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Vertical Gaze Direction and Postural Adjustment: An Extension of the Heuer Model

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The authors provide a consideration of the vergence system and suggest an extension of the original model proposed by H. Heuer, M. Bruwer, T. Romer, H. Kroger, and H. Knapp (1991) to explain why preferred vertical gaze angle is downward when fixating proximal targets. The practical implication of the revised model is that heterophoria (open-loop vergence bias) provides an indication of potential vergence effort. The extended model has several advantages: It allows for modification of workstations, is consistent with models of the accommodation and vergence system, is compatible with clinical data, and provides a more complete explanation of extant research data. The extended model was able to predict oculomotor responses, explain postural adjustments, and provide ergonomically useful data.

This article is concerned with the issue of why observers prefer to view proximal targets with declined gaze. We modify an extant model that relates this phenomenon to the angle of ocular vergence, and we suggest a simple method of assessing the relationship between vertical gaze direction and vergence effort. We then extend our research to explore the interactions between preferred gaze angle and postural adjustment in an initial attempt to elucidate this complex relationship.

Many individuals work with computer displays with no adverse problems. For a number of people, however, work with such displays is associated with ocular discomfort (e.g., eye strain; Jackson et al., 1997) and musculoskeletal problems (e.g., neck and shoulder discomfort; Grandjean & Hunting, 1977). The incidence of such problems is surprisingly high: A recent comprehensive study (Jackson et al., 1997) found that 41% of 571 computer users from a hospital setting complained of adverse visual symptoms, with 33% complaining of general problems (33% of those complaining of symptoms reported both visual and general difficulties). The problems associated with computer displays should not be thought of as benign: In severe cases, the problems are associated with stress and clinical depression (Mino et al., 1993). Furthermore, the incidence of adverse symptoms has been found to rise as the time spent working with computer displays increases (Jackson et al., 1997; Scullica & Rechichi, 1993). Some progress has been made in understanding the etiology of both ocular (Pickwell, Kaye, & Jenkins, 1991) and musculo-

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skeletal (Bergvist, Wolgast, Nilsson, & Voss, 1995) discomfort. On the other hand, little attention has been paid to the potential for ocular and musculoskeletal factors to interact in the creation of discomfort for a workstation user. This article is concerned with the potential for vertical gaze direction to cause a complex interaction between the ocular and postural control systems.

It has been established that the preferred gaze angle is steeply downward when fixating on a near target (Heuer, Bruwer, Romer, Kroger, & Knapp, 1991; Heuer & Owens, 1989; Hill & Kroemer, 1986; Kroemer & Hill, 1986), although current recommendations for computer users are not consistent with these empirical findings. Heuer and colleagues (Heuer et al., 1991; Heuer & Owens, 1989) have proposed a model that relates preferred vertical gaze angle to dark vergence (discussed later). We refer to this model as the *Heuer* model. Tyrrell and Leibowitz (1990) built directly on the study of Heuer and Owens (1989): Specifically, they examined the relationship between dark vergence and visual fatigue and reported a significant (but low) correlation between measures of dark vergence and four symptoms of visual fatigue. Although some progress has therefore been made in determining the relationship between vertical gaze angle and visual fatigue, the precise mechanism requires elucidation, and, moreover, it remains unclear at a practical level how workstations might actually be modified on the basis of dark vergence data. Tyrrell and Leibowitz have pointed out that it "is important to realise that the present analysis is based upon a somewhat simplified view of ocular-motor effort. For example, any contributions made by the accommodation system to visual fatigue have been ignored" (p. 355). The purpose of this article is to present a more detailed picture of oculomotor function, which takes into account the accommodation system, and to extend the original model proposed by Heuer et al. (1991). The revised model holds certain descriptive advantages, but, more importantly, it allows for practical implementation in the design of workstations. We specifically tested the model to determine whether it provided qualitatively similar results to those reported by Heuer et al. and to ensure its ability to provide useful data. These data were then used to consider the relationship between the visual and postural systems.

The Accommodation and Vergence System

In order to comprehend the extension of the Heuer model, it is important to understand the components of the oculomotor system that are responsible for providing clear and single vision (accommodation and vergence eye movements, respectively). If an observer wishes to change fixation from a distant object to one nearer (or vice versa), the retinal image of the target object is initially defocussed (*blur* describes this error of focus), and there is a fixation error between the target and the angle of ocular vergence (*disparity* refers to this error of fixation). In order to bring clarity to the retinal image, the eye must focus in a process known as *accommodation*, and to overcome disparity, the eyes must change vergence angle to maintain fixation with corresponding retinal areas (if noncorresponding points of the retinae are stimulated, then double vision will result). We used a graphical representation of accommodation and vergence in order to describe the most salient features of these systems (see Figure 1).

Accommodation is driven by blur information, and vergence is driven by disparity (see Schor, 1983, 1986, for a comprehensive overview). An initial change in vergence angle or accommodative state is initiated by a phasic element within the vergence and accommodation system, respectively. The phasic controller acts to rapidly eliminate blur and disparity so that a clear and single image is achieved. A tonic controller in the vergence and accommodation system then adapts to reduce any steady-state demands placed on the phasic response component (e.g., Carter, 1965; Schor, 1979). The tonic controller ensures that the accommodation and vergence system are kept in the middle of their functional range. In order to further maximize system efficiency, the accommodation and vergence responses are neurally cross-linked (see Schor, 1986) so that accommodation produces vergence eye movements (accommodative vergence) and vergence causes accommodation (vergence accommodation).

It is possible to measure the constant resting point (or bias) that exists within the vergence system by opening the normal feedback loop to vergence (i.e., by removing any disparity information). Vergence bias may be measured in complete darkness (dark vergence) or in the

