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The Impact of Viewing Stereoscopic Displays on the Visual System

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Abstract

The study examined the effects of varying the accommodation-convergence conflict created by stereoscopic displays which are now commonly used for the viewing of virtual environments, television and cinema. These displays will dissociate the naturally co-varying accommodation (focusing) and convergence (eye position) demands by placing an image geometrically behind or in front of the screen, and it has been suggested that the unnatural conflict between these demands will cause discomfort. Commercially available stereoscopic equipment was used to create a stimulus with four different levels of conflict, one of which was a control condition of zero conflict. Sixteen participants, each with normal visual systems, were presented with all four conditions in a balanced experimental design. The changes in visual discomfort, near heterophoria, distance heterophoria and visual acuity were assessed. Clear changes in comfort were observed, although no significant associated physiological changes were observed. The model which best describes the relationship between the conflict and the discomfort is one in which a small amount of conflict does not cause visual discomfort, whereas a larger amount will do so. This finding is consistent with expectations based on historical optometric experiments, which indicate that the normal visual system can maintain comfortable vision whilst experiencing small discrepancies between the accommodation and convergence demands. Our results indicate that visual discomfort occurs beyond a given conflict threshold and continues to rise as the conflict increases. They are consistent with the idea that this threshold is idiosyncratic to the individual. The principal implication of these findings is that people with normal visual systems should not experience asthenopic symptoms as a consequence of the accommodation-convergence conflict if the difference between the stimulus to each system is small.

Categories H.1.2 User/Machine Systems - Human factors ; H.5.2 User - Ergonomics ; I.2.10 Vision and Scene Understanding -3D/stereo scene analysis *;* I.3.6 Methodology and Techniques - Ergonomics ; I.3.7 Three-Dimensional Graphics and Realism - Virtual reality ; J.3 Life and medical sciences - Health ; K.4.1 Public Policy Issues - Human safety ; K.8.0 Games.

1. Introduction

The demand for 3D viewing experiences has driven technological development to the point where stereoscopic displays and content are widely available. In addition to a variety of industrial applications, such as product design, medical training and astronomical imaging, stereoscopic systems are now available for the home entertainment market. The creation of 3D television and gaming technology, following its use in the early 1990s for the viewing of virtual environments, represents a fundamental change to home-entertainment. However, the acceptance of such systems will depend, in part, on their ability to provide comparable levels of visual comfort relative to conventional 2D displays [MIS04].

The generation of visual discomfort associated with viewing stereoscopic displays is an important health issue, and anecdotal evidence indicates that worldwide concern exists regarding this problem (see e.g. [LIFH09]). The Italian government, for example, recently recalled 7,000 sets of 3D glasses from cinemas as they 'did not display tags proving they would not cause short-term vision problems to users' [Reu10]. In this context, display designers need to know the design criteria that will ensure the viewing of 3D images does not cause problems.

Despite the extensive body of research related to the effects of viewing stereoscopic images there is no clear understanding of how discomfort is caused [UH08]. A number of authors, e.g. Mon-Williams, Rushton and Wann [MWR93], have

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suggested that the discrepancy between the accommodation and convergence demands, inherent in stereoscopic VR displays but absent in non-stereoscopic displays, may cause discomfort. This model is shown as (A) in Figure 1. On the other hand, other authors (e.g. Peli, [Pel89]) claim that the discrepancy does not cause discomfort; this model is shown as (B) in Figure 1. Siegel and Nagata [SN00], however, suggest that only the production of small on-screen disparities, i.e. 'microstereopsis', will overcome the problem of the accommodation–convergence conflict. Others, such as Lambooij et al. [LIFH09], Pastoor [Pas95] and Yano, Emoto and Mitsuhashi [YEM04], propose that an accommodation-convergence stimulus discrepancy threshold exists whereby disparities of 1° or larger will cause discomfort. In an unpublished study, Howarth and Bradbury [HB94] created a graphical form of this predicted relationship between visual discomfort and the accommodation-convergence conflict. This model (expanded recently by Howarth [How11]) is based upon traditional optometric data obtained whilst measuring the limits of the oculomotor system [Mor68, Gos95] and is shown as (C) in Figure 1. Optometric studies show that there is tolerance for imprecision in both accommodation (the depth of field of the eye) and convergence (Panum's fusional areas [see HR95 and How11]) which produces the expectation that a small amount of conflict should not produce adverse symptoms.

