ERGONOMICS, 1998, VOL. 41, NO. 3, 280–285

Gaze angle: a possible mechanism of visual stress in virtual reality headsets

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Keywords: Gaze angle; Head-mounted displays; Virtual reality; Visual stress.

It is known that some Virtual Reality (VR) head-mounted displays (HMDs) can cause temporary deficits in binocular vision. On the other hand, the precise mechanism by which visual stress occurs is unclear. This paper is concerned with a potential source of visual stress that has not been previously considered with regard to VR systems: inappropriate vertical gaze angle. As vertical gaze angle is raised or lowered the 'effort' required of the binocular system also changes. The extent to which changes in vertical gaze angle alter the demands placed upon the vergence eye movement system was explored. The results suggested that visual stress may depend, in part, on vertical gaze angle. The proximity of the display screens within an HMD means that a VR headset should be in the correct vertical location for any individual user. This factor may explain some previous empirical results and has important implications for headset design. Fortuitously, a reasonably simple solution exists.

1. Introduction

The use of Virtual Reality (VR) head-mounted displays (HMDs) can produce temporary deficits of binocular vision (Mon-Williams *et al.* 1993). The causal mechanisms, however, have not been completely explicated. The possibility that a number of factors may interact makes it difficult to determine what causes deficits in binocular function. The consequence of this situation is that HMD manufacturers have difficulty knowing how current systems might be modified to prevent potential visual problems.

Various reports exist of adverse visual symptoms following use of VR systems (Regan and Price 1994). Mon-Williams *et al.* (1993) showed that these symptoms are associated with changes in the visual system. One of the major physiological changes reported following the use of binocular VR system has been an 'esophoric' shift in heterophoria. Heterophoria is the bias that exists in the vergence eye movement system under open-loop conditions (i.e. when retinal disparity is removed). Heterophoria is a common clinical measurement as it provides some indication of whether the binocular visual system is under any stress. Heterophoria is relatively easily measured using standard clinical techniques, as the vergence angle which exists when binocular fusion is broken by covering one eye with a Maddox rod (a lens that prevents fusion of retinal images; see §2). If the visual axes are convergent then the system is described as *esophoric* and if divergent, *exophoric*.

Mon-Williams *et al.* (1993) proposed various causal mechanisms related to headset engineering to explain the observed change in heterophoria after VR HMD use. It has also been suggested that a more fundamental problem might be present in binocular systems, due to a conflict between natural ocular-motor responses and VR display characteristics (Wann *et al.* 1995). Within the ocular-motor system, accommodation (focus) and vergence are physiologically coupled so that accommodation results in vergence and vice versa. Binocular (stereoscopic) VR systems require a user to accommodate on the display screen to ensure clear vision while making vergence eye movements to maintain single vision. Binocular VR systems therefore require the normal relationship between accommodation and vergence to be modified in some manner and it has been proposed that these adaptive pressures may explain some of the observed changes in heterophoria (Wann *et al.* 1995). Although most early HMDs were designed as binocular systems, many VR displays now present the two eyes with an identical image and are referred to as bi-ocular displays. Binocular displays require ocular-motor changes via vergence eye movements when different objects are viewed in depth, whereas bi-ocular displays do not.

If the conflict between accommodation and vergence is responsible for the changes in heterophoria within VR systems, then removal of the conflict should remove the observed changes in heterophoria. Some evidence for this was provided by Rushton *et al.* (1994) who reported that the majority of 50 participants did not show changes in heterophoria following use of a bi-ocular display. On the other hand, clinically significant changes in heterophoria were still identified in a minority of participants. Moreover, Howarth and Costello (1996) have reported changes in heterophoria following the use of two different bi-ocular HMDs. Interestingly, an esophoric shift was found following the use of one system, and an exophoric shift after exposure to the other. It has been suggested (Mon-Williams *et al.* 1993, Howarth and Costello 1996) that these shifts in heterophoria might be due to *induced prism*. If the user is not looking through the centre of the lenses within a bi-ocular head-mounted display, then prismatic power may be induced. The effect of induced prism is to alter the demands placed upon the vergence system so that inducing prism may cause visual stress and a consequent change in heterophoria.