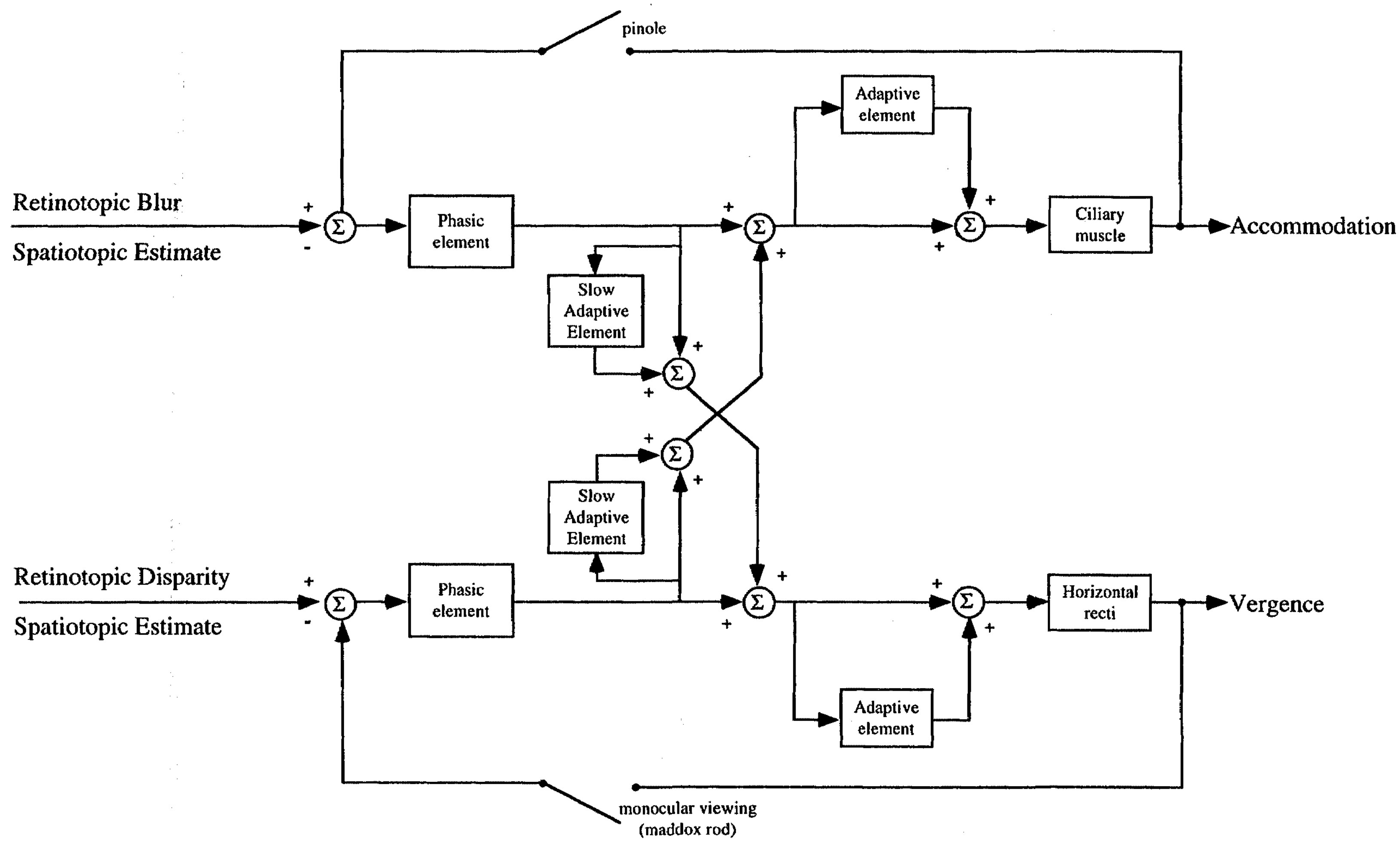


Figure 1. A heuristic model of the vergence and accommodation control system (modified from Schor & Kotulak, 1986).

presence of light (heterophoria). Heterophoria and dark vergence are related but reflect very different states of extra-ocular muscle tonus. The eyes generally converge to a point about 120 cm from an individual in the dark but are approximately parallel when distance heterophoria is measured (e.g., Owens & Leibowitz, 1980). The actual extent to which the eyes approximate a parallel position (orthophoria) varies between individuals. When the heterophoria is convergent, the system is described as esophoric, and when heterophoria is divergent, the system is described as exophoric. It is also possible to measure the resting point of accommodation (tonic accommodation) by removing any blur information (this may be achieved by viewing through a pinhole).

One important difference between measurements of heterophoria and dark vergence is the contribution of accommodation. Dark vergence necessarily lacks any accommodative stimulation, whereas heterophoria may be influenced by accommodative state through accommodative vergence. If heterophoria is measured at distances of 6 m or greater (599.99 cm), then the accommodative stimulus is effectively zero. It is possible, however, to measure heterophoria at more proximal distances (a standard clinical measurement), in which case the accommodation system influences heterophoria through accommodative vergence. Owens and Tyrrell (1992) have suggested that the relationship between heterophoria and dark vergence can be predicted if the strength of the accommodative vergence cross-link, the accommodative response associated with the measured heterphoria, and the resting position of accommodation in dark are known.

The Extended Heuer Model

The extended model rests on the premise that the eyes adopt a vertically aligned resting position (the primary position) and that this position is under constant neurological control. Movements away from this position require innervation of the appropriate musculature. The extraocular musculature is arranged so that the muscles do not act independently. The synergistic coupling of the two sets of muscles that raise and lower the eyes creates a secondary divergent and convergent pull on the eye, respectively. The increased divergence or convergence can either increase or decrease the demands placed on the horizontal muscles when making vergence movements to a proximal target. A cost (effort) is involved in converging as well as lowering the eyes, and when fixating proximal targets, the eyes are able to reduce the convergence cost by simultaneously lowering gaze. It has long been noted (cf. Hering, 1977; Hill & Kroemer 1986; von Helmholtz, 1924) that observers choose to reduce vergence demands by declining the gaze of sight (i.e., decreased vergence demand is selected at the cost of increased vertical effort). This is consistent with observations that vergence effort may be a primary determinant of visual fatigue when fixating on near targets (cf. Jaschinski-Kruza, 1994; Mon-Williams, Wann, & Rushton, 1993; Pickwell et al., 1991). We suggest that heterophoria measures provide a good indication of the change in vergence effort (increase or decrease) that is created for a given change in vertical gaze direction so that the vergence costs may be ascertained for any given vertical gaze direction.

In the absence of any fusional (disparity) or accommodative (blur) stimulation, the eyes adopt a vertically aligned resting position with the optical axes in an approximately parallel position. This position is the primary position of the eyes (defined by von Helmholtz, 1924, as the position from where there is no rolling of the eye on upward, downward, rightward, or leftward gaze) and represents the homeostatic state of the eyes in the horizontal and vertical planes. The relative position of the two eyes can be measured in this resting state to provide the vertical and horizontal heterophoria. All movements away from this point require innervation of the appropriate musculature.

It is important to realize that the muscles responsible for vertical eye movements do not act independently but rather combine to work as one unit. This arrangement means that raising or lowering the eyes involves the synergistic combination of either the superior (raising) or inferior rectus together with the superior (lowering) or inferior oblique. Hering (1977) demonstrated that raising the eyes produces innervation of the inferior obliques and that this innervation creates a secondary horizontal divergent pull on the orbits. Conversely, as gaze is declined, the superior obliques are innervated and the eyes adopt a relatively convergent position. Therefore, as observed by Hering, raising or lowering the eyes when fixating on distant objects requires a change in innervation of the horizontal musculature (the lateral and medial recti) to maintain parallel visual axes. Hering provided numerous observations in support of this fact.

As an object is moved toward an observer, it is necessary for the eyes to converge to maintain single vision. As the vergence angle increases, the demand placed on the horizontal musculature becomes greater (the vergence demands are inversely proportional to distance and therefore rapidly increase as egocentric sagittal distance decreases). It is possible, however, for an observer to exploit the mechanical properties of the eye when fixating on a near target by declining the line of sight to reduce the demands on the horizontal musculature. Heuer et al. (1991) have pointed out that movement of the eyes in a vertical plane has a certain cost (i.e., effort is required to lift or lower the eyes from the primary position). Hering (1977), however, provided a simple demonstration to show that it is the demand placed on the horizontal musculature that is the limiting factor in obtaining clear single binocular vision of proximal objects. A target (such as the tip of a pen) should first be fixated as close as possible to the eyes without producing double images. If the target is then moved upward, double vision will be produced, but closing one eye indicates that the target is within the range of vertical monocular movement. This demonstration shows that the vergence pressure placed on the horizontal musculature limits the range of clear, single, and comfortable binocular vision.

