Chapter

6

Optometric and Perceptual Issues with Head-mounted Displays

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6.1 Introduction

Most virtual reality (VR) systems employ head-mounted displays (HMDs). Many such systems are also designed to provide stereo depth and use head tracking to enable the virtual world to change in response to the user's movements.

The current state of HMDs and other VR technology falls short of accurately simulating many aspects of the visual world. Differences between the real world, for which the human visual system had a few million years to adapt, and the novel HMD may result in degradation of image quality and/or cause discomfort and visual changes. Concerns about possible harmful effects are reminiscent of similar worries that accompany the introduction of almost any new wide-use technology. Such concerns were raised with the introduction of television, computers and visual display terminals (VDTs), microwave ovens, and, most recently, cellular phones.

This chapter describes a few possible mismatches between the visual system's response to the real world and its response to the virtual world of the HMD. Some of these mismatches result in unwanted perceptual effects including stress to the visual system, discomfort, and, presumably, long-term changes to the visual system. These unwanted effects may or may not impact the acceptance of the technology. Many of the mismatches that result in these negative consequences can be reduced or eliminated by proper design and better technologies. Others appear to be inherent limitations of HMDs and must be carefully considered in the design of applications and software.

6.1.1 Classification of HMDs

Monocular HMD refers to a system with one optical channel presenting an image to one eye. Historically, HMDs evolved first as helmet-mounted displays in military applications, and most of these systems were monocular. More recently, the Private Eye (Reflection Technology, Waltham, MA) was developed as a monocular HMD for the civilian consumer market (Peli, 1990).

If the system is presenting images to both eyes it is called *binocular*. Binocular systems are further classified as being *stereo* or *bi-ocular*. A stereo system presents two slightly different images to each eye to create the perception of depth. The same system can also present the same image to both eyes, in which case it is said to be bi-ocular. The i-glasses system (Virtual I-O, Seattle, WA) (Peli, 1998), like many others, can operate in both modes, while the Glasstron (Sony, Japan) and the Visette 2000 (Virtuality Entertainment, UK) are designed to be bi-ocular only.

Monocular and binocular systems can operate either as *see-through* or as *opaque* systems. A see-through system enables the user to see the image in the device superimposed on a view of the outside world using a beam splitter or half-silvered mirror. The helmet-mounted military systems just mentioned were used to present graphic or alphanumeric information superimposed onto the real world view. These systems are therefore classified as see-through.

See-through systems are considered for use in various applications, such as maintenance or wiring, where graphic display of a diagram can help the user match the real system through the display. I have proposed using a see-through device to provide an augmental view of the real world for the visually impaired by providing enhanced feature outlines superimposed on the see-through view (Peli, 1997). See-through devices can be made opaque using a mechanical visor (i-glasses) or electronic adjustable LCD shutters (Glasstron). Imaging systems designed for full video images are generally opaque (although some systems are designed as see-through). When the video is on, its contrast masks all but very bright real world scenes; when the video display is muted, the outside view becomes clear. The i-glasses and the Glasstron systems (Yoshimatsu, 1995) work this way.

HMD systems may be further classified on the basis of the type of image used: *synthetic* (computer-generated) or *photographic* imagery. Synthetic imagery is typically used in computer games and computer models (e.g., architectural models or molecular models). Photographic images are used in telepresence, robotics, endoscopy, and HMD systems for the visually impaired (Massof and Rickman, 1992; Peli, 1995).

HMD systems may be classified on the basis of numerous dimensions. The classification chosen here was selected to emphasize distinctions made in the chapter that may be relevant to design considerations. Other classifications may be of value when other aspects of the technology are considered. [For example, see Wells and Haas (1995) for field of view classification.]

6.2 Optometric Issues

HMDs create an unfamiliar visual environment in which many of the natural relations between various stimuli are changed. These changes may in turn cause changes in the visual system, leading to symptoms of discomfort, and possibly even cause some long-term harm. Although very little direct evidence has been presented for discomfort and none for harm, there is indirect evidence that would support such concerns. This section identifies the various optical and optometric issues that have been suggested as possible causes for changes in the visual system due to HMD use. The nature and magnitude of the various effects are evaluated, and ways to address various issues are discussed.

6.2.1 Instrument myopia

Instrument myopia refers to improper accommodation (focusing) of the eyes of a user of an optical instrument (Richards, 1976; Wesner and Miller, 1986). It is also called *proximal accommodation* (Ong and Cuiffreda, 1995), reflecting the assumption that the user accommodates to a short distance due to his or her knowledge that the image actually resides inside the small instrument despite the fact that it is optically imaged at a greater distance (Hennessy, 1975; Leibowitz and Owens, 1975). The eye also focuses at a near distance in the absence of a good stimulus for accommodation (e.g., complete darkness or an empty field such as the sky on a clear day). The resting position of the accommodation system seems to be at a near distance. Individual dark focus or positions of rest can be more than 1.5 D (see Table 6.1) and vary from individual to individual.

The phenomenon of instrument myopia has two possible consequences for HMD use. First, accommodative spasm has been suspected as a precursor to the development of myopia (nearsightedness). In fact, there is evidence that instrument myopia, as well as other near-point work, results in transient myopia. But this myopia is indeed transient and disappears within minutes of task completion (Rosenfield and

TABLE 6.1 The Dark Focus of Accommodation Reported for Various Populations of Young Adults

Study	Population (number of subjects)	Dark focus (mean ± SD)
Leibowitz and Owens (1978)	Students (220)	1.50 ± 0.77
Simonelli (1980)	U.S. Air Force recruits (154)	1.19 ± 1.50
Norman and Ehrlich (1986)	18-year-olds (12)	1.10 (NA)
Morse et al. (1994)	Army aviators (16)	0.48 (NA)

Ciuffreda, 1994). It was suggested that long-term HMD use, especially by children, may cause or accelerate the development of myopia. For this and other reasons, most manufacturers warn against the use of their devices by children. For example, Nintendo recommends that its Virtual Boy not be used by children younger than 7 and Sony restricts the use of its Glasstron to children 15 y of age or older. [Earlier designs by Sony used a nominal focal distance of 1.2 m. But the adjustable focal distance set by users was found to be close to their position of rest, and some had a myopic change following 2 h of use (NikkeiElectronics, 1993).]

Jones (1993) investigated the effect of instrument myopia in virtual displays and found that overaccommodation occurs only when the exit pupil is small. With their natural pupils, observers noticed the blur resulting from the improper accommodation (closed-loop condition) and its correction. Jones concluded that the problem of instrument myopia in such displays will manifest itself only in devices with a very small exit pupil or wide depth of focus. Rosenfield et al. (1993) demonstrated that proximal accommodation can be sustained over an extended time. However, it appears that unlike the natural accommodative response to object distance, where sustained accommodation causes adaptation, in the open-loop condition needed for proximal accommodation, there is no adaptation to the sustained effort to accommodate. This finding also supports the idea that instruments or displays with wide depth of focus, which may cause proximal accommodation, are less likely to cause sustained myopia via adaptation, whereas instruments with narrow depth of focus will not even cause proximal accommodation because of the blur feedback.

