Vision Research 105 (2014) 159–165

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The rate of change of vergence–accommodation conflict affects visual discomfort

Joohwan Kim [a,*], David Kane [a], Martin S. Banks [b]

[a] *Vision Science Program, University of California, Berkeley, Berkeley, CA 94720, USA*
[b] *School of Optometry, Vision Science Program, University of California, Berkeley, Berkeley, CA 94720, USA*

ARTICLE INFO

Article history:
Received 22 July 2014
Received in revised form 30 September 2014
Available online 28 October 2014

Keywords:
Vergence
Accommodation
Dynamics
Cross-link
Discomfort

ABSTRACT

Stereoscopic (S3D) displays create conflicts between the distance to which the eyes must converge and the distance to which the eyes must accommodate. Such conflicts require the viewer to overcome the normal coupling between vergence and accommodation, and this effort appears to cause viewer discomfort. Vergence–accommodation coupling is driven by the phasic components of the underlying control systems, and those components respond to relatively fast changes in vergence and accommodative stimuli. Given the relationship between phasic changes and vergence–accommodation coupling, we examined how the rate of change in the vergence–accommodation conflict affects viewer discomfort. We used a stereoscopic display that allows independent manipulation of the stimuli to vergence and accommodation. We presented stimuli that simulate natural viewing (i.e., vergence and accommodative stimuli changed together) and stimuli that simulate S3D viewing (i.e., vergence stimulus changes but accommodative stimulus remains fixed). The changes occurred at 0.01, 0.05, or 0.25 Hz. The lowest rate is too slow to stimulate the phasic components while the highest rate is well within the phasic range. The results were consistent with our expectation: somewhat greater discomfort was experienced when stimulus distance changed rapidly, particularly in S3D viewing when the vergence stimulus changed but the accommodative stimulus did not. These results may help in the generation of guidelines for the creation and viewing of stereo content with acceptable viewer comfort.

1. Introduction

In natural viewing, changes in viewing distance lead to the oculomotor adjustments of vergence and accommodation. Vergence is the eye movement in which the two eyes rotate in opposite directions to maintain binocular fixation on objects at different distances; inaccurate vergence leads to diplopia (double images). Accommodation is the change in focal power of the crystalline lens in the eye; inaccurate accommodation yields blurred images. In natural viewing, the stimuli to vergence and accommodation are consistent with one another: Looking at a nearer object requires convergence and an increase in lens focal power, while looking at a farther object requires divergence and a decrease in focal power. Because the distances to which the eyes must converge and accommodate are generally the same, the two responses are coupled such that changes in vergence produce changes in accommodation, and vice versa (Cumming & Judge, 1986; Fincham & Walton, 1957; Krishnan, Shirachi, & Stark, 1977; Semmlow & Wetzel, 1979). The coupling is produced by cross-links in the neural control system that governs oculomotor adjustments for near and far viewing.

Many models have offered explanations of how vergence and accommodation are driven by sensory input (Hung & Ciuffreda, 2002; Hung & Semmlow, 1980; Rosenfield & Gilmartin, 1988; Schor, 1992). Schor (1992) divides vergence and accommodation responses into three components: tonic, phasic, and cross-link. The tonic components change slowly and help maintain vergence and accommodation at appropriate values. The phasic components change quickly enabling fast reactions to changes in object distance. Interestingly, the cross-links are driven by the phasic, not tonic components. This helps vergence and accommodation respond quickly (Cumming & Judge, 1986; Schor, 1986, 1992; Schor & Kotulak, 1986).

To quantify vergence distance, we use diopters (D) instead of the more conventional meter angle (MA) so that vergence and accommodation distances can be expressed in the same units. Fig. 1 illustrates how these three components—tonic, phasic, and cross-links—cooperate to drive vergence in response to a step change in object distance. The overall response should equal the

---

[*] Corresponding author.
E-mail addresses: joohwankim@berkeley.edu (J. Kim), d.kane.berkeley@gmail.com (D. Kane), martybanks@berkeley.edu (M.S. Banks).

http://dx.doi.org/10.1016/j.visres.2014.10.021
0042-6989/© 2014 Elsevier Ltd. All rights reserved.

sum of the responses from the three components. Initially the vergence stimulus and response are both at 1 diopter (D). Then the stimulus undergoes a step change to 2D. Because the vergence and accommodative stimuli undergo the same change, the signs of the phasic and cross-link responses are the same, so they work together to drive vergence rapidly to the appropriate value.

Some situations stimulate different amounts of vergence and accommodation. A well-known example is optical correction for refractive error. The new spectacles or contact lenses change the accommodative stimulus by a fixed amount in diopters relative to the vergence stimulus. The resulting disagreement between the accommodative and vergence stimuli is called the *vergence–accommodation conflict*, and can induce visual discomfort and fatigue (Percival, 1928; Sheard, 1930). Through a great deal of experience with patients, eye doctors have established guidelines for avoiding adverse effects. One such guideline is a description of the conflicts that can be tolerated while maintaining single and sharp vision; this is the *zone of clear single binocular vision* (ZCSBV; Fry, 1937; Hofstetter, 1945). There is a smaller range of vergence–accommodation conflicts (within the ZCSBV) that do not cause discomfort; this is the *zone of comfort* (Percival, 1928; Sheard, 1930).