This simple mechanical model explains why observers prefer to view proximal targets with declined gaze. The practical implication of this model is that measurement of heterophoria at different gaze angles should reveal the degree to which the eyes must change vergence angle to compensate for vertical movements away from the primary position. For example, if the eyes are elevated, then the horizontal axes will become divergent. This should be reflected as an exophoric shift when heterophoria is measured, and the degree of exophoria will indicate the extent to which the horizontal musculature must compensate for the increased divergence to view an object in this location with single vision. In the same way, if convergence is required, then lowering vertical gaze may reduce the demands on the vergence system. In order to determine the effect of vertical gaze angle at closer distances than optical infinity, it is necessary to take the accommodative contribution to vergence into account. This may be achieved by providing an adequate accommodative stimulus to the viewing eye when measuring heterophoria. Heterophoria may therefore provide an indication of the vertical gaze angle at which the vergence demand is minimized for a given viewing distance. A heterophoria measure may also indicate whether a screen in situ is placing excessive demands on the oculomotor system. As well as being central to the extended model, heterophoria measurements have many practical advantages: (a) Heterophoria is commonly measured in ophthalmic assessment, ensuring compatible ergonomic and clinical data, (b) heterophoria is easily measured at a workstation, and (c) the accommodation response is taken into account.

The preceding consideration suggests that heterophoria may provide a useful measure when exploring the relationship between vertical gaze direction and visual fatigue. We therefore tested the extended model to determine whether heterophoria measures provide useful data with qualitatively similar results to those reported by Heuer et al. (1991) for dark vergence.

Experiment 1

Method

Participants. The same group of 12 participants took part in Experiments 1 and 3. The 12 participants (6 men and 6 women) consisted of university staff (secretarial assistants) and students, who were unpaid volunteers naive to the purpose of the experiments (age ranged from 20 to 30 years, $M = 25$, $SD = 4$). All were familiar with keyboard and monitor workstations, and all were able to touch type. All participants had normal or corrected eyesight with no anomalies of binocular vision. All of the participants 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 (using standard clinical tests; see Bennett & Rabbetts, 1989). Snellen vision–visual acuity of all participants was 6/6 (metric equivalent of 20/20) in both eyes (right and left, with the normal improvement in acuity with binocular viewing), and all had good near eyesight (N5) with accommodation normal for age (Bennett & Rabbetts, 1989). All participants had normal binocular vision without any suppression and normal stereoacuity.

Procedure. Experiment 1 was designed to establish the relationship between vertical gaze angle and heterophoria. If the extended Heuer model is correct, then heterophoria measures should become increasingly divergent on elevated gaze and increasingly convergent on lowered gaze. Heterophoria measurements were taken at six different gaze directions (20° and 5° above and 10°, 25°, 40°, and 55° below the ear–eye line[1]). Four heterophoria measurements were taken at each gaze direction. Participants were positioned so that their ear–eye line corresponded to 10° above the horizontal. A headrest was provided to help with the maintenance of this posture throughout the duration of the experiment. The center of a 65-cm radius arc was aligned with the outer canthus of the eye to ensure that the visual target always remained 65 cm away from the eye. 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 1,000-W light placed behind a NEC TI-23A CCD camera (Santa Clara, CA), and the movement of these markers was automatically digitized with a MotionAnalysis Corporation VP110 video digitizer (Santa Rosa, CA). 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 with a tangent screen directly fixated by one eye and viewed through a Maddox Rod (Clement Clarke, London) by the other (a standard clinical technique). A small white light emitting diode (LED) was positioned in the center of the tangent screen, and this was placed in line with the right eye. A thin, high contrast (93%) black vertical line on a white background (i.e., 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 illumination was adjusted so that both the fixation target and the red line were visible (approximately 200 lux). The participant focused on the central line for 15 s, and then the left eye was uncovered for approximately 0.25 s. The left eye was covered and uncovered using electronic shutter goggles (Translucent Technologies, Toronto, Canada), which take 1 ms to change from being opaque to transparent and 3 ms to return back to an opaque state. 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, the vergence system was esophoric and when to the right of the central fixation point, 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 × 1 cm).

The experiment also sought to determine, for each participant, the upper and lower limits of vertical gaze outside which the target at 65 cm away was perceived to be intolerable to view. In addition, participants were asked to identify an optimal target position (also for a constant target distance of 65 cm), which corresponded to the most comfortable gaze angle. We hypothesized that the preferred gaze angle should be related to the point at which heterophoria reaches its most convergent position for lowered gaze.

Two ascending and two descending trials were used to identify the tolerable gaze angle range. In the ascending condition (A), the visual target (four lines of 12-point text, subtending approximately 16 arc/min) began at 70° below the horizontal and was slowly raised (10 deg/s) around the constant radius arc until the participant indicated that the current position was tolerable to view. The protocol was repeated for

[1] The ear–eye line is an anatomical reference line formed between the outer canthus of the eye and the tragus. The line acts as a suitable reference because it moves with the head and is not dependent on where the head rotates.

the descending condition (D), except that the visual target began at 40° above the horizontal and was slowly lowered.

To identify the optimal target position, we used a staircase method (one ascending and one descending trial). The participants were instructed to make an initial judgment of optimal position, reevaluate, and then make fine adjustments up or down until the most comfortable position was located. The order for the presentation of conditions was A, D, A, D, A, D for Participants 1–6 and the reverse for Participants 7–12. Gaze angles were recorded by an optoelectronic movement recording system (Optotrak, Northern Digial, Waterloo, Canada). Optotrak measures the three-dimensional position of small infrared light emitting diodes (IREDs); it is factory precalibrated and has a static positional resolution of within 0.2 mm. The data (recorded at 100 Hz) were stored in computer memory for later analysis.

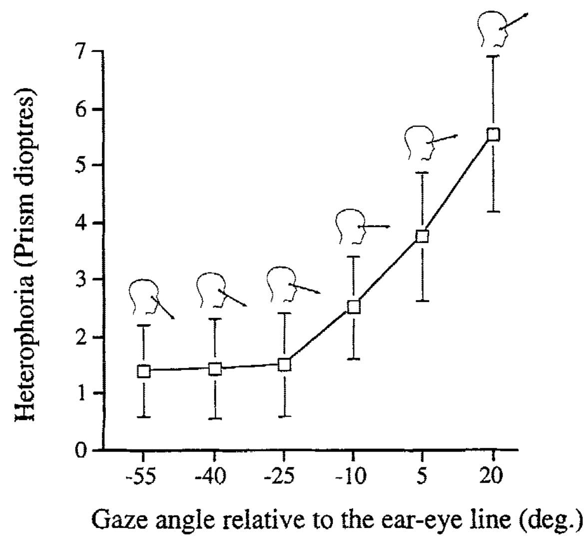


Figure 2. Mean (n = 12) heterophoria values for six gaze directions when the target distance was 65 cm. The ear–eye line was 10° above the horizontal. Error bars indicate ±1 *SD*.

Results and Discussion

Our results clearly demonstrate that open-loop vergence bias (heterophoria) varies with vertical gaze angle (Figure 2), suggesting that the stress placed on the vergence system during fixation of proximal targets will depend, in part, on vertical gaze angle. As the viewing angle increases, vergence bias becomes more divergent. The opposite is true as vergence angle is lowered and the eyes adopt a convergent resting position. It can be seen that the relationship is not linear, with the slope becoming nearly flat at low gaze angles. The relationship is best described by the following quadratic equation: $y = 0.328 + 0.091 + 0.001x^2$ (the quadratic component was statistically reliable, $p < .02$, resulting in an $r^2 = 0.99$). The quadratic form may be explained by a reduction in the action of the inferior obliques relative to the inferior recti at extremes of gaze. The individual heterophoria measurements showed very little variation (1Δ) between the four measures taken at each vertical gaze direction. As indicated by the standard deviation bars, however, the relationship between the change in heterophoria and gaze angle showed a large degree of interparticipant variability, both in magnitude and slope. These results have good qualitative and reasonable quantitative agreement with those reported by Heuer and colleagues for their dark vergence data (Heuer et al., 1991; Heuer & Owens, 1989).