The second effect of instrument myopia relates to resolution and image acuity. The resolution ability (visual acuity) of the user may be optimal at the resting focus (Kotulak and Morse, 1994). It was therefore suggested that focal distance of the HMD should be set to about 1 m to improve resolution. This may not be a critical consideration for the current generation of HMDs because their resolution is much lower than the acuity of normal observers. Current high-resolution systems have 640 pixels over a field of about 22°, corresponding to about 2 minarc per pixel, while human resolution is at the level of 2 pixels per minarc. Higher-resolution systems, in terms of the number of horizontal pixels, typically spread the pixels over correspondingly larger fields of view and thus the display resolution is the same. For example, Sony uses 1068 pixels over a field of view of 44° (Matsui and Kawamura, 1995) or 800 pixels over a 100° field of view (1000HRvp VIM® product sheet, Kaiser Electro-Optics). With future improvements in resolution the effect of instrument myopia on user's acuity and display quality may require revisiting.

The visibility of the pixel boundary in current low-resolution displays may lock the user's accommodation to the distance of the display screen. This phenomenon is related to the Mandelbaum effect (Mandelbaum, 1960), where looking through a mesh screen at a far target may restrict the range of fusible disparity. This phenomenon may impact low-resolution displays. A recent study by Gleason and Kenyon (1997), however, demonstrated that the blurring of a distance image seen through a mesh screen is not caused by a shift in accommodation to the screen but is of sensory origin. Those findings suggest that a visible pixel boundary may cause the impression that the image is blurred even when accommodation is accurate.

Fowlkes et al. (1993) pointed out that motion or simulator sickness, like lens accomodation, is due to the activation of the parasympathetic division of the nervous system. They suggested that the two phenomena might, therefore, be connected. In their study they found a relative shift inward of the dark focus for subjects who felt sick following motion simulation experiments; those who were not sick showed a smaller shift. Although the effect was consistent with this hypothesis in only two of the three experiments, Fowlkes et al. concluded that the myopic shift in HMD and other simulators may be a result of the activation of the parasympathetic system associated with motion sickness.

Possible solutions. How can the accommodation spasm that may be associated with instrument use be reduced? Increasing the depth of focus may merely reduce the visual effect of the spasm. In fact, some of the studies just cited suggest that increasing the depth of focus may induce spasm. An adjustable-focus system may induce even more spasm than a fixed-focus system, as demonstrated in a study of Apache helicopter pilots using a helmet-mounted display (Kotulak, 1995; Kotulak and Morse, 1995). However, pilot focus adjustment performance did improve with training and with the use of a visible distant target. Therefore, during the design stage, it is important to consider the user population, the level of familiarity and training users will have with the device, and whether an individual user or multiple users are using each device. Adjustable-focus systems may be more useful for trained users or if the device is adjusted for an individual user once, at dispensing, and then fixed. An adjustable system for general use should have a limited range of adjustment of about 1.0–1.5 D to permit fine adjustment, but should prevent the user from setting the display for a large accommodation demand. Using systems with a narrow depth of focus (wide exit pupils), which provide visual feedback of the blur due to improper accommodation, may be the best approach to controlling instrument myopia in HMDs.

6.2.2 Convergence and accommodation

To understand the issues associated with alignment of focus and convergence of the visual system, it is necessary to become familiar with the functioning of the binocular system, which coordinates the operation of both eyes as a pair in the three-dimensional real world. A number of concepts used in clinical optometry are needed to understand these issues; jargon will be kept to a minimum.

In the real world, an observer moves his or her gaze among targets of interest at different distances. For each target, the lenses of the eyes must be focused to obtain a clear image and to converge both eyes on the target, to facilitate the fusion of the two eyes' images into a single precept. The distance of the target determines the focusing or accommodation *demand* in diopters. This demand, in diopters, is the reciprocal of the distance of the target from the eyes in meters. Thus a target at 2 m creates a 0.5-D accommodative demand. Convergence demand is measured in degrees, or in prism diopters (Δ), and is determined by both the distance to the target and the distance between the eyes [interpupillary distance, or IPD (Fig. 6.1)]. A prism diopter (1 Δ) is the angle subtended by 1 cm at a distance of 1 m (1 Δ = 10 milliradians)

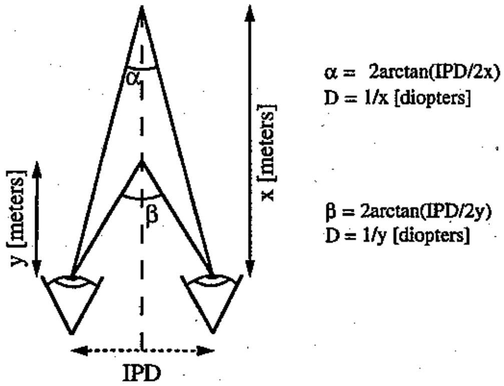


Figure 6.1 The accommodation (*D*) and convergence demands (α and β) of real-world targets depend on the target distance (*x* or *y*) and the observer's IPD. The demands are calculated as illustrated.

(Fig. 6.2). It is a convenient unit since, as is shown in Fig. 6.1, the convergence demand (in prism diopters) of a target at any distance is given by the product of the IPD in centimeters and the accommodative demand.

$$\text{Convergence demand } [\Delta] \cong \text{Accommodation demand } [\text{D}] \times \text{IPD } [\text{cm}] \qquad (6.1)$$

For real-world targets a line of demand can be plotted that represents the accommodation and convergence needs for all observers with a given IPD (three examples are shown in Fig. 6.3). For different IPDs, the demand lines converge at far distances (only one line is shown for distances farther than 25 cm). Thus if the accommodative demand is set at less than 1 D (farther than 1 m), we can consider one demand line for all users. For an observer to see a target clearly and singly with both eyes open, both demands should be met. Some tolerance, however, is permitted. In the accommodation system, depth of focus permits some misregistration of accommodation response and demand. In the convergence system, a slight (typically a few minutes of arc) misalignment of the eyes from perfect convergence, called fixation disparity, does not disrupt single vision. If for some reason the response difference from the demand is larger than these tolerances, then either a blurred image or double vision will result.

To simultaneously satisfy the convergence and accommodation demands of real-world targets, the visual system has evolved a coupled control system for both mechanisms. (Actually, pupillary constriction is also connected with convergence and accommodation, in what is called the *visual triad,* but has only a minimal effect in our application.) Thus, when the eyes accommodate they will converge even without convergence stimuli. (For example, the eyes converge even when one

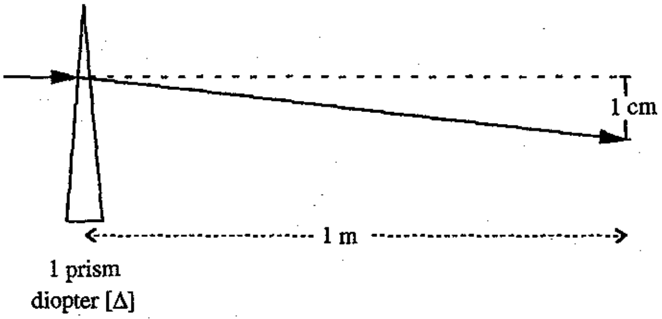


Figure 6.2 A prism diopter [Δ] is a unit of prism power that will cause a ray of light to deviate by 1 cm at a distance of 1 m. Thus, 1 Δ = 10 milliradians.