The authors wish to draw attention to another potential cause of visual stress that has not been previously identified with regard to these VR systems. As vertical gaze angle (the vertical orientation of the eyes with respect to the head) is changed, then so the effort required of the extra-ocular muscles becomes modified (Heuer and Owens 1989, Heuer *et al.* 1991). A model has previously been proposed by Heuer and Owens (1989) to explain preferred vertical gaze direction from measurements of 'dark vergence'. On the basis of this model it has been stated that measurement of dark vergence might allow for the optimum design of VDU workplaces. Unfortunately, however, the practicalities of measuring dark vergence rule it out as a technique for use with HMDs. The authors therefore used a modified technique to study the relationship between gaze angle and visual stress. The advantage of the measures used is that they readily lend themselves to modification for use in the design of head-mounted displays.

The display screens within an HMD are situated extremely close to the eyes and consequently very small changes in headset position will create large changes in gaze angle. This mechanism may explain the complexity of previous research findings and has ramifications for those who design HMDs. An experiment was undertaken in order to determine the effect of different vertical gaze angles on the stress placed on the vergence system as estimated by open loop vergence bias (heterophoria).

2. Method

Heterophoria measurements were taken in six participants at five different gaze angles (20° above, and 0, 20, 40, and 60° below ear-eye line). The six participants (21 – 35 years of age) were members of staff in the department of Human Movement Studies, University of Queensland. All the particpants frequently used computer displays without any adverse symptoms and none of the participants had any history of visual problems. All of the participants were screened for visual problems by an optometrist. Four heterophoria measurements were taken at each gaze position and the order of the measurements was pseudo-randomized (ascending and descending orders were avoided). Gaze angle was altered by changing ocular direction while maintaining a constant head position, such that the ear-eye line remained horizontal. Head support was provided for the participants to help them to maintain this position. Spherical-reflective markers were attached to the outer canthus of the left eye and the mastoid process, on a line joining the tragus and the outer canthus. During the experimental sessions, the reflective markers were illuminated by a 1000 W light placed behind a NEC TI-23A CCD camera, and the movement of these markers automatically digitized using a MotionAnalysis Corporation VP110 video digitizer. *Post hoc* checks of head position were carried out by using the two-dimensional coordinates of each marker obtained by calculating the centroid of the marker outline for each digitized video frame.

Heterophoria was measured using a tangent screen viewed through a Maddox rod (a standard clinical technique). A small white LED was positioned in the centre of the tangent screen and this was placed in line with the right eye. A thin, high contrast vertical line (e.g. a good accommodative stimulus) acted as a fixation target on either side of the LED and participants were asked to maintain focus on this line. The participant focused on the central line for 15 s and then the left eye was uncovered for approximately 0.25 s. When the left eye was uncovered the participant observed a thin red vertical line (created by the Maddox rod) on the tangent scale. The participant reported the position of the red line by stating which number the line passed through. When the line was to the left of the central fixation point then the vergence system was esophoric and when to the right, exophoric. Measurements were made in prism dioptres (Δ): a clinically useful measure corresponding to the power of a prism that displaces a target at 1 m by 1 cm. The screen was located at 33 cm from the participant (requiring accommodation of 3 dioptres) which corresponds to the accommodative demands present in a number of VR headsets (Mon-Williams *et al.* 1993).

Statistical analysis consisted of calculating the coefficient of determination for the individual mean data points as a function of gaze angle (as a measure of effect size) and comparing the magnitude of the linear Pearson Product Moment Correlation (r) with the critical value of r (0.381, df= 28, alpha= 0.05) at which r is significantly different from zero.