The data on preferred gaze direction revealed that the mean upper limit for the tolerable viewing angle was 5° above the ear–eye line (*SD* = 6), whereas the mean lower limit was 63° below the ear–eye line (*SD* = 7). When asked to identify the most comfortable target position, all the participants selected a location well below the ear–eye line (see Figure 3). The range of optimal vertical gaze direction ranged from 19° to 36° below the ear–eye line with a mean location of 26.8° (*SD* = 4.9) chosen across participants.

Comparison of Figures 2 and 3 shows that there is a good correspondence across participants between preferred gaze angle and the angle at which heterophoria first reaches maximum esophoria (approximately 25° below the ear–eye line). The high agreement gives support to our contention that heterophoria provides a useful indicator of optimal vertical screen position. We further suggest that positioning a computer screen above this position may produce visual fatigue, as visual discomfort can result from high activation of the horizontal recti. Indeed, anomalies of vergence may be the primary cause of visual discomfort when fixating on near targets (e.g., Jaschinski-Kruza, 1994; Mon-Williams et al.,

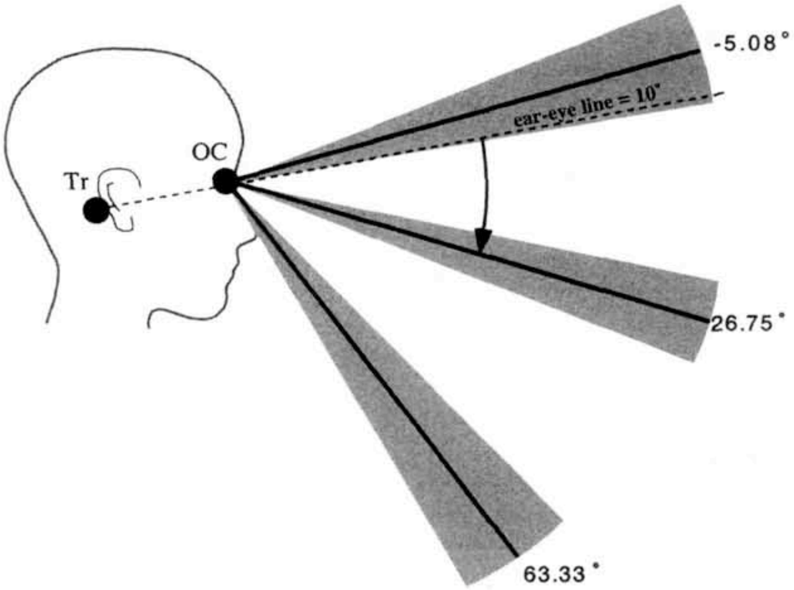


Figure 3. The average ($n = 12$) perceived optimal gaze angle (26.75°). The upper and lower limit for perceived tolerable gaze angles was 5.08 above the ear–eye line and 63.33 below the ear–eye line, respectively. The shaded area indicates ±1 *SD*. Tr = Tragus; OC = outer canthus.

1993; Pickwell et al., 1991). The data presented here indicate that elevated vertical gaze angles result in increased vergence effort, and consequently, if prolonged, such situations have the potential to create visual discomfort.

It is worthwhile to compare the current data on preferred gaze angle with data from other studies and with the recommendations contained within guidelines for computer users. The preferred gaze angle data have close quantitative agreement with those reported by Heuer et al. (1991) but are about 10° higher than those reported by Hill and Kroemer (1986; Kroemer & Hill, 1986). The difference between studies is not surprising when one considers the relatively small number of participants and the high variation found across participants in all of the studies. Current guidelines recommend that the top of the monitor be placed at eye level. We assume that the ear–eye line is 10° above the horizontal. If, as recommended by the guidelines, a 20-cm high screen were viewed at 65 cm, the viewing angle would be approximately 19° at the center of the screen and 28° at the bottom of the screen (as in some data entry tasks). This means that current recommendations place the monitor at a position that is higher than the optimum preferred position for 9 out of the 12 participants from this experiment when viewing the center of the screen. It should be noted, however, that gaze angle will be optimal for these observers when viewing the bottom of the screen. This observation highlights the point of fixation on the monitor as another factor that requires consideration when trying to establish why an individual is having problems with his or her computer workstation. We therefore concur with Heuer et al. (1991) that preferred gaze angle should be established on an individual basis rather than attempting to produce a universal recommendation on computer monitor height on the basis of mean data.

Experiment 2

As the extended model takes the accommodation response into account, it is possible to make some predictions regarding the relationship between preferred gaze angle and sagittal viewing distance. The model predicts that the relationship between vertical gaze angle and heterophoria should increase as a monitor gets closer. This prediction is made on the basis that accommodative effort increases with decreasing distance, which, in turn, causes an increase in the vergence demands because of the effect of accommodative vergence. In addition, the heterophoria should show an increasingly divergent bias (e.g., the participant should become relatively more exophoric as sagittal distance decreases), as accommodative vergence only produces about 60% of the total closed-loop vergence response.

As a consequence of the changes in heterophoria, the optimal gaze angle should lower because a decreased target distance increases the amount of convergence required for comfortable fixation, and, as previously outlined, the vergence demands are decreased with lowered gaze. The model further predicts that a lower angle will be preferred with binocular vision (as accommodative vergence is only about 60% of the total closed-loop vergence response). These predictions were tested in Experiment 2. The exploration of preferred gaze angle in Experiment 2 is also an empirical continuation of the studies run by Hill and Kroemer (1986; Kroemer & Hill, 1986) and Heuer and colleagues (Heuer et al., 1991; Heuer & Owens, 1989).

Method

Participants. A separate group of 6 participants took part in Experiment 2. The 6 participants (4 men and 2 women) consisted of staff (faculty members, research assistants, and technical and secretarial assistants) from a university population (age ranged from 22 to 35 years, $M = 29$, $SD = 4.5$). All were familiar with keyboard and monitor workstations, and all were able to touch type. All of the participants 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 (using standard clinical tests; see Bennett & Rabbetts, 1989). All participants had normal or corrected eye sight with no anomalies of binocular vision. Snellen vision–visual acuity of all participants was 6/6 in both eyes (right and left with the normal binocular advantage), and all participants had good near eyesight (N5) with accommodation normal for age (Bennett & Rabbetts, 1989). All participants had normal binocular vision without any suppression and normal stereoacuity.

Procedure. Heterophoria measurements were taken in the 6 participants at five different gaze angles (20° above and 0°, 20°, 40°, and 60° below ear–eye line). Gaze angle was altered by changing ocular direction while maintaining a constant head position, such that the ear–eye line remained horizontal. The screen was located at three distances from the participants: 33 cm, 50 cm, and 100 cm (requiring accommodation of 3 dioptres, 2 dioptres, and 1 dioptre, respectively[2]). Four heterophoria measurements were taken at each gaze position, and the order of the measurements was pseudorandomized (strictly ascending or descending orders were avoided).