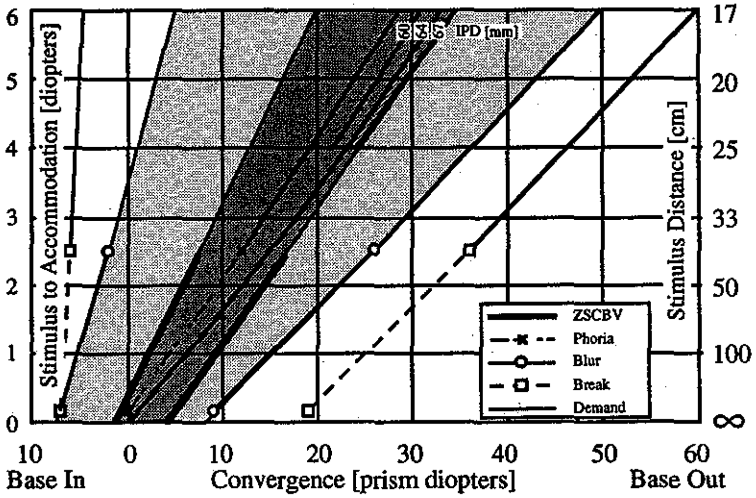


Figure 6.3 Graphic representation of accommodation and convergence demands and the zones of single clear binocular vision (ZSCBV) for an average person. A demand line is associated with the person's IPD (three different lines are illustrated), but the various lines converge at greater distances. The ZSCBV and the comfort zone, representing the middle third of the ZSCBV, are illustrated by light and dark shading, respectively. Operating outside of the comfort zone may cause eyestrain and/or headaches. The range outside the ZSCBV is the zone where single vision is maintained by changes in accommodation resulting in blurred vision. With further strain, binocular vision is disrupted, resulting in double vision (outside the break lines). In this graph, convergence is referred to the center of rotation of the eye, 2.7 cm behind the spectacles.

eye is covered. This is an open-loop condition for the convergence system because no visual stimulus for convergence exists.) When both eyes are open, a small correction in the convergence loop may be needed (in addition to accommodative convergence) for perfect alignment. The difference between this open-loop convergence angle and the convergence demand is called *heterophoria* (or *phoria* for short). Each observer has a different heterophoria that is considered the operating point of the individual's binocular system. If the eyes are underconverged for the target's demand (i.e., the eye behind the cover points outward compared with the direction of the fixation target), the heterophoria is called *exophoria;* when the eyes overconverge, the heterophoria is called *esophoria*. The average phoria for the population is 1 ± 2 Δ exophoria for a distant accommodation target, and 3 ± 5 Δ exophoria for a target at 40 cm (Goss, 1986).

The accommodation and convergence demands for an observer can be changed by using lenses or prisms, respectively. Placing positive (convex) lenses in front of the eyes will reduce the accommodation demand, while negative lenses will increase it, moving the demand line (in Fig. 6.3) down and up, respectively. In both cases the convergence demand is unchanged. Similarly, the convergence demand can be changed by using prisms. Base-out (BO) prisms (prism base toward the ear) increase the convergence demand and base-in (BI) prisms (base toward the nose) reduce it, moving the demand line right and left, respectively. When tested under these unnatural conditions, the visual system demonstrates limited flexibility that permits it to operate under such varying demands. By using such prisms and lenses, one can map the range over which the demand can be changed while the observer is able to maintain single clear binocular vision (Fig. 6.3). Outside that zone of single clear binocular vision (ZSCBV), the observer will have either blurred or double vision. Although inside the zone clear vision is maintained during testing, no one would wish to wear such lenses for an extended period of time. If observers must operate for any length of time close to the edge of the ZSCBV, they are likely to feel eyestrain, develop headaches, and even lose clear or single vision. The narrow middle third of the zone is referred to as the zone of comfortable single clear binocular vision by Percival's criterion (Borish, 1970), indicating that the outside two-thirds are uncomfortable.

Misalignment of convergence and accommodation. This discussion applies to both stereo and nonstereo binocular HMDs. In HMDs, a virtual image is created at some distance from the user's eyes, and this distance sets the accommodative demand for the user. If the IPD of the user is the same as the distance between the optical centers of the channels, then the physical convergence of the two optical channels sets the convergence demand. Since the visual system would be most comfortable with the natural relationship that exists for real-world targets, such correspondence is a basic design consideration. Achieving it for all observers can be difficult, however. If the accommodative demand does not match the convergence demand, the situation is equivalent to placing a prism in front of the eye(s) in the real-world situation.

Convergence of the optical systems can be achieved by creating a concentric system for each channel (i.e., the lens is concentric with the display) and positioning each channel at an angle to the other [Fig. 6.4(*b*)]. Such a system is used in both Nintendo's Virtual Boy and Sony's Visortron (NikkeiElectronics, 1993). A converging system can also be generated by decentering the display relative to the center of the lens [Fig. 6.4(*c*)]. Such a strategy was implemented by Sony in a system designed to provide adjustment of the convergence linked to changes in the accommodative demand (see Sec. 6.4.3).

Before addressing the possible approaches used, and the difficulties encountered in aligning such systems, let's consider what happens if the convergence demand is not matched to the accommodative demand (e.g., if a BO or BI prism is placed in front of one eye).

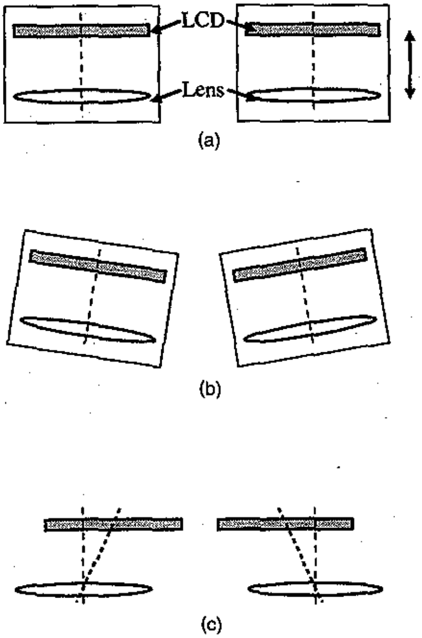


Figure 6.4 Adjusting the accommodation demand and the convergence demand in an HMD. (*a*) The accommodation demand in a concentric system is determined by the distance *d* between the LCD screen and the lens used to view it. (*b*) Convergence demand can be varied by converging two concentric systems relative to each other. (*c*) The convergence demand can also be varied by moving the two screens closer or farther apart while keeping the lenses in the same position. Both approaches have been implemented in commercial units.