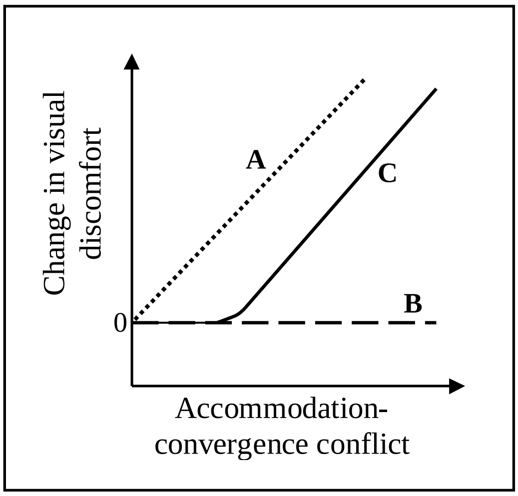

Figure 1 : *Three models of the relationship between the accommodation-convergence conflict and visual discomfort.*

A number of studies have examined the production of symptoms in the presence of the accommodation-convergence conflict, none of which have provided a definitive answer. Hoffman, Girshick, Akeley and Banks [HGAB08], Emoto, Nojiri and Okano [ENO04], Emoto, Takahiro and Okano [ETO05] and Yano et al. [YEM04], in particular, examined the differences in visual discomfort when viewing stereoscopic and non-stereoscopic images. In each of the studies the authors claim the introduction of an accommodation-convergence conflict was responsible for increases in discomfort (implicitly supporting model [A] in Figure 1), but experimental design issues render these findings inconclusive [How11]. The primary problem in these studies is that the metric used was the severity of the symptom present at the end of the trial. Given that the symptoms were not evaluated at the beginning, it is not possible to say that the stimulus used gave rise to the symptoms, as they could have already been present when the trial started.

In order to provide design solutions for new technology, viable models of human performance and comfort are required. The primary aims of this study were, therefore, to ascertain which of the three current models is correct and identify the subsequent opportunities for design guidance. Pilot work indicated that participants were, indeed, likely to experience visual discomfort, and so an additional aim was to examine whether there were any associated changes in the oculomotor system. When one eye is covered visual feedback is prevented, and generally the eye moves to take up a 'position of rest' [Gos95]. The relative position of the two eyes is termed 'heterophoria', and on theoretical grounds one might expect it to change during a trial. This is because it is directly related to the vergence and accommodation systems, and so heterophoria changes were measured along with changes in visual acuity.

2. Methods

To examine these questions, participants played a computer game for 20 minutes on four different occasions. Each of these trials presented the participants with a different level of the accommodation-convergence conflict. Three different stereoscopic conditions were used along with a control condition, in which the disparity was zero. The minimum disparity (0.3°) possible with the experimental equipment provided the first stereoscopic condition, the maximum (4.3°) disparity achievable provided the second, and a medium disparity midway between the two (2.4°) produced the third. The order of conditions was counter-balanced using a Latin Square design to avoid treatment order bias, and to control the effect of habituation. Participants were randomly assigned to the various condition orders and were only allowed to view one condition within a given 24 hour period.

2.1 Participants

A total of 16 unpaid participants (nine females and seven males, mean age: 28.6 years, age range: 20-47 years) were recruited from amongst university students and staff, as well as members of the public. Each participant completed a health screening questionnaire and an informed consent form before being allowed to take part in the experiment.

Participants were required to have binocular vision, the capability to execute vergence movements with both eyes, and no strabismus ('squint', or 'lazy eye'). Distance visual acuity was taken as a measure of general visual function and participation was dependent on subjects achieving a logMAR score of 0.0 (equivalent to a Snellen score of 6/6 [20/20]) or better, when optically corrected. (Participants with a refractive error were required to wear their corrective eyewear during the experiment.) The ability of participants to maintain a clear, single image of a target object presented with the maximum disparity was a further requirement. All of the participants met these criteria.

2.2 Stimulus

The stimulus was a puzzle-based computer game developed by Kokakiki LLC called 'Ziro'. The object of the game was to remove numbered blocks from the gaming area by manoeuvring blocks of equal number adjacent to one another and subsequently 'fusing' them together. None of the participants had difficulty with the game, and none reported experiencing diplopia (double vision) whilst playing.

This stimulus was selected for a number of reasons: participants were only required to use the mouse and could, therefore, avoid diverting their gaze to the keyboard; the gaming area remained stationary, which minimised the chance of causing visually induced motion sickness [BBG08; KDK10; How11]; the gaming area orientation remained constant, thus providing a constant vergence demand across the gaming area. The data reported by Yano et al [YEM04] suggests that (at the fixation distance used) there is little difference in the stimulus strength provided by convergent and divergent disparities and, for consistency, only divergent disparity was used.