Experiment 2 also sought to establish the relationship between sagittal distance and preferred vertical gaze angle. This relationship was studied a month after the heterophoria measurements were taken to ensure that the results of the separate measures did not interact. Two ascending and two descending trials were used to identify the tolerable gaze angle range. In the ascending condition, the visual target (four lines of 12 point black text subtending approximately 16 arc/min on a white background, 93% contrast at 500 lux) began at 70° below the horizontal and was slowly raised (10 deg/s) until the participant indicated that the current position was tolerable to view. The protocol was repeated for the descending condition, except that the visual target began at 40° above the horizontal and was slowly lowered. To identify the optimal target position, we used a staircase method (one ascending and one descending trial). The participants were instructed to make an initial judgment of optimal position, reevaluate, and then make fine adjustments up or down until the most comfortable position was located. The order for the presentation of conditions was randomized. Gaze angles were recorded by Optotrak. These measures were taken for viewing distances of 100 cm, 50 cm, and 33 cm.

[2] It is easiest to describe the accommodation responses in terms of dioptres. These are the reciprocal of distance in meters so that 1 dioptre corresponds to 100 cm, 2 dioptres corresponds to 50 cm, and so forth.

Results and Discussion

Pearson product–moment correlations were calculated for the individual mean data points as a function of gaze angle for each distance, and the 95% confidence intervals of these correlations were calculated using Fisher *Z* transformations. The correlation coefficients were considered to be significant if the 95% confidence intervals did not include zero. For $n = 30$ (5 Conditions × 6 Participants), the 95% confidence interval does not include zero when the correlation coefficient is greater than .381. Coefficient of determination was calculated as a measure of effect size. The effect of distance on the heterophoria–gaze angle relationship was assessed by calculating linear equations of least square fit for each participant and for each distance and by submitting the gradient and intercept values to one-way repeated measures analysis of variance (ANOVA). Preferred monocular and binocular gaze angle data were also submitted to a one-way repeated measures ANOVA. Multiple ANOVA are preferable in this situation because multivariate analyses of variance do not fully control for experimentwise error rate (Huberty & Morris, 1989).

The results of Experiment 2 concurred qualitatively and quantitatively with those of Experiment 1: Heterophoria varied with vertical gaze angle (see Table 1), and this relationship had good agreement with preferred gaze angle. This effect was consistent across participants, regardless of viewing distance ($r = .49$, .48, and .47 for 33 cm, 50 cm, and 100 cm, respectively, all $ps < .05$), with a linear fit explaining about 25% of the variance in each case. Table 1 contains summary statistical descriptions. The effect of increasing viewing distance from 33 cm to 100 cm was a decrease in the gradient of the relationship from 0.11 dioptres per degree to 0.05 dioptres per degree. The change in gradient did not reach statistical significance, $p < .12$. The change in sagittal distance also reduced the bias, as expressed in the *y*-intercept, from 2.5 Δ to −0.9 Δ, and this change was statistically significant, $p < .02$. The preferred gaze angle lowered as egocentric sagittal distance decreased with monocular viewing, and this relationship approached, but did not reach, statistical significance, $F(2, 15) = 2.84$, $p < .09$. The preferred binocular viewing gaze angle also lowered as egocentric sagittal distance decreased, and this relationship did reach significance, $F(2, 15) = 3.44$, $p < .05$. Comparison of the monocular and binocular preferred gaze angle showed that the difference between conditions (a lower angle was selected when viewing binocularly) was statistically significant, $F(1, 34) = 12.11$, $p < .05$. The preferred gaze angles (binocular and monocular) were bounded by the tolerable angles as reported in Experiment 1. The preference for lowering gaze angle with decreasing egocentric distance and binocular viewing was consistent across all of the participants. This aspect of the results provides an experimental validation of Hering's

Table 1
Summary Data for Heterophoria and Preferred Gaze Angle Measurements

Heterophoria and preferred gaze angle	Distance: 33 cm *M*	33 cm *SE*	50 cm *M*	50 cm *SE*	100 cm *M*	100 cm *SE*	*F*(2, 15)	*p*
Gradient (Δ/degrees)	0.11	0.09	0.08	0.07	0.05	0.04	2.77	.11
Intercept (Δ)	2.50	3.64	0.78	2.71	−0.89	1.71	5.86	.02
Preferred monocular gaze angle (degrees)	27.92	6.09	26.60	2.67	22.25	3.44	2.84	.09
Preferred binocular gaze angle (degrees)	34.33	3.01	33.00	3.07	27.42	2.10	3.44	.05

Note. The first two rows provide heterophoria measurements and the second two rows display preferred gaze angle measurements. Standard errors indicate ± 1 *SD*.

(1977) original observation that the vertical binocular fixation field is smaller than that "accessible with monocular vision" (p. 65).

Experiment 3

Experiments 1 and 2 established that heterophoria measurements provide a useful indicator of optimal vertical gaze angle. Observers can, in general, vary the vertical gaze angle adopted to view any given visual target by altering the posture of the head and neck. Extension (backward bending) of the neck will rotate the head backward and lower the vertical gaze angle, leading to reduced vergence effort. Postures involving neck extension are, however, implicated in the causation of musculoskeletal discomfort (Bergvist et al., 1995). The posture adopted to view any given visual target is thus likely to represent a compromise between visual and musculoskeletal discomfort. Experiment 3 sought to determine the relationship between body posture and vertical target location. A control experiment was first conducted to ensure that typing per se, does not affect adopted posture. The actual experiment studied the various postures adopted by individuals when viewing a target placed in different vertical locations.

Method

Participants. Experiment 3 used the same 12 participants who took part in Experiment 1.

Procedure. In the first part of Experiment 3, the participants self-selected the height of the seat pan and the backrest inclination of an adjustable chair designed according to ergonomic principles (Posture Seating Inc., Brisbane, Australia). Participants were blindfolded and asked to adopt a relaxed posture. This posture was maintained for 5 min while the participants listened to music. Joint angle data were collected in the last minute at a frequency of 10 Hz. This procedure was then repeated, and participants were required to type a previously recorded dictated document while blindfolded for a duration of 5 min.

Following the control condition, participants were instructed to view a small screen television (4.5 × 5.5 cm) mounted at 15° intervals on a 65-cm arc. The arc was positioned so that its center was in line with the eye in the primary position. The television was placed at one of the following six positions: +30°, +15°, 0°, −15°, −30°, and −45° with respect to a virtual horizontal line passing from the eye through the center of the arc. The conditions were presented in random order with each position used three times. The television displayed a single word written in a contradictory color (e.g., the word *red* would appear written in green). The letters were of a size equivalent to 24 point text (subtending approximately 32 arc/min), and the average monitor luminance was 40 cd/m^2. The participants were asked to name the color indicated by the word rather than the color it was written in (this Stroop task is commonly used in psychological paradigms and was chosen to divert participants' attention from the actual purpose of the experiment). Each position was viewed for a period of 1 min, with data collection occurring during the last 10 s (10 Hz).

IREDs were placed on the outer canthus, the mastoid process, C7, and the greater trochanter. The markers were used to define head and neck angles (see Figure 3). These angles were then used to describe the position of the head and neck, modeled as three rigid links articulated at two pin joints: the antlanto-occipital joint and midway between C7 and T1. The position of the head with respect to the external environment was described by calculating the position of the ear–eye line with respect to the horizontal. Two-dimensional joint kinematics were recorded by Optotrak (10 Hz).

Results and Discussion

Figure 4 shows the average joint positions for the control conditions (listening to music vs. the typing task). When typing, participants tended to position their head so that the ear–eye line was approximately 12° above the horizontal. Similar angular joint positions were recorded for the music listening and the typing blindfolded conditions, indicating that a typing task per se does not alter the self-selection of head, neck, and trunk position.