When an observer first looks through such a system, if the misalignment is large enough, vision may be blurred or double. For smaller misalignment, vision may remain clear but continued use may cause some eyestrain. If the observer continues to use the system, then after a few minutes his or her visual system will start to adapt to the new demand under a process called *prism adaptation* (Carter, 1963; Howarth, 1996). The visual system appears to change its baseline (tonic) convergence operating point (heterophoria) to match the new demand. Adaptation is not always complete, and there are differences in adaptation to BI and BO prism demands (Goss, 1986; Howarth, 1996). If adaptation is incomplete, then continued use may result in further stress that may be aggravated by stereo stimuli (see later in this chapter). If adaptation is fairly complete, one must consider what happens after use of the HMD and return to the real world and its demand line (Piantanida, 1993). A person with a healthy, strong binocular system is likely to readapt in a few minutes and return to baseline. However, some users with less functional systems may have various symptoms, such as blur or double vision and eyestrain (Mon-Williams et al., 1993; Piantanida, 1993). Double vision, if it persists more than a fraction of a second, can be very unpleasant and scary. It should be emphasized that there are no reports of double vision persisting after use of HMDs, although reports of blur, eyestrain, and headaches are abundant (Howarth and Costello, 1996b; Mon-Williams et al., 1993). Howarth (1996) tested the effect of mismatch between accommodation and convergence demands by placing prisms in front of subjects playing solitaire on a desk-top CRT. He found prism adaptation and reports of increased symptoms after 15 min of play. However, the reported level of ocular symptoms was significant only for prisms of more than 4 Δ (BI or BO).

Effect of user IPD on the mismatch between accommodation and convergence demand. Various manufacturers have taken different approaches to adjusting the convergence and accommodative demands in HMDs. One difficulty in finding a simple solution rests with the fact that the demand line depends on the observer's IPD. If the image distance is large (>1 m), the demand difference is fairly small (Peli, 1995) (Fig. 6.3). The simplest approach, therefore, is to set the focus at a fixed level and assume a nominal user's IPD (i.e., 65 mm). An observer with an IPD smaller than the interocular distance (IOD) of the HMD will look through the inner parts of both lenses used to image the displays. This situation is functionally equivalent to having prisms in front of the eyes (Fig. 6.5) because the eyes' optics are not concentric with the system's optics. The prismatic effect of the lenses has been identified in the literature as potentially a major problem in HMD use (Melzer, 1994; Piantanida, 1993; Regan and Price, 1996; Wann et al., 1995). These authors hypothesized that observers whose IPDs differed from the system's interocular distance (IOD) would suffer from eyestrain and headaches. Regan and Price's (1996) study failed to find such an effect for the 53 subjects thus tested. However, when only those subjects whose IPD was smaller than the IOD were evaluated, there was some correlation of the magnitude of difference between the subjects' IPD and the system's IOD and symptom report. Despite the unclear result, Regan and Price concluded that the IPD may play a role in visual discomfort.

The reason for the concern raised in the literature is the fact that in spectacle correction the prismatic effect is fairly significant. Determined approximately by Prentice's rule (Atchinson et al., 1980; Fannin and Grozvenor, 1987), the prismatic effect (Fig. 6.6) is:

$$\text{prismatic effect } [\Delta] = \text{Lens power } [D] \times \text{decentration } [\text{cm}] \qquad (6.2)$$

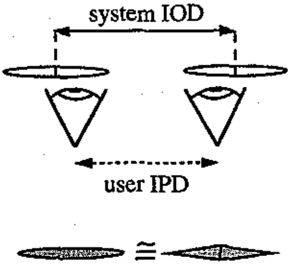
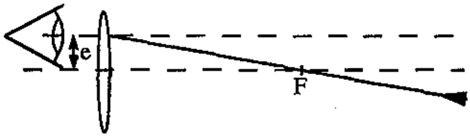


Figure 6.5 The presumed prismatic effect when user IPD is smaller than the system's IOD is in the base-out direction due to the effect of the positive power lens used. The prismatic effect is that of a negative-power lens, as illustrated in Fig. 6.7.



Prentice's Rule :

$$\text{prismatic effect}[\Delta] = \frac{e[\text{cm}]}{F[\text{meters}]}$$

Figure 6.6 Prentice's rule: the prismatic effect of a lens decentered relative to the eye's pupil is simply a result of the ray-bending action of the lens.

Since the lenses used in most HMD systems are high power (20 to 30 D), it has been suggested that the prismatic effect due to decentration would be large (Wann et al., 1995). In fact, it is very small and thus unlikely to present a problem if the optical image distance is sufficiently large. Only the power of the lens in excess of what is needed to bring the optical image of the screen (here called the virtual screen) to infinity participates in the decentration-induced prismatic effect (Fig. 6.7). For a virtual screen distance of 2 m, and a full 10-mm difference between the user's IPD and the system's IOD, the prismatic effect will be only 0.5 Δ (Peli, 1995). Note that a prism imbalance of 0.5 Δ is the permitted tolerance for spectacles under the standard for ophthalmic prescription (ANSI Z80.1-1972). Therefore, if the virtual screen position is kept at a distance of 2 m or more, the prismatic effect due to mismatch of the user's IPD and system's IOD is acceptable. It should also be noted that the deviation induced by the prismatic effect will not be caused by a positive lens, as illustrated in Fig. 6.5 and discussed by Piantanida (1993), but rather it will be the effect of a negative lens, as illustrated in Fig. 6.7. This can be verified by ray tracing.

Decoupling of convergence and accommodation in stereo systems. While an optimal design or a satisfactory compromise for matching the accommodation and convergence demand to the situation in the real world may be achieved in the HMD for bi-ocular systems, the situation is more complicated for stereo systems. The introduction of depth using disparity between the images results in a need to decouple the normal relationships between convergence and accommodation. In the real world, shifting fixation from an object at one distance from the observer to another object at a different distance requires a change in both convergence and accommodation, as described earlier. In a binocular stereo display (HMD or otherwise) this is not the case. Since the images are always displayed on a screen of fixed distance (virtual or real), accommodation should be maintained at the same level for all targets. When disparity is introduced to stimulate the perception of depth by moving a portion of the image on each of the two screens lat-

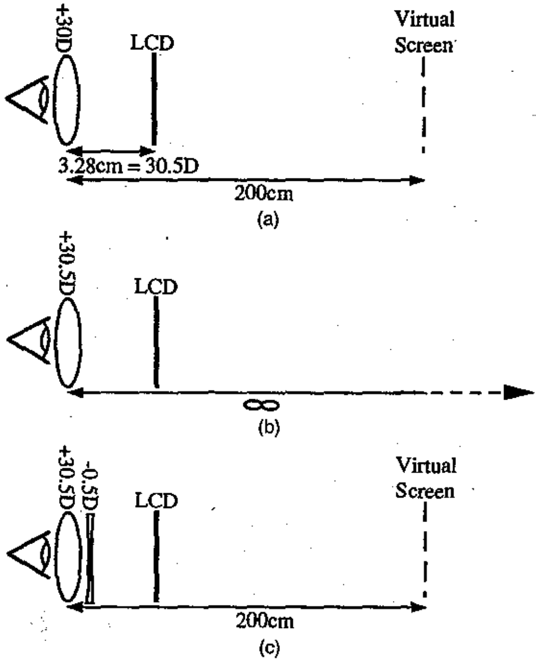


Figure 6.7 A schematic illustration of the prismatic effect in HMDs. (*a*) In this system the LCD screen is slightly inside the focal point of the lens, resulting in a virtual image at a distance of 2 m. (*b*) If the lens power is increased by 0.5 diopter, it will move the virtual image to infinity. With the image at infinity, decentration of the pupil relative to the lens does not cause any prismatic effect. (*c*) The image can be returned to the original position by adding a negative lens of −0.5 diopter. This lens is the only one contributing to the prismatic effect with pupillary decentration.

erally in opposite directions, convergence should change toward the simulated distance of the target, either in front of or behind the screen (Fig. 6.8). This has the same effect as introducing prisms in front of the eye (Fig. 6.9), which gives a constant convergence change, except that the situation in the stereo display case is dynamic. Either the depth in the image may be changing with time or the user may fixate static objects at different apparent depths. In either case, the dynamic nature of the situation prevents the static prism adaptation discussed above.