The hardware used to present the stereoscopic images employed an active shutter glasses system. An Acer GD245HQ widescreen LCD monitor was connected to a NVIDIA GeForce GTX470 graphics card, which was housed within a custom-built Novatech PC. NVIDIA GeForce 3D Vision software was used to render the separate left-eye and right-eye images, which were alternately displayed at a binocular frequency of 120 Hz. The LCD shutter glasses were synchronised with the display via an infra-red transmitter so that each eye received its designated image at 60 Hz. The image disparity was controlled by a scroll-wheel on the transmitter. To ensure constant stimulus parameters over the trial, each participant had their chin resting on a chin rest, and their brow against a brow bar. In this way they maintained their head in a fixed position, and the display, which was placed 65 cm away, created a vertical visual angle of 25.6° and a horizontal visual angle of 44.1°.

Using the LCD shutter glasses to view stereoscopic images activated the lenses and resulted in a reduction in the light transmission relative to the transmission of the inactive lenses. For consistency across test sessions, the participants were required to wear a pair of inactive glasses during the 2D control condition, which were fitted with neutral density filters matched to the reduction of the active lenses. The use of these filters ensured consistent stimulus luminance at the eye, and equality of screen brightness over all conditions.

2.3 Procedure

Participants were briefed on the rules of 'Ziro' before their first test session and were allowed to familiarise themselves with the game by completing three levels. A brief rest period was provided before the data collection phase began.

The data collection for all test sessions followed the same format: collection of pre-test physiological response data; completion of the pre-test discomfort symptom questionnaire; 20 minute test session; completion of the post-test discomfort symptom questionnaire; collection of post-test physiological response data. Post-test physiological responses were recorded in the opposite order to the pre-test measurements.

2.3.1 Subjective (symptom) evaluation. Participants used a Likert scale discomfort symptom questionnaire to rate their level of visual discomfort. The questionnaire was based on research by Howarth and Istance [HI86] and by Kuze and Ukai [KU08] and used eight discomfort symptoms to 'prime' participants. After evaluating these symptoms, participants then provided a score of 'general visual discomfort' on a seven point rating scale, thereby producing an integrative metric of discomfort [HI86].

2.3.2 Objective evaluation. Near heterophoria was measured with a Maddox Wing (Clement Clarke Ltd.). Distance heterophoria was measured using a Maddox Rod and a measurement scale, which was positioned at a 5m. viewing distance.

Visual acuity was measured using Bailey-Lovie style letter charts designed to conform to BS 4274-1:2003 [BL76; BSI03]. High (90%) contrast (black letters on a white background) and low (10%) contrast (grey on white) charts were used to provide a more extensive assessment that was more suited to real-world situations [HC97]. Participants completed these monocular tests with their preferred eye at a viewing distance of 5m. The average background luminance of the chart was 245 cdm^{-2} and luminance variation across the charts did not exceed 7%, as per BS 4274-1:2003 guidelines [BSI03].

Refractive error was examined indirectly, by measuring monocular high contrast visual acuity when participants viewed the test chart through a +1 Dioptre lens. By making participants artificially myopic ('short-sighted') with the lens it was possible to ascertain whether the stimulus had changed their refractive error by measuring changes in visual acuity. This is because a myopic change (increase) in the eye's optical power over the trial would worsen visual performance, but a hypermetropic change (a decrease in optical power) would improve visual performance.

Upon completion of each test session the participants were provided with a ten minute rest period. They then confirmed that any experimental effects had sufficiently diminished by signing a post-test consent form before leaving the premises. All data collection was conducted in the vision research facilities within the Loughborough University Environmental Ergonomics Laboratory. The procedures complied with the tenets of the Declaration of Helsinki and had received prior approval from the Loughborough University Ethical Committee.

2.3.3 Data analysis. Although the subjective scales used were not at an interval level of measurement, the data have been averaged to allow visualisation in Figures 2 & 3. However, for statistical analysis *non*-parametric tests were performed using Meddis' system for analysis of variance by ranks [Med89]. This provided tests equivalent to the Wilcoxon's signed ranks, Mann-Whitney U, Spearman's Rho and Page's Trend tests.

3. Results

Not all participants experienced a change in visual discomfort, and the number who did so is shown in Table 1. A score change of 0 represents no increase in discomfort, whereas changes of 1-2 and 3-4 represent a slight and moderate increase of discomfort respectively.