In contrast to the control experiment participants, participants in Experiment 3 responded to a changed visual target location by an approximately linear change in both head inclination and

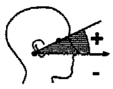
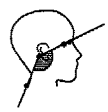
	Ear-eye 		Head 		Neck 		Trunk 	
	Music	Type	Music	Type	Music	Type	Music	Type
Mean	16.2	12.4	148.0	145.3	120.6	120.8	108.6	107.6
SD	6.5	8.9	9.5	6.9	6.9	8.4	6.3	5.1

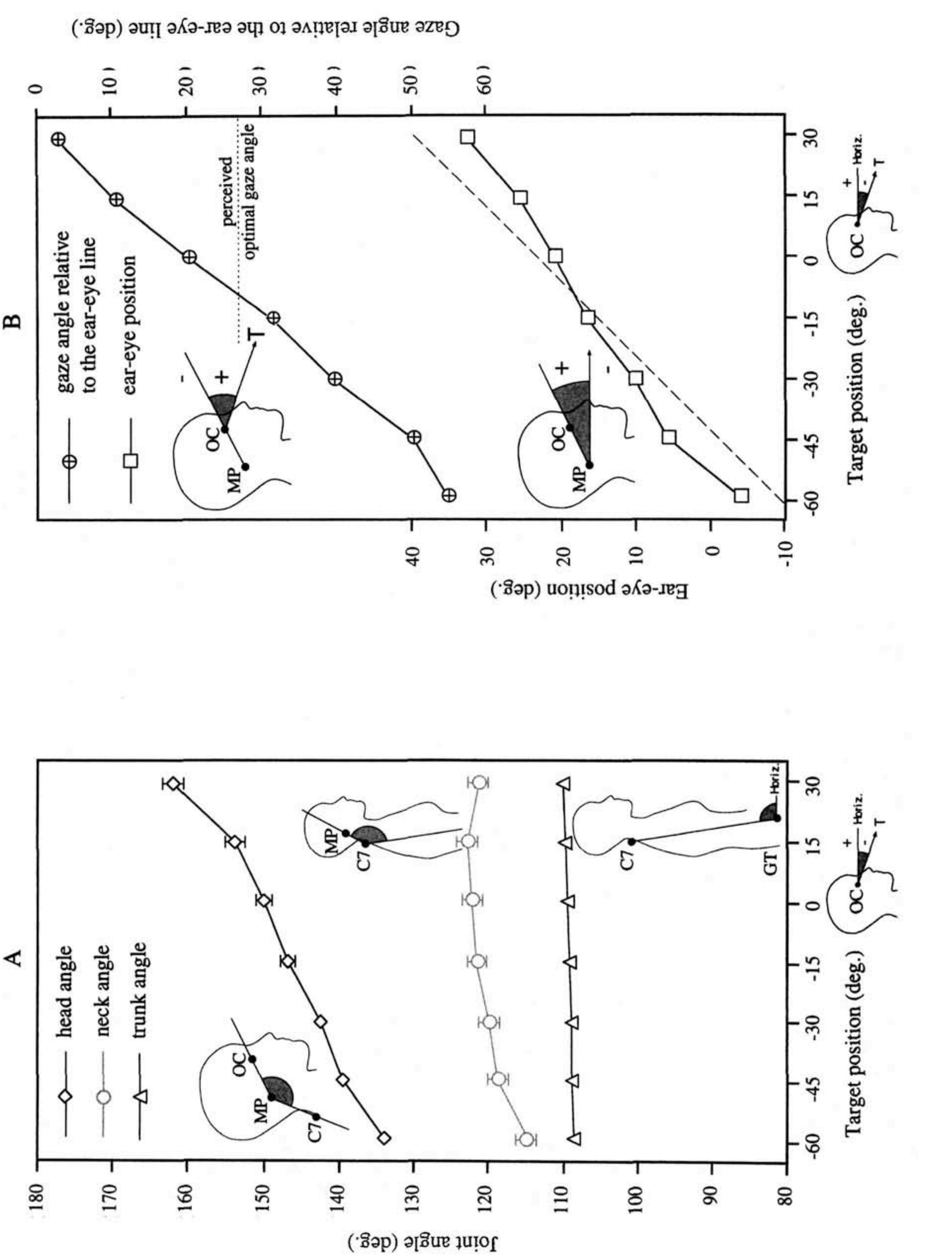
Figure 4. A comparison of average (n = 12) joint angular positions adopted in a music listening task versus a typing task.

gaze angle (see Figure 5). Fixation on a visual target that varied through a 90-degree vertical range was achieved by an average change in head orientation (ear–eye line) of 37° and a change in gaze angle relative to the head of 52° (the average ratio of head inclination to gaze angle change was equal to .71). Although all participants exhibited linear changes in both variables (all individual participant correlations were greater than .93), considerable individual differences existed in the ratio of changes in head orientation to changes in gaze angle relative to the head (from 0.45 to 1.12). It might be speculated that the individual differences in this ratio are, at least in part, a consequence of individual differences in the vertical gaze angle–heterophoria relationship.

Changes in head orientation were achieved predominantly through altering the posture of the atlanto-occipital joint (measured here as head angle) and, to a lesser degree, by changing cervical posture (neck angle; see Figure 5). The average change of 37° in head orientation across the target locations was produced by an average change in head angle of 28°, a 7° change in cervical spine, and a 2° change in trunk inclination. The significance of these findings is that fixation of high visual targets is achieved by compromising preferred visual gaze angle (contributing to visual discomfort due to extra-ocular muscle control fatigue) and adopting a posture of the head and neck involving cervical flexion and atlanto-occipital extension (a so-called *forward head posture*). The forward head posture has been identified as causing musculoskeletal disorders in the neck and shoulders (e.g., Burgess-Limerick, Plooy, Fraser, & Ankrum, in press; Caillet, 1991).

These results suggest that locating video monitors at the orthodox eye level position requires users to either compromise their preferred gaze angle (leading to visual discomfort) or to adopt a so-called *forward head posture* involving a combination of flexion at cervical joints and extension at the atlanto-occipital joints. It has previously been established (although not well quantified) that such forward head postures are associated with symptomatic complaints such as headaches (Watson, 1994). The results indicate that the relationship between the oculomotor system and the muscular–postural system must be taken into account either when designing workstations or when exploring why a user is suffering from ocular and musculoskeletal discomfort.

Figure 5 (opposite). The average (n = 12) adopted head, neck, and trunk angular positions (A) and adopted gaze angle and ear–eye position (B) for each of the seven target locations. The dashed line represents an isomorphic relationship in which the perceived optimal gaze angle is maintained regardless of target position, and the ear–eye line follows the target. MP = mastoid process; OC = outer canthus; GT = greater trochanter; Horiz. = horizontal; T = target.


A
head angle
neck angle
trunk angle
OC
MP
C7
GT
Horiz.
T
Joint angle (deg.)
Target position (deg.)
B
gaze angle relative
to the ear-eye line
ear-eye position
perceived
optimal gaze angle
Ear-eye position (deg.)
Gaze angle relative to the ear-eye line (deg.)

Experiment 4

Experiment 4 was designed to assess ratings of comfort and discomfort as a function of good and poor viewing angle–vergence combinations (we are grateful to two anonymous reviewers for suggesting this logical extension to the previous three experiments).