The analysis above has considered the *stimulus* or demand for accommodation and vergence. However, as discussed earlier, the oculomotor *response* can be different from the demand. In looking at the response to stereo images, Hiruma and Fukuda (1993) as well as Okuyama et al. (1996) demonstrated that in response to a step change in stereo image

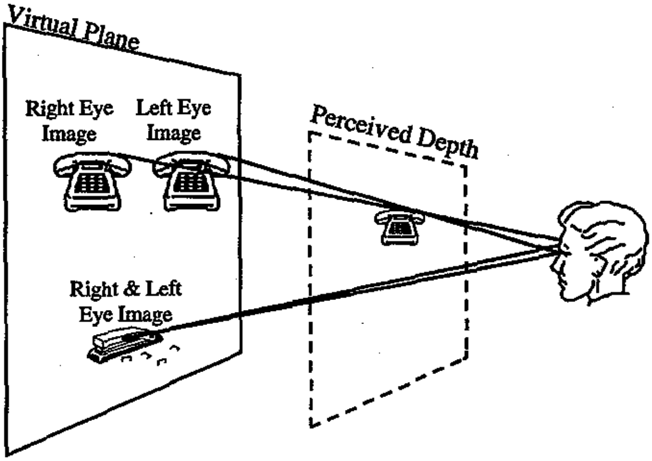


Figure 6.8 Decoupling of accommodation and convergence demands in stereo displays. Images presented without disparity (the stapler) require that both accommodation and convergence be for the distance of the virtual screen and be coupled as in viewing real objects. The images presented with disparity (the telephone) remain at the virtual screen with regard to accommodation demand but require a different convergence.

distance, the accommodative response is triggered together with the convergence response. However, unlike the real stimulus situation where the two responses remain stable, these researchers found accommodative overshoots and an unstable steady state during use of the stereo display. Hiruma and Fukuda found that accommodation follows

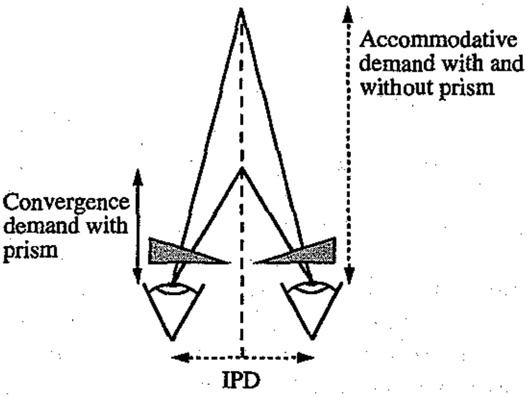


Figure 6.9 Illustration of the decoupling of convergence and accommodation demands using prisms. The effect is identical to that caused by the stereo display in Fig. 6.8.

the convergence induced by the disparity only up to about 0.3 D; they attributed this to the depth of focus of the eye. They did not directly measure their subjects' depth of focus, nor did they try to increase the depth of focus to test this hypothesis. Morita and Hiruma (1996) showed that the convergence of both eyes is about halfway between the screen and the stereo image distance when there is a large disparity. Thus, it appears that during a dynamic change in an image's displayed distance, the convergence and accommodation changes are linked, as in natural viewing. Only if fixation of the target is extended to a few seconds do some changes (most likely in accommodation) take place to maintain fusion. The cost of changes is optical blur.

Since the dynamic decoupling of accommodative and convergence demand does not occur for real-world objects, we have few data on its possible effects. However, decoupling does occur during viewing of stereo movies, and although this genre never really caught on, I know of no report on the ill effects of stereo movies except for motion sickness, which may be associated with exaggerated motion rather than the stereo display itself. Motion sickness effects are also common with various nonstereo wide-field displays such as the OmniMax theater at the Boston Museum of Science or the 360° movies shown at Disney World.

Visual training can be directly related to the effects of the decoupling of accommodation and convergence in HMDs (Scheiman and Wick, 1994). Visual training is a treatment for various binocular abnormalities where a variety of eye exercises are prescribed. It is usually applied to persons having symptoms due to reduced binocular function. A common thread through all visual training excercises is the gradual but challenging application of decoupling of accommodation and convergence through the use of polarized or anagliph (red/green) targets, lenses, prisms, or apertures (Fig. 6.10). During the initial stages of these exercises, it is common for patients to suffer from an increase in symptoms such as headaches and eyestrain. With continued training, patients are able to increase their fusional ranges and generally get relief from the initial training-induced symptoms as well as from the daily symptoms that led to the diagnosis.

The effect of these exercises on persons without binocular abnormalities has also been examined. Daum (1982, 1983) found a statistically significant increase in negative (BI) fusional vergence range for normal subjects following conventional therapy, while Major et al. (1985) reported an even larger increase with computerized training. Goodson and Rahe (1981) found no change with training, but they trained at the far point, where the negative fusional range is limited. Most closely related to the issue of HMDs is the study by Griffin et al. (1982), who found no changes in negative fusional ranges for far point using stereoscopic movies.

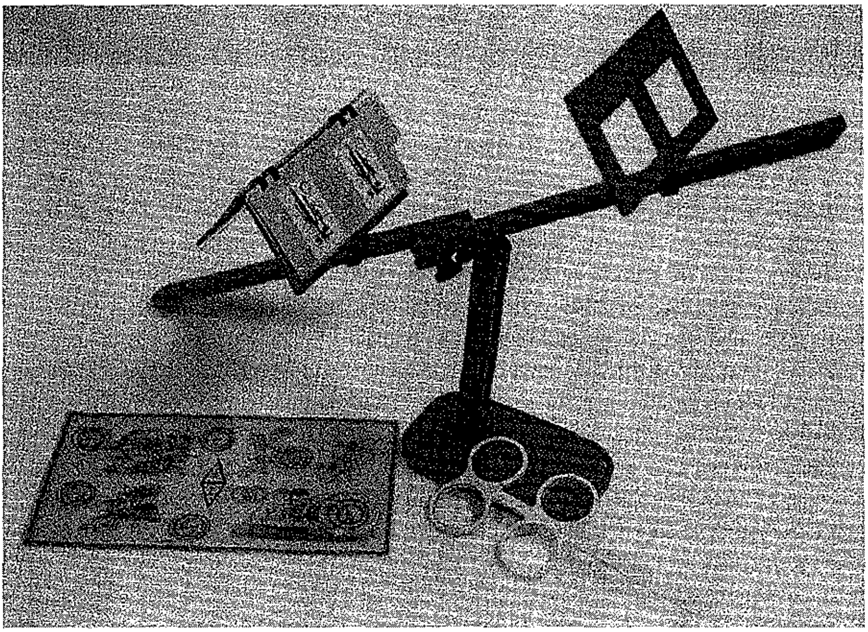


Figure 6.10 Devices used for visual training implementing decoupling of accommodation and convergence demands. The standing instrument with the two apertures limits the view of each eye to one of the images. Sliding the aperture closer and farther from the observer changes the divergence demand (a single aperture is used to impose convergence demand). The four lenses include a pair of base-in prisms and a pair of base-out prisms that can be exchanged rapidly while looking at any image or at the natural environment, thereby demanding a change in convergence without a change in accommodation. The multiimage panel is separating eye's view using red and green filters. The absolute disparity can be modified by sliding one panel across the other. Within each setting the different objects represent differing disparities.