Change in discomfort score	Condition			
	2D	Minimum-3D	Medium-3D	Maximum-3D
0	11	12	7	9
1	4	3	5	3
2	1	1	4	1
3	0	0	0	2
4	0	0	0	1

Table 1: *Changes in General Visual Discomfort*

The mean pre- and post-testean 'general visual discomfort' scores for each condition are presented in Figure 2. A score of 0 represents no discomfort. On average, there was a clear increase in discomfort over the trial for all of the conditions: 2D ($p < 0.02$), minimum-3D ($p < 0.03$), medium-3D ($p < 0.003$) and maximum-3D ($p < 0.001$).

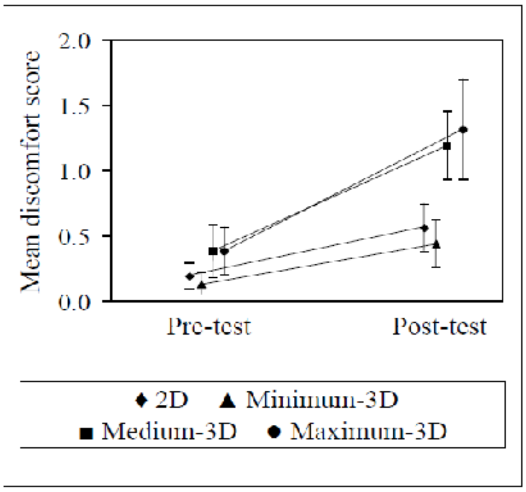

Figure 2: *Mean pre- and post-test general visual discomfort scores (vertical bars represent ± 1 s.e. [standard error of the mean]). For visual clarity, the scores are offset slightly.*

The mean changes in discomfort scores are presented in Figure 3. It is clear that the increases in discomfort for the 2D and minimum-3D conditions are similar and smaller than the changes recorded in the other two conditions, and that the greatest change experienced by participants was in the maximum-3D condition. The solid line represents model "C" in Figure 1.

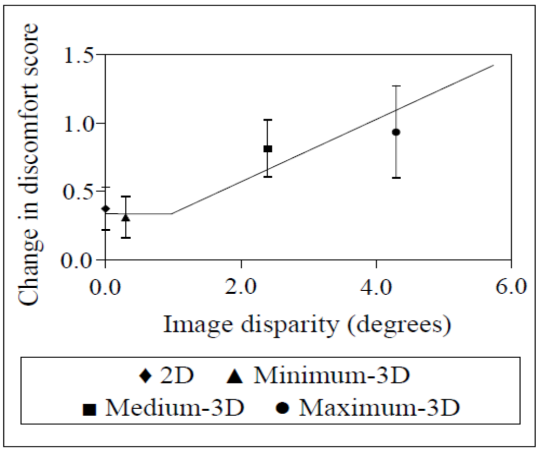

Figure 3: *Mean changes in general visual discomfort (vertical bars represent ± 1 s.e.). The solid line represents the relationship between general visual discomfort and the accommodation-convergence conflict described by model "C" in Figure 1.*

In order to examine the different models presented in Figure 1 quantitatively, Page's Trend test was applied to the data showing the change in general visual discomfort over the trial. Although the monotonic condition trend of 1,2,3,4 (which represents line A in Figure 1) was statistically significant ($L = 421$, $z = 2.769$, $p = 0.003$, 1 tail) the two-branched condition trend 1,1,3,4 (which represents line C in Figure 1) provided a better fit to the data ($L = 386$, $z = 2.952$, $p = 0.002$). This indicates that a small amount of accommodation-convergence conflict is tolerated, and does not give rise to adverse symptoms, whereas a large amount of conflict is not tolerated (even though vision remained single). The dataset, as a whole, did not fit the trend predicted by Peli [Pel89] of no change in comfort (line B, Figure 1). The other symptoms included on the questionnaire were subjected to the same analysis, but 'general visual discomfort' was the only symptom which changed significantly.

To examine the relationship between the changes in discomfort and those of the physiological parameters the participant group was first dichotomised according to whether or not participants experienced any increase in discomfort during the maximum-3D condition. No association was seen between changes in heterophoria and discomfort for either near heterophoria ($Z = 1.117$, 1 tail) or distance heterophoria ($Z = 0.452$, 1 tail).

Further analysis of the correlation (Spearman's Rho) between heterophoria and the discomfort changes in the maximum-3D condition failed to reveal the presence of any relationship (near, $\rho = 0.146$, $Z = -0.564$, 2 tail; distance, $\rho = 0.194$, $Z = -0.751$, 2 tail).