Method

Participants. Six of the participants from Experiments 1 and 3 took part in Experiment 4. The remaining participants were unavailable for a variety of reasons.

Procedure. Participants were asked to read text (four lines of 12 point black text subtending approximately 16 arc/min on a white background, 93% contrast at 500 lux placed 65 cm away) for 5 min and to judge how comfortable or uncomfortable the viewing position would be if maintained for 1 hr. The center of a 65-cm radius arc was aligned with the outer canthus of the eye to ensure that the visual target always remained 65 cm away from the eye. Head angles were recorded by the Optotrak optoelectronic movement recording system. The data (recorded at 100 Hz) were continually monitored to ensure that the correct head posture was maintained. Four conditions were studied: These conditions were selected on the basis of the data collected within Experiments 1 and 2. The four conditions were (a) a high visual target (+60°) viewed with a high vertical gaze angle (+20° above the ear–eye line) and an extended head (+40° above horizontal): This configuration would be predicted to lead to high visual discomfort and high musculoskeletal discomfort; (b) a low visual target (−20°) viewed with a low vertical gaze angle (+20° below the ear–eye line) and a flexed head (ear–eye line zero with respect to horizontal): This configuration would be predicted to lead to low visual discomfort and low musculoskeletal discomfort; (c) a middle visual target (+20°) viewed with a low vertical gaze angle (−20°) and an extended head (+40°): This configuration would be predicted to lead to low visual discomfort and high musculoskeletal discomfort; and (d) a middle visual target (+20°) viewed with a high vertical gaze angle (+20°) and a flexed head (ear–eye line zero with respect to horizontal): This configuration would be predicted to lead to high visual discomfort and low musculoskeletal discomfort.

In order to meet the requirements of our ethical committee, it was necessary to ask the participants to "judge the level of comfort or discomfort that you would experience if we replaced the text with a computer screen and you had to continue reading for an hour." The participants rated the comfort level for both visual (eyes) and musculoskeletal (head–neck) systems on a Likert scale from 1 (*comfortable*) to 10 (*uncomfortable*) for each condition. The scales for half of the conditions were printed from left to right, and the other half were printed from right to left. The visual scale appeared above the musculoskeletal scale in half of the questionnaires and vice versa in the other half of the questionnaires. The order of printing was pseudorandomized across participants and over conditions. The questionnaire was printed on one side of a page per condition, and symbols were used to label the questionnaires. None of the participants had any difficulty in making the requested judgments.

One-tailed Wilcoxon signed-ranks tests were used to determine whether the reported visual comfort varied as predicted between high and low gaze angle conditions and whether the reported musculoskeletal comfort altered as a function of head orientation (flexed or extended).

Results and Discussion

The results for the subjective ratings of visual and musculoskeletal comfort or discomfort are presented in Figure 6. All of the participants terminated the high gaze angle condition early (complaining of ocular aesthenopia), but all held the position for at least 2 min.

The participants found conditions in which the required gaze angle was high (20° above ear–eye line) to cause greater visual discomfort than those conditions in which the gaze angle was low (20° below ear–eye line). Wilcoxon signed-ranks tests indicated that these differences were statistically reliable, regardless of head orientation (one-tailed, $p < .02$ in both cases). Similarly, the reported musculoskeletal discomfort was greater in those conditions in which the head was extended when compared with those in which the head was flexed. In this case, however, Wilcoxon

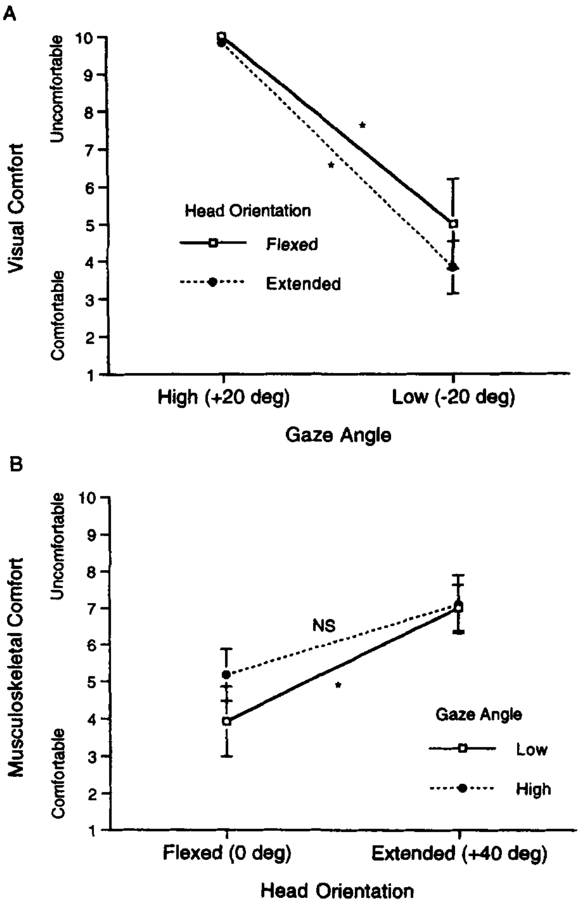


Figure 6. Mean (and standard error bars) for ratings of visual (A) and musculoskeletal (B) comfort on a scale of 1 to 10 reported by 6 participants as a function of head orientation and gaze angle. Differences that were not statistically reliable are indicated by NS. $*p < .02$.

signed-ranks tests indicated that the effect was significant between low gaze angle conditions ($p < .05$), but not between high gaze angle conditions. This interaction may be due to participants terminating the high gaze angle conditions earlier than 5 min because of visual discomfort and, consequently, being less able to accurately judge musculoskeletal comfort for those trials. The results of Experiment 4 indicate that the positions that would be predicted (on the basis of the relationship between vertical gaze direction and vergence effort) to cause discomfort do, indeed, cause fatigue and discomfort.

General Discussion

The National Institute for Occupational Safety and Health has reported that working with computer displays is a leading cause of work-related disorders. Visual fatigue (Jackson et al., 1997) and musculoskeletal discomfort (Bergvist et al., 1995) are commonly associated with computer workstations. The results reported here suggest that visual and musculoskeletal factors may interact in a complex fashion, depending on the vertical location of a computer display. We have proposed an extension of the original Heuer model and have shown that it can explain why preferred gaze is downward. We now consider the ability of the extended model to predict and explain extant research studies along with the more important issue of how heterophoria measures may be useful at an applied level.

The extended model explains why the maximum amount of accommodation varies according to vertical direction of gaze. Ripple (1952) measured the near point of accommodation while participants looked up 20°, down 20°, and down 40°, and Ripple discovered that the point of maximum accommodation decreased and increased with elevated and lowered gaze, respectively. This finding is predictable from the extended model: As the eyes increase convergence, accommodation increases through vergence accommodation. The increased vergence bias on downward gaze would give rise to an increase in maximum accommodation, with the opposite effect occurring when gaze was raised (exactly as Ripple found). Ripple also found that this effect was further increased by changing gaze in an oblique direction. This result may be explained by increased action of the oblique muscles when moving the eye along the plane of their insertion, with a corresponding increase in their secondary action (viz., increasing divergence through the inferior obliques or convergence through the superior obliques).