Stereoscopic 3D (S3D) displays also stimulate different levels of vergence and accommodation. The viewer's distance from the screen, which is generally fixed, determines the accommodative stimulus. The viewer's distance and the content on the display determine the vergence stimulus. The content can vary significantly thereby changing the vergence stimulus. Thus, S3D viewing generally creates time-varying vergence–accommodation conflicts: to maintain single, sharp vision, the viewer must converge and diverge the eyes depending on the moment-to-moment content while holding accommodation on the screen. Doing this would be best achieved by counter-acting the cross-links that attempt to drive vergence to be consistent with accommodation and vice versa. However, the attempt to counter-act the cross-links may well cause some or all of the discomfort and fatigue reported by viewers of S3D media (Hoffman et al., 2008; Howarth, 2011; Lambooij et al., 2009; Shibata et al., 2011; Tam et al., 2011; Yang & Sheedy, 2011).

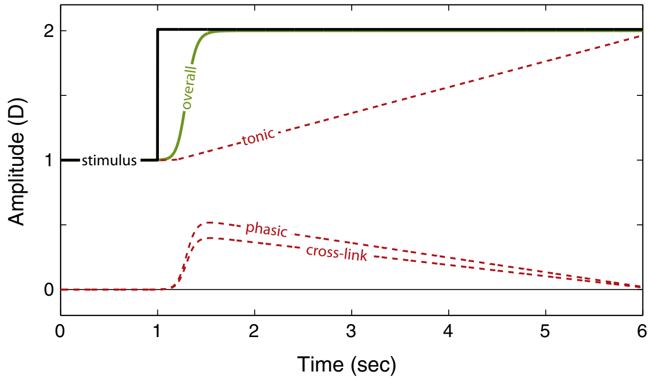

Fig. 1. Vergence response to a step stimulus in natural viewing according to the model of Schor (1992). Response in diopters is plotted as a function of time. The black line represents the stimulus, which is at a distance of 1D initially and then steps to a distance of 2D. The dashed red lines represent the responses of the tonic, phasic, and cross-link components. The green solid line represents the vergence response itself, which is the sum of the three component responses. The initial response is mostly supplied by the phasic and cross-link responses. The tonic response increases slowly, but eventually maintains vergence at the appropriate value. Accommodative responses, which are not shown here, would be very similar. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Shibata et al. (2011) measured the zone of comfort for S3D viewing and found that it is reasonably similar to the zones defined for optical correction. However, the dynamics of the conflict in S3D viewing may be an important determinant of the ensuing discomfort and fatigue. Speranza et al. (2006) and Jung et al. (2012) found that faster motion in depth in S3D content induces greater discomfort, but they did not determine whether the cause of the discomfort was motion in depth *per se*, or changes in the vergence–accommodation conflict. Given that rapid changes drive the phasic components of the vergence–accommodation cross-links, we hypothesize that rapid changes in the vergence–accommodation conflict cause more discomfort than slow changes do. We tested this hypothesis by comparing discomfort in natural and S3D viewing with rapid and slow changes in stimulus distance.

2. Methods

2.1. Apparatus

To simulate natural and S3D viewing, we used a volumetric stereo display (Love et al., 2009; Fig. 2). The configuration is the same as a conventional stereoscope except for the switchable lenses in front of each eye and the novel display technique. The lenses changed focal power among four possible values that were separated by 0.6 D. The changes in the focal power were synchronized with the frames of the corresponding display screen. The lenses went through the four focal powers as images appropriate for each focal distance were displayed in a time-multiplexed fashion. As the lenses change focal power from plane 1 to plane 4, the displays synchronously present images appropriate for those four distances. The lenses switch power at 180 Hz, so the cycle through four focal states occurs at 45 Hz. With this method, an apparent 3D volume is created and viewer accommodation through that volume brings different planes in and out of focus at the retina. The displays were CRTs (Iiyama HM204DT) running at 180 Hz, resulting in a 45 Hz refresh rate for the volumetric 3D scene.

When focal distance corresponded to one of the four possible focal states of the lenses, we illuminated pixels during that one focal state, but not the other three. To simulate stimuli in-between focal planes, we used depth-weighted blending (Akeley et al., 2004; Ravikumar, Akeley, & Banks, 2011). The left side of Fig. 3 shows how depth-weighted blending simulates a 3D surface between two focal planes. The image locations on each plane are determined by projecting each object point along the appropriate line of sight. Image intensity depends on the dioptric distance from the object to the corresponding point as illustrated on the right side of the figure. The stimuli created in this fashion have an appearance that is a good approximation to natural viewing (Ravikumar, Akeley, & Banks, 2011) and can drive accurate accommodative responses (MacKenzie, Dickson, & Watt, 2011; MacKenzie, Hoffman, & Watt, 2010).

Because the apparatus has multiple focal planes, image quality is very dependent on viewer position; the images on different focal planes only align on the retina when viewed from a specific location. To achieve accurate alignment, we positioned the subject with a custom bite bar. A hardware and software calibration procedure conducted for each subject assures accurate alignment (Akeley et al., 2004; Hillis & Banks, 2001). The subject remained on the bite bar throughout the experiment. If the subject normally wears an optical correction (i.e., spectacles or contact lenses), they wore it during the calibration procedure and during the experiment itself.

The apertures of the lens assemblies occluded the frames of the CRTs. Because the apertures were very close to the eyes, their edges were very blurred. Therefore, there was no useful cue to fusion from either the CRT frames or the apertures.