We expected to find small changes in distance vision, commensurate with a temporary myopic shift often found with close work [e.g. OC95]. The prediction made was that when viewing the test chart through the +1 Dioptre lens the participants' vision would be slightly worse. Although this was the result found for the 3D conditions, the opposite was found for the 2D control condition. Opposite results were found with the low contrast and the high contrast charts viewed without a lens. Vision improved for all four conditions with the high contrast chart, but worsened for three of the four conditions with the low contrast chart. The size of these changes was such that they had no practical significance, and the lack of consistency between conditions (and lack of any rank ordering between conditions) leads to the conclusion that the refractive elements of the visual system were essentially unaffected by the stimulus.

4. Discussion

The first aim of this study was to differentiate amongst the three current models of the relationship between the accommodation-convergence conflict and visual discomfort. The average results suggest that the best representation of the relationship is as shown by line C in Figure 1, in which a small amount of conflict has no effect whereas a large amount produces adverse symptoms. However, when individual's results are considered, the possibility of Line C describing some people, and line B describing others, cannot be discounted.

Although the results show that the visual system does tolerate a small amount of conflict before discomfort is experienced, they do not provide a definitive value for the threshold. Pastoor [Pas95] and Lambooij et al. [LIFH09] suggest that the threshold value is a disparity of approximately1°. This threshold value is also recommended by Iwasaki, T., Kubota, T. and Tawara [IKT09], who used a different criterion of accommodation tolerance. However, Yano et al [YEM2004] showed a clear reduction in comfort at the lower disparity values of disparities of +/- 0.82° (after failing to observe any comfort zone around the fixation plane). No previous study has shown both the flat portion and the sloped portion of the function, and consequently, there is little experimental data available with which to estimate the threshold value.

At this point it must be considered that this threshold value could vary substantially from person to person. One aspect that is clear from the data shown in Table 1 is the difference between the numbers and responses of people in each condition. This needs further investigation before definitive guidance can be provided to designers. In the condition with the largest disparity, seven participants reported an increase in discomfort, but nine reported no change. The disparity introduced in this condition (4.3°) was substantially larger than the 1° value suggested elsewhere [LIFH09] as a limit, yet the majority of the participants were still free from discomfort after 20 minutes. Others have also reported finding differences between individuals. Yano et al. [YEM04] reported clear differences amongst their six participants, and although Hoffman et al. [HGAB08] did not report data from individual participants, their graphs show that *some* of the participants reported their experience to have been worse under conditions of no-conflict. These findings are consistent with clinical reports which show that people vary widely in their responses (including discomfort) to binocular stimuli [Gos95].

There is a further problem in comparing results from different studies because of the different exposure times used. Kooi and Toet [KT04] examined a number of errors and misalignments in binocularly-presented displays but only exposed participants to experimental displays for five seconds. It seems unlikely that asthenopic symptoms would develop within that period, which questions the comparability of these data with our own. In contrast, Emoto et al. [2004, 2005] exposed participants for around an hour, and Ames (2003) exposed a sample subset for up to two hours. It seems reasonable to suggest that discomfort would increase with longer exposures to the accommodation-convergence conflict, as is the case with visually-induced motion sickness [e.g. HC97] but this has not yet been established definitively. Emoto et al. [ENO04, ETO05] only reported the findings gathered at the end of the period, and the increasing problems that Ames' participants experienced could have been a consequence of the wearing of head mounted displays to view the stereoscopic images.

There are two further features of the data which warrant comment. The first is that, like those of Hoffman et al. [HGAB08], some of our participants reported an increase in discomfort during the control condition. This was not unexpected, given that the participants were playing a computer game at a fixed distance of 65 cm and also had to maintain a fixed head position for twenty minutes. These changes were relatively small in the control condition [and the minimum-3D condition], and were reported by fewer than a third of the participants.

The second is that some participants reported the presence of symptoms at the outset, before exposure to the stimulus. As mentioned earlier, previous studies such as Hoffman et al. [HGAB08], Yano et al. [YEM04], Emoto et al. [ENO04, ETO05] have all measured symptoms at the end of the trial, but failed to establish whether they were also present before the participant was exposed to the stimulus. Our data suggest that care is needed in the interpretation of the results of these studies.

In summary, by showing that a large amount of conflict between the accommodation and vergence demands of stereoscopic 3D images produces a change in discomfort, whereas a small amount does not, definitive evidence has been provided that shows the conflict produces asthenopia. The results lend support to the model of the relationship between symptoms and the conflict in which there is a "zone of comfort" around the no-conflict condition [How11]. Introducing a small disparity – placing the image geometrically at a distance which differs from the optical distance – is tolerated because of the optical range of the depth of field and/or the vergence range provided by Panum's fusional areas. The physiological measures taken did not provide evidence of oculomotor changes associated with the change in comfort, and the genesis of the discomfort remains unknown.

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