The extended model is also able to explain why changing head inclination (by altering body position) rather than ocular position has a similar effect on resting vergence and thus preferred gaze direction. Hill and Kroemer (1986; Kroemer & Hill, 1986) reported that participants prefer an increasingly lower angle of gaze when moved from an upright position to a supine one. Heuer and colleagues (Heuer et al., 1988; Heuer & Owens, 1989) demonstrated that dark vergence becomes more divergent if the body (and thus head) is tilted backward. The effect reported by Heuer and Owens was not as large as that found for changing eye inclination, but, in common with Kroemer and Hill, the effect was shown to increase as a function of head inclination. This result may be explained by the fact that the eyes adopt a constant primary position, regardless of head location. It has been suggested by Jampel and Shi (1992) that the constancy of the primary position is maintained through active neurological control to counteract the effects of gravity as head position is altered. As the head is tilted forward or backward, the vestibular system will compensate by causing a conjugate change in ocular position. Assuming that the mass of the extra-ocular muscles and orbital tissues lies posterior to the center of rotation of the eye, force due to gravity will normally act to elevate the eye. As the head is tilted backward, the gravitational effect becomes smaller, creating a lowering of the eyes. If a constant position is to be maintained by the eyes within the head, it will then be necessary for the extra-ocular muscles to exert a greater force to elevate the eyes. As previously argued, elevating the eye will create an increase in relative divergence. The increased divergence will be reflected in measures of vergence resting state and will result in the adoption of a lower gaze angle when fixating on proximal targets.

We have thus far considered the predictive and descriptive powers of the extended model. The crucial issue is, however, how workstations may be improved to reduce visual fatigue and musculoskeletal problems. Heuer et al. (1991) suggested that measurement of dark vergence might become an "important variable in workplace design" (p. 391). We propose that the measurement of heterophoria may have a more useful role than dark vergence in guiding the design of workstations. Heterophoria measures are relatively easy to take in a workplace setting, may be used to determine the optimal vertical gaze angle, are useful in investigating whether an existing computer position is problematic, and take the contribution of the accommodative system into account. The measures have the added advantage of corresponding with standard clinical techniques for assessing binocular vision.

The contention that heterophoria (or dark vergence) may guide workplace design raises two questions: (a) What significance do heterophoria measurements have and (b) if heterophoria measures have significance, how can they help reduce visual or musculoskeletal fatigue for an individual experiencing adverse symptoms with computer use? It is necessary to first consider the practical implications of changing heterophoria as a function of gaze angle. In the initial consideration of the vergence system, it was emphasized that a tonic element exists in the feed-forward pathway and that this component acts to minimize any demands placed on the phasic controller. It follows that if the eyes maintain a convergent position for a prolonged period of time, they will become relatively more esophoric and after prolonged divergence, become more exophoric. Maintenance of fixation in elevated gaze should therefore create an exophoric shift, and fixation of a low point should cause esophoria. Heuer et al. (1988) reported exactly such a shift in vergence resting state in response to raised and lowered gaze.

Given such pliability in the vergence system, one might ask whether it matters that a particular vertical location creates large vergence demands if the system is able to adapt to such demands through the tonic component. Perhaps the most important conclusion to be drawn from the present study is that individuals show large variations in the optimal line of gaze with regard to vergence bias. The large individual differences are predictable from the fact that the relative positions of extra-ocular muscle insertion differ to a large extent across individuals. In fact, Hering (1977) described anatomical variation and drew attention to individual differences in his original consideration of this issue. The individual differences suggest that for some observers, vertical gaze angle will have little effect on the vergence demands, but for others, the vertical gaze angle may dramatically alter the requisite vergence effort. A large increase in vergence effort will not necessarily produce visual problems: It is possible that any increased demands will be readily accommodated by the adaptable element within the vergence system. On the other hand, it has been established that symptomatic individuals have reduced tonic adaptability (Fisher, Cuiffreda, Levine, & Wolf-Kelly, 1987). A reduced ability to adapt to steady state viewing, together with large vergence demands may therefore cause some individuals to suffer from visual fatigue. Furthermore, the demands may be increased during the course of a day if a user constantly changes fixation (it is known that the tonic element is susceptible to fatigue; Schor & Tsuetaki, 1987). It is also necessary to realize that the degree of effort that constitutes too large a vergence demand varies from individual to individual (North & Henson, 1981) and between age groups (Winn, Gilmartin, Sculfor, & Bamford, 1994). Importantly, it has been shown that individuals with binocular vision anomalies lack the ability to adapt to induced changes in vergence bias (Henson & Dharamshi, 1982), and this has been hypothesized as being one of the causes of binocular vision problems (Schor, 1979). In line with these findings, it has been found that abnormalities of the accommodation and vergence systems are associated with visual problems occurring during computer use (Collins, Brown, & Bowman 1991; Yeow & Taylor, 1991).

The results of the current study suggest that the response to increased vergence effort may be an alteration of body posture. The effect of adopting a posture to reduce visual stress may be to successfully alleviate the visual problems without producing any adverse consequences. An alternative scenario is that the change in posture will occur at the expense of creating musculoskeletal difficulties or, in the worst case, may fail to alleviate visual fatigue and introduce additional postural discomfort. Another possibility is that individuals with existing musculoskeletal problems may be forced to compromise optimal gaze angle, producing symptoms of visual discomfort. The data reported within this article demonstrate the large degree of individual variability that may arise in both the ocular and postural responses to visual stimuli. The variation suggests that it is important to evaluate a workstation with regard to the individual, rather than relying on guidelines that rely on mean responses. One limitation in the present study is the limited time over which participants observed the visual targets before judging the potential visual and musculoskeletal discomfort (Experiment 4). The limited time was necessary within the experimental constraints (predicting discomfort and then asking participants to endure an uncomfortable situation was judged to be undesirable), but future research should be directed toward documenting the relationship between visual and musculoskeletal discomfort for existing vertical monitor locations.

The preceding deliberation suggests that vergence demand is one factor that should be considered when dealing with a computer user who is experiencing visual and musculoskeletal problems. The close relationship we have reported between heterophoria measures and preferred gaze angle does, however, raise the question as to whether it is actually necessary to measure heterophoria. We suggest that assessing preferred gaze under closed-loop conditions (e.g., following the tip of a pen with both eyes open) is a useful entry point in an initial assessment. We propose, however, that heterophoria measures have a useful role to play within the process of understanding visual and musculoskeletal problems occurring through computer usage. Assessing the change in heterophoria as a function of vertical gaze angle will provide information on the extent to which vertical screen position needs to be modified for a given user. The measures may also be easily implemented on a screen *in situ,* with the data from such measures then being used as part of an overall ophthalmic examination of oculomotor function (see Jackson et al., 1997; Jaschinski-Kruza, 1994, for a detailed consideration of other important ophthalmic measures). Heterophoria may be seen as one important component within an overall consideration of ocular function and workstation layout. As we have highlighted within this article, it is important to ensure that measures of preferred gaze angle or heterophoria are taken at a sagittal distance that corresponds to the normal distance at which the computer is located (although, this distance may in turn be one factor requiring consideration; cf. Jaschinski-Kruza, 1988).

In summary, heterophoria is one factor among many that needs to be considered when designing the optimal workstation for an individual. Visual discomfort may deter someone from adopting the optimum postural position for the reduction of musculoskeletal problems (e.g., lower back pain). On the other hand, musculoskeletal factors may force a user to adopt a gaze angle that will eventually result in eye strain. Our work suggests an easily developed test that indicates the vergence demand for any given vertical target location. It can be seen that the design of an adequate workstation or the assessment of an individual experiencing problems with an existing workstation must follow a holistic approach and take a number of factors, including heterophoria, into account.

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