One can anticipate that use of stereo HMDs, which strain the fusional mechanisms through decoupling of convergence and accommodation, may initially lead to some symptoms. This should be followed by adaptation, which may include an increase in fusional range and more stable binocular function. Visual training, however, is applied in a gradual manner under tight supervision and with individually tuned progress. The probability of achieving similar results through HMD use of game software not specifically designed for that purpose is low. We have no information on the effects of large stereo depth changes used to impress users of various entertainment systems.

Mon-Williams et al. (1993) did report discomfort and some visual system changes even with a very short period (10 min) of stereo HMD use (VPL XL EyePhone system). They attributed the difficulties to the stereo nature of the display (Wann et al., 1995), since a second study (Rushton et al., 1994) found fewer symptoms with a bi-ocular system

(Visette 2000, Virtuality Entertainment Ltd.). However, the effect of stereo decoupling was not established, since a different HMD was used and many other parameters differed in the two studies. Howarth (1996) simulated the dynamic change of stereo displays by changing the prisms worn by observers playing solitaire on a CRT every 5 min. With this slow pace of change he found a significant reduction in the level of prism adaptation compared to 15 min of continuous prism exposure. Less than half of the subjects reported increased discomfort and the level of change was small. However, it must be noted that the rate of change used in that study (5 min) is probably too slow to simulate the typical conditions of a stereo display. Howarth and Costello (1996b) and Howarth (1998) reported a variety of symptoms and visual system changes in a study comparing three HMD systems and two desktop CRT control conditions. They concluded that the differences in effects appear to be device dependent rather than a generic effect of HMD systems in general.

A study comparing the effects of the i-glasses used in both stereo and bi-ocular mode and a desktop CRT system found no difference in visual system changes among the three devices (Peli, 1998). A difference in subjective discomfort was found between the CRT and HMD conditions but not between the stereo and bi-ocular conditions. These results also fail to provide clear support for the notion that the effects of decoupling are responsible for the discomfort or visual changes reported in the literature. More research is needed before any firm conclusions can be drawn regarding differences between stereo and bi-ocular HMD systems.

Changes in the accommodative convergence to accommodation (AC/A) ratio. The AC/A ratio represents the amount of convergence change (in prism diopters) induced by a change of 1 D in accommodation demand without a corresponding change in convergence demand. The AC/A ratio is thought to be a fixed physiological parameter for each individual. Its change represents a decoupling of the normal binocular relationships. A study by Howarth (1995) reported a change in decoupling between accommodation and convergence expressed as change in the AC/A ratio. Although such decoupling may raise concerns, a review of the literature indicates that the effect may not be rare and that recovery is rapid.

In the past, AC/A ratios have been thought to be unaffected by visual training (many reports cited by Flom, 1960). However, Manas (1958) reported an increase in AC/A (average 0.5 Δ/D) following training, as did Flom.

Laterally displacing periscopic spectacles requires an increased and variable convergence to accommodation demands similar to the effects of stereo display systems, where closer simulated targets require more convergence while accommodation demand remains fixed. The decreased AC/A ratio found by Howarth (1995) in three of the five devices he tested could not be a result of the same effect.

AC/A changes were also noted following optical decoupling between convergence and accommodation (Miles et al., 1987). Miles et al. found that with laterally displacing periscopic spectacles there was an increase in the AC/A. BO and BI prisms caused the expected prism adaptation and there were some secondary cross-effects by which BO caused an increase in AC/A. Cyclopean spectacles resulted in little AC/A change. However, exercise alone (shifting fixation without any lenses) also caused a small effect and a larger effect on the convergence accommodation to convergence (CA/C) ratio. In analyzing their results, Miles et al. concluded that accommodation or convergence fatigue associated with visual exercises may have caused the observed changes in AC/A rather than the disruption of the cross-link between the accommodation and convergence systems.

Fisher and Ciuffreda (1990) measured the effect of laterally displacing periscopic spectacles under natural viewing conditions. They found prism adaptation but no change in AC/A ratio. In discussing the difference between their findings and those of Miles et al. (1987), they pointed out that Miles et al. had their subjects make frequent and systematic large shifts in fixation distance, while Fisher and Ciuffreda's subjects simply operated in the natural environment. They concluded that maintaining a high degree of demand on the system under such dynamic conditions may be necessary for inducing even minimal short-term adaptation of the AC/A ratio. This is frequently the case when playing stereo games in VR systems. Many of the games induce large disparity to create large depth effects and require frequent and continuous changes.

It should be noted that Miles et al. (1987) found that the subjects returned to pretesting AC/A even without binocular vision exposure within 2 h. The recovery with normal binocular vision may be very fast, although it was not tested. The long-term effects of the visual training reported by Flom (1960) disappeared when measured 1 y later. It is not known when during the year the changes disappeared. It is important to note that the small effect of a single 30-min weekly treatment session did result in a measurable effect following 12 wk of training.

The decrease in AC/A seen in Howarth's (1995) study, reported earlier, may be one result of convergence accommodation decoupling in stereo devices or simply accommodative fatigue (Schor and Kotulak, 1986). Both have been demonstrated in such devices (see the following text). Proper design of game software may reduce the effect. Moreover, the change in AC/A induced is likely to be transient even when generated under extreme demands and repeated over a long period as in visual training.

Changes in accommodation. Changes in the accommodation response following HMD use have also been reported. Inoue and Ohzu (1990b) reported slower accommodative response (by about 30 percent) following 1 h of stereo display use. They also reported a smaller accommodation response to convergence (disparity) stimuli when the screen was farther away (360 versus 100 cm). This might indicate use of accommodative convergence to meet the changing convergence demand. As Inoue and Ohzu noted, such response should cause blurring of the images, but no blurring was reported in that study or in any other. Iwasaki et al. (1994) reported an increased delay in accommodative response following 15 min of exposure to stereo display compared to 45 min for nonstereo viewing of a CRT. The consequence of such fatigue is not known, nor is the time course for recovery of normal function known.

Despite much discussion of the possible harmful or disturbing effects on binocular vision of the use of HMDs, and stereo HMDs in particular, the research published to date provides little evidence that such effects occur (Wilson, 1994). We still do not know whether the decoupling of convergence and accommodation that occurs in stereo HMD has significant short- or long-term effects on the user. The studies reviewed earlier show few short-term effects. To my knowledge, no studies have been published describing long-term effects in adults or children, although the possible effects were considered in a recent review of the literature (Rushton and Riddell, 1998). The actual effects, if any, will come to light with the increased use of these devices and with studies directly addressing changes that might occur with long-term use. However, the data so far do not seem to support the level of concern expressed in the literature. Some efforts at providing display systems that avoid the decoupling of convergence and accommodation demands are described in a later section.