3. Results

The results clearly demonstrate that heterophoria varies with vertical gaze angle (figure 1), suggesting that the stress placed on the vergence system during use of head-mounted displays will depend, in part, on the vertical gaze angle. The results also illustrate that the angle at which the eyes have the smallest heterophoria measurement is typically somewhat below the ear-eye line (mean = 34°). As the gaze angle raises from this point then the heterophoria becomes more divergent. The opposite is true as vergence angle is lowered, and in this case the eyes adopt a convergent resting position. Although this effect was consistent across participants ($r = 0.49$. $p < 0.05$) and a linear fit explains 25% of the variance, the relationship between change in heterophoria and gaze angle showed a large degree of inter-individual variability. Whilst five participants demonstrated increased exophoria with increasing gaze angles (individual $r = 0.74$; 0.83; 0.91; 0.94; 0.98), one participant showed an inverse relationship ($r = -0.59$).

4. Discussion

These results confirm that vertical gaze angle may alter the demands placed on the vergence system and that heterophoria measurements provide a useful measure of this relationship. It is important to note that there were large individual variations in the relationship between heterophoria and gaze angle. The vertical position of the display screens in HMDs may consequently cause visual stress for some individuals. It should not be assumed that the user will adjust the headset if the gaze angle is inappropriate. The major determinant of an HMD's position on the head is the

