Both systems can thus be stimulated through crosslink components (i.e. convergence accommodation and accommodative convergence) and, therefore, stereoscopic displays can strongly influence this synkinesis (Eadie, Gray, Carlin, & Mon-Williams, 2000).

Models of the vergence system imply two components in vergence response, an initial 'transient' fast pre-programmed component and a slow 'sustained' feedback component (Hung, Ciuffreda & Rosenfield, 1996; Schor, 1992). The first component yields the motor signal to rapid depth changes, and the second minimizes the vergence error within neurological tolerances. The vergence response also depends on the contribution of different motor controllers that respond to specific inputs, such as binocular disparity, retinal defocus and proximity (Howard & Rogers, 1995). Here, we consider the contribution of disparity vergence and accommodative vergence to the overall response, because proximal vergence should barely participate in the response to disparity below 4° (Schor, 1992). There are a few studies dealing with the possibility that vergence dynamics could vary when disparity and focus cues are available (Hung, Semmlow & Ciuffreda, 1983; Hung, Ciuffreda, Semmlow, & Horng, 1994; Maxwell, Tong & Schor, 2010). The dynamics of disparity vergence when accommodation is open-loop has been shown to be similar to the one when correct blur cues are presented (Maxwell, Tong & Schor, 2010). However, no quantitative study has been conducted to explore whether vergence dynamics could differ between a condition with correct blur cues and a condition with constant accommodation (Maxwell, Tong & Schor, 2010), although a number of points suggest that the accommodation-vergence conflict could affect vergence dynamics. Firstly, the conflict has been shown to increase time to fuse (Hoffman et al., 2008). Secondly, it has also been demonstrated that accommodative vergence and disparity vergence have different dynamics (i.e. different velocities Maxwell, Tong & Schor (2010)). Thirdly, the contribution of disparity vergence drives the transient response, while that of accommodative vergence only occurs at the end of the transient response (Hung, Semmlow & Ciuffreda, 1983; Semmlow & Wetzel, 1979). Lastly, because of synkinesis, accommodation would tend to inhibit vergence that conflicts with itself (Patel, Jiang, White, & Ogmen, 1999). The dynamics of vergence response could thus vary when both cues provide different information, because of the influence of each controller on the initial response.

The contribution of accommodative vergence to the total vergence response can be explored using a cue-conflict paradigm, where focus and disparity cues are either conflicting or congruent. In these conditions, the conflict can alter the normal functions of the visual system (Hoffman et al., 2008; Howarth, 2011; Rushton & Riddell, 1999; Ukai & Howarth, 2008; Wann, Rushton & Mon-Williams, 1995). For instance, binocular fusion can be slower and stereoacuity thresholds can be worse (Hoffman et al., 2008). Furthermore, displaying discrepant stimuli can both provide an immediate effect and an after-effect on the vergence system (Emoto, Niida & Okano, 2005; Hoffman et al., 2008). Changes in the dynamic characteristics of such a system can be studied using main sequence analysis (Bahill, Clark & Stark, 1975; Munoz, Semmlow, Yuan, & Alvarez, 1999). It has been used extensively in the literature, for example, to assess the dynamic changes to repetitive step stimuli (Munoz et al., 1999). It also portrays how the dynamic responses of a system can change with increasing amplitude (e.g., Kasthurirangan, Vilupuru & Glasser, 2003). In a first experiment, we assessed the effect of the conflict on vergence response. In a second experiment, we examined the effect of prolonged exposure to the accommodation-vergence conflict on vergence response.

2. Experiment 1

Vergence responses were examined in a conflict viewing condition and a match viewing condition. The conflicting stimuli presented incongruent disparity and blur information for the second fixation position, i.e., after a disparity step (in front or behind the screen plane). The matching stimuli provided corresponding disparity and blur information at the target depth. Based on previous work (Hoffman et al., 2008), the conflict condition was expected to reduce the velocity of the vergence system, as well as its response amplitude and its reaction time.

2.1. Method

2.1.1. Participants

A total of 14 observers took part in the study. Two participants were discarded, both because they revealed very poor performances in judging relative disparities (under the chance level) and because of their difficulty in fusing the stimuli (presenting overly long reaction times). Two more were discarded because they had large difficulties performing the task (less than 50% of trials were valid). The ten remaining participants were tested according to a full counterbalanced order. They were on average 29.3 years old (ranging from 22 to 49 years old). All had normal or corrected vision and presented stereoacuity threshold at least inferior to 30 arc minutes as assessed by the Randot Stereo Test. They gave their informed consent before beginning the experiment.

2.1.2. Apparatus

We designed a specific apparatus depicted in Fig. 1(A). The participants' head was placed in a chinrest located 1.3 meters from the 3D display (Hyundai S465D 46″ HDTV LCD Polarized monitor), on an optical table (Newport, 120 × 90 cm), which served as a firm mechanical connection for all elements of the system. The apparatus was composed of a vertical beam splitter (360 × 255 mm, Edmund Optics), located in front of the eyes of the participants, and tilted 45° to the sagittal plane. Perpendicular to the sagittal plane, an optical bench (2.8 m) was used to move a 2D display (Dell 1908FP 19'' LCD monitor) at the desired distances thanks to a slider device mounted on the bench. The center of both displays was carefully aligned along the subject's midline using visible light. We visually checked that alignment was correct by displaying a set of vertical and horizontal lines crossing at the center of each screen. Participants wore polarized glasses to fuse left/right views; the displaying method was to present left/right views interleaved line-by-line. To minimize display crosstalk visibility, we placed the participant's cyclopean eye on the axis perpendicular to the center of the screen. Stimuli were displayed using Matlab and the Psychtoolbox extensions (Brainard, 1997). Vergence movements were recorded using a binocular eye-tracker (Eyelink 1000, SR-Research) with a sampling rate of 2000 Hz and a spatial resolution of 0.01°.

2.1.3. Procedure and stimuli

There were two conditions labeled (1) the conflict viewing condition, and (2) the match viewing condition. Participants had to fuse disparity step stimuli, which always started in the middle of a 3D screen plane. Convergent and divergent vergence responses were measured for the disparity amplitudes of 0.75°, 1.0°, 1.25° and 1.5° (see Fig. 2(A)). We used a fixation target (35 arc minutes radius) formed of a white fixation cross (18 arc minutes) surrounded by a frame composed of small squares of various shades of grey (5 by 5°) to help maintain stereoscopic fusion (see Fig. 1(B)). This visual pattern yielded the perception of relative