6.2.3 Secondary effects of stereo display

Inoue and Ohzu (1990a) reported that subjects were able to fuse the stereo image over a wider range of disparity when the display was large (75 in.) than when it was small (21 in.). However, observation distances were proportional to viewing distance (350 and 100 cm, respectively), resulting in almost equal field size in terms of visual angle. The effect reported, therefore, was not an effect of field size, but rather an effect of screen distance and of expressing the fusional range in units of accommodation demand. Nagata (1996) tested a change of apparent size both at a fixed distance and with different distances, and demonstrated that fusional ranges were directly affected by peripheral field size. He found an increase of about a log unit of disparity threshold when the field size was increased from 6.3 to 38°.

Nagata (1996) further demonstrated that the reduction in the range of disparities that could be fused was a function of the sharpness of the peripherally nonfixated patterns. He measured the limit of disparity of a fixated target before diplopia was reached in the presence of different peripheral field environments. For two of the three subjects, Nagata found that large disparities were better tolerated when the peripheral images were blurred than when they were sharp. Even larger disparities were tolerated in the presence of uniform backgrounds. This suggests that blurring image details that are not fixated would improve comfort with HMDs or other stereoscopic displays, as this places less strain on the fusional system.

Wöpking (1995) studied the discomfort induced by viewing static stereo images as a function of the level of disparity and blur of the out-of-fixation pattern. He found an overall decrease in viewing comfort with an increase of disparity and an increase in background sharpness. This is important in the current context because in the real world, objects at depths that differ from that of the fixated target are blurred, whereas in a virtual environment they are (unnaturally) in focus. Wöpking found that with a relatively sharp background (higher than 5.6 c/°), disparities of 70 arcmin created an annoying sensation. He also concluded that a large amount of blurring is needed to avoid eyestrain. Note that this experiment was carried out using uncrossed disparity for the background and a fairly large screen distance (2.75 m). Thus, the result is not very surprising. Nevertheless, it is interesting to realize that subjects can actually report this condition as annoying.

These findings provide further support for the idea that natural viewing conditions in a stereo display require more than the correct convergence and accommodation demand. Apparently it is also important to maintain the natural situation in which the nonfixated image features, which are at different distances, are blurred. Omura et al. (1996) did mention the need for such correction and proposed using random motion to create blur in a graphic display. A recent paper by Blohm et al. (1997) demonstrated the effectiveness of such processing in a system that can be implemented in HMDs.

The sharpness at all displayed depths that is commonly found in 3 D demonstration video programs or computer graphics results in an unnatural appearance of the scene because it removes the monocular depth cue of depth of focus. This problem may be more common to early-generation demonstration videos. Future program directors can assume that they can capture the viewer's eye and attention at a specific part of the image and use a reduced depth of focus in the cameras to produce a more realistic and possibly more comfortable stereo image.

Systems that avoid decoupling of convergence and accommodation. A number of systems have been proposed and demonstrated that reduce or eliminate the problem of accommodation and vergence decoupling in stereo displays. One such design for HMDs provides for a hardware system that more closely simulates the real-world situation of coupling convergence and accommodation demands (Kajiki et al., 1996; Omura et al., 1996; Shiwa and Kishino, 1995; Shiwa et al., 1996). This approach is based on real-time monitoring of binocular eye movements to determine which target the user is fixating at any point in time. The stereoscopic depth of the target is known, and thus a mechanical optical system can modify the virtual display's distance to match the accommodation demand with the convergence demand. One limitation of this approach is that the optical depth of the whole image is changing in response to the user's convergence response. The delay associated with the convergence itself and with the mechanical optical change is likely to present an unnatural change in focus in response to eye movements rather than the natural covariation of focus and convergence.

Dolgoff (1997) developed a stereo system that avoided the accommodation-convergence decoupling by using two distinct focal distances. His is a desktop system and may not be easily convertible to HMD. The system optically superimposes (via a beam combiner) images of two complementary views of the same scene at two different focal distances. Objects that are closer to the observer are presented on the closer screen and objects that are farther from the observer are displayed on the farther screen. Occlusion of the latter by the former is addressed by an LCD light valve between the two. This system uses real-world disparity and focal changes and thus requires no glasses. It also provides for (partial) parallax cues. The main limitation is that only two distances can be presented reliably with the focal and disparity cues. Dolgoff claims, but cites no evidence, that only two different planes are needed to create a satisfactory "real depth" experience. In a real-world environment objects of interest may be at many distances. Furthermore, in the proposed configuration, only desktop and about arm's-length distances could be properly simulated.

6.2.4 Monocular occlusion

The use of a monocular HMD disrupts normal binocular vision by presenting two distinctly different images to each eye. Although some temporary disruptions of binocular function have been reported in adults, the main concerns are with the possible effects of partial monocular occlusion on children. It should be emphasized that most of the concerns raised in the literature are based on indirect conjecture from what is known about binocular vision, development in general, and the effects of *complete* occlusion, as discussed in the following text. Furthermore, I know of no studies or case reports that illustrate detrimental effects of intermittent use of monocular displays on visual function in children or adults.

Monocular occlusion in children. Normal development of visual function in each eye depends on the normal development of binocular function during the early years of life. If binocular vision is interrupted during those years, in addition to the loss of stereopsis, one of the eyes will also lose visual acuity and may be severely impaired (a condition called amblyopia). Normal binocular function can be interrupted in a number of ways, such as by a misalignment of the eyes (strabismus), by significantly different refractive error causing blurring of images in one eye (anisometropia), or by a substantial difference in image size (aniseikonia) resulting from spectacle correction of anisometropia. Binocular function also can be interrupted by occlusion of one eye, resulting from either complete occlusion (drooping lids) or an opacity resulting from congenital cataract in one eye. If the occlusion is removed during the early critical years of visual development, the visual function of the occluded eye can be recovered. However, if the occlusion is removed beyond that critical period (ages 6–9 y), visual acuity loss is permanent. Note that in the conditions discussed so far the disruption of binocular vision is constant, while the disruption possible with HMDs is intermittent.

Rushton and Riddell (1998) reviewed the literature concerning plasticity in the developing visual system of children as it may be affected by use of HMDs. While acknowledging the lack of direct evidence in the literature about any serious changes in visual development, they did find substantial reasons for possible concerns and recommended research approaches that would increase our knowledge about these issues.

The critical period during which amblyopia may be induced by interruption of binocular function is estimated to end at age 8 (Awaya and Miyake, 1988) or age 9 (Bishop, 1981). Sensitivity to monocular visual deprivation is high until age 5 and decreases until the system matures (Bishop, 1981). Although a monocular HMD does not actually occlude the eye, and form vision is maintained in both eyes, it clearly interrupts normal binocular function. Therefore, until further information is available on the effects of such interruption of binocular vision, it would be prudent to avoid the use of the device by children 6 y of age or younger and limit its use by children 6–9 y of age.