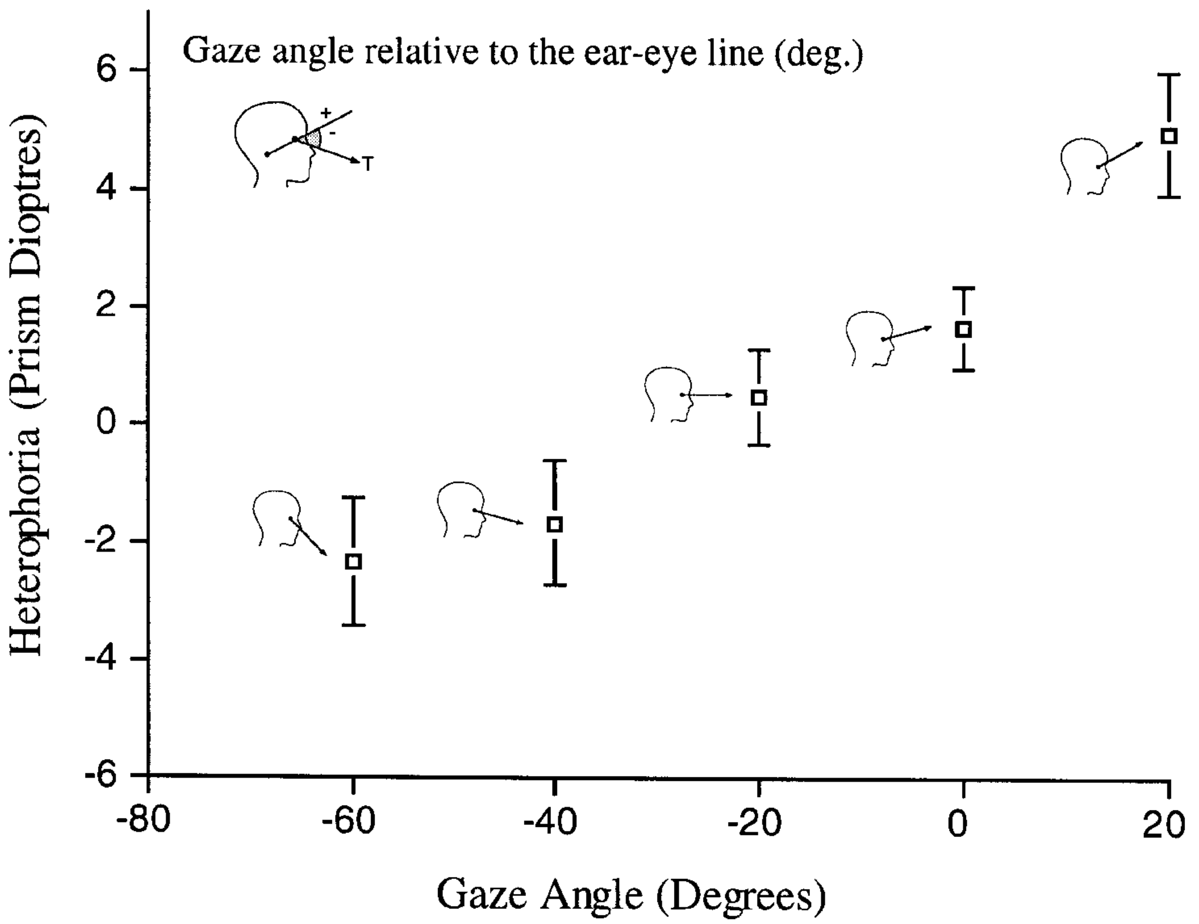

Figure 1. Heterophoria plotted as a function of gaze angle. Each data point is the mean of six participants. Standard error bars are shown to indicate the variability between participants. Individual standard error bars were smaller than the symbol size. Positive values indicate exophoria and negative values indicate esophoria. The schematic heads give an approximation of target position relative to the head.

design of the headset together with the musculoskeletal position of greatest comfort. Once the HMD is in place it is highly unlikely that a user will equate eye strain with the vertical location of the headset. It should also be noted that the majority of HMDs allow for initial adjustment of head position after which time the headset is fixed in place (normally by means of a headband that is tightened).

The authors have previously used a software calibration routine that allows for the measurement of heterophoria within a VR headset (essentially this routine displays a tangent screen on one screen and a vertical line on the other). Use of this routine allows a user to adjust a VR headset until the heterophoria measures reach a minimum value. Furthermore, the authors have described a routine that enables any demands placed upon the vergence system by a VR system to be minimized (Wann *et al.* 1995). Use of this software has previously been considered only in relation to the induction of prism but it is now suggested that it may be beneficial when adjusting an HMD's position on the head.

The results reported here have implications for those carrying out research into the ergonomic factors that need to be considered in relation to HMDs. These findings predict certain adaptive changes within the ocular-motor system according to gaze angle. The vergence system has a tonic component that decreases steady-state demands (Carter 1965, Schor 1979). If the eyes maintain a convergent position for a prolonged period of time, than the binocular system will become relatively more esophoric and vice versa. Maintenance of fixation in elevated gaze would therefore lead to an exophoric shift and lowered gaze would cause a change in the esophoric direction. The magnitude of the heterophoric change that has been observed with an alteration in gaze angle is greater than that reported after using VR systems. It is possible, therefore, that the different changes in heterophoria previously observed in bi-ocular systems (Rushton *et al.* 1994, Howarth and Costello 1996) are a consequence of the different gaze angles required by the respective headsets, and individual variations in adjusting the headsets.

There are logical grounds to suggest that some of the changes in heterophoria following VR use may be more readily explained through inappropriate gaze angle than induced prism. Although powerful lenses are used within VR headsets, it is the power of the lens with relation to the screen that dictates the strength of any induced prism. HMDs that are collimated to infinity (the screens placed at the focal length of the lens) therefore have an effective power of zero and cannot create induced prism. It is not possible for the screens to be placed further away than the focal length of the lenses, as this would result in optical defocus. It is possible, however, for the screens to be placed within the focal length although this will create an accommodative demand. In this situation, the lenses will then have an effective power equal to the accommodative demand. The power of the lens is therefore limited by the amount of accommodation that may be comfortably maintained within a headset. The consequence of this is that only small degress of prism are generally induced within a headset. Furthermore, the creation of an accommodative demand will cause an esophoric shift due to the synergistic linking of accommodation and vergence. This does not mean that induced prism can play no part in the creation of visual stress in a VR system but, if it does play a role, it must be co-occurrent with other factors. It is, moreover, particularly difficult to explain existing empirical reports of exophoric shifts (Rushton *et al.* 1994, Howarth and Costello 1996) via a mechanism of induced prism.

In summary, these results illustrate that gaze angle has the potential to cause changes in visual function. It is important to emphasize that we are not proposing that this is the only potential cause of visual stress within an HMD. It seems likely that a number of factors have the potential to combine and produce a stressful environment. On the other hand, reduction of a known problem would appear prudent and manufacturers of HMDs may wish to allow for some adjustment of vertical screen position and also to provide some mechanism by which users may assess the demands placed upon their visual system at various gaze angles.

Acknowledgement

This research was supported by ESPRC grant L16125 and a University of Queensland NSR Grant.

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