Monocular occlusion in adults. Continuous monocular occlusion may affect the visual systems of adults as well. The effects may be more severe for people with weak binocular systems. Following complete continuous occlusion of one eye for about 1 wk, patients with eyestrain symptoms had substantially increased phorias (Marlow, 1921). Smaller effects were also noticed in cases where the occlusion was occasionally interrupted. Sethi (1986) reported large changes in horizontal phoria position following only 4 h of monocular occlusion for normal observers. When binocular vision was restored, recovery was very fast, following an exponential time course with a time constant of about 1 min.

Vertical phoria changes are considered more important clinically than lateral phoria changes. Ellerbrock and Loran (1961) reported significant changes in vertical phoria after less than 2 h of occlusion and measurable changes in less than half an hour. They explained the fact that they found phoria changes where others did not by the use of a measurement technique that eliminated all possibility of fusion stimuli before or during the measurements. This indirectly suggests that the recovery of the system is very rapid once binocular vision is reestablished. In another study, after 8 days of continuous occlusion all subjects developed large phorias (both lateral and vertical), reported severe diplopia, failed all tests of stereopsis, and had slightly reduced contrast sensitivity (Brown et al., 1978). These effects all persisted for several hours, but all capacities returned to normal within 24 h.

Changes in phoria also occur when normal binocular vision is interrupted without occlusion, such as when using night vision goggles (Sheehy and Wilkinson, 1989). The changes reported in this case were much smaller. In another study, phoria changes were measured following 45 min of active use of a monocular HMD for a word processing task (Peli, 1990). Only one out of the three subjects had a small, measurable increase in exophoria, while following 4 h of complete occlusion of one eye, two of the three subjects had a measurable change in phoria. None of the subjects in that study reported diplopia or any symptoms of visual discomfort following occlusion or use of the monocular HMD.

Viirre et al. (1987) measured eye movements of monkeys subjected to patching of one eye for a week. They found changes in the saccadic patterns of the covered eye, including a decrease in saccadic step magnitude and a postsaccadic drift in the temporal direction as well as in the vertical component during horizontally directed saccades. All of these changes were noted in the covered eye and normal function recovered within 1 day after removal of the patch without any noticeable effect on the noncovered eye. Similar monocular changes were noticed in the vestibular ocular reflex (VOR) under the same conditions.

Thus, while monocular display use is likely to change phoria, and possibly saccadic eye movements, the effect appears to be temporary and the return to baseline phoria level and normal saccadic patterns is rapid. These changes are likely to be even smaller if a peripheral display position is used that permits intermittent binocular viewing of the environment. The symptomatic effects of such long-term use still remain to be evaluated.

6.3 Visual Perceptual Issues

In addition to optical effects, HMDs may create perceptual changes that may lead to changes in the visual system and cause symptoms. The main concern with these changes, however, is with their impact on the acceptance of the technology. This section identifies various visual perceptual changes that may occur with HMD use. Whenever possible, the impact on design or methods to reduce the effects are discussed.

6.3.1 Head motion, vestibular effects, and image motion

During normal viewing conditions the VOR generates compensatory eye movements that counter the effect of head movement to maintain a stable image on the retina. Acceleration of the head is detected by the vestibular apparatus in the inner ear. Signals from this biological accelerometer generate the VOR. The compensatory eye movements are controlled in an open-loop system. The gain of this system is on the order of 0.7–0.8 for passive motion (Demer et al., 1987a) and 0.96 for active head motion (Collewijn et al., 1983). The residual error is corrected by the tracking visual mechanism. The joint operation of the two mechanisms, called the visual vestibular ocular reflex (VVOR), adequately compensates for all image motion during head motion, thus providing a stable retinal image of the world.

These same mechanisms that serve to stabilize the retinal image in natural conditions may result in retinal slip and image degradation when an HMD is used. The eye movements that compensate for an ordinary 90° head turn can exceed 100°/s (Demer et al., 1987b). If no head tracking is provided, eye movements driven by VOR during head motion will cause the HMD image to slip across the retina and will result in reduced acuity and apparent image motion (oscillopsia) causing significant image degradation (Peli, 1990). HMDs used in VR systems frequently include head tracking and displays that compensate for these movements and should present a stable environment. However, in many cases, such compensation is not included or is very crude and partial. In addition, lag in the response of systems resulting from a lag in the eye tracker itself or from the time needed to compute the updated view also results in retinal slip.

The VOR may be inhibited or suppressed by the visual fixation mechanisms (Burde, 1981). Thus, when a target is moving with the head, as with the HMD, the visual mechanism may completely suppress the vestibular response.

The VOR is strictly reflexive and not under voluntary control. However, because it is an open-loop system, the gain must be adjusted under different modes of operation. The plasticity of the gain calibration for the VOR system has been demonstrated in many animal and human experiments. Adaptation of the VOR to moderate changes in the demand, as induced by spectacle correction, is very rapid and is completed within 4–20 min (Collewijn et al., 1983). Adaptation of the VOR gain to the extreme demands imposed by reversing prisms (Gonshor and Melvill-Jones, 1976) or telescopic spectacles (Demer et al., 1987b; Gauthier and Robinson, 1975) is limited in range, never reaching complete adaptation. I am not aware of any study evaluating the level of adaptation and time course for an HMD, except with an imaginary target (Barr, 1926, cited in Collewijn et al., 1983).

Adaptation to unequal VOR demands for the two eyes is almost impossible. When the discrepancy is large, the adaptive process of both eyes is controlled by the eye that provides the more meaningful information (Collewijn et al., 1983). The use of a monocular HMD presents this type of unequal demand situation where one eye needs normal VOR gain of about 1.0 to continue perceiving the world as stable, whereas the other eye (the one using the display) must completely eliminate the VOR gain. There are some suggestions from studies with monkeys that the VOR may adapt differently in each eye following monocular occlusion (Snow et al., 1985; Viirre et al., 1987). However, only small changes in VOR gain took place, and it is unlikely that a large difference, like those required by the monocular HMD situation, could be accommodated.

The effects of passive and active rotary and linear motion on perceived image motion and the ability to read using a monocular HMD (the Private Eye) have been reported (Peli, 1990). For passive motion, the subject sitting in a chair was rotated back and forth through an angle of about 30° at peak velocities of about 15°/s. The vestibular eye movements resulted in perceived motion of the displayed image. Image motion was noted throughout the rotation, but it was greatest at the two extremes of the range, where acceleration is increased due to a change in direction. Here small print became illegible due to the motion blur. Following a short adaptation period the perceived image motion was reduced except for the points of direction reversal, where acceleration is very high.

Image motion and text degradation were noticeable only during the initial acceleration and final deceleration of linear motion testing. During the constant-velocity phase, the display remained completely stable and legible. Possible effects of linear or translational VOR were discussed by Miles (1991), but very few data are available. Active rotations were obtained by the subjects standing up and rotating their heads with their body trunks stable, or rotating in a chair with their feet on the ground. Active rotation induced increased image motion. As a result, text legibility decreased throughout the range of movement.

See-through HMDs (such as the Sony Glasstron or the Virtual I-O i-glasses) present a unique conflict of demands for the visual/vestibular system. When operating with a see-through display (without head tracking), retinal image stability requires a normal vestibular gain of about 1.0 for the outside view and a gain of 0 for the displayed image. Obviously the two requirements cannot be met simultaneously, and in this situation one image or the other will be blurred during head motion.

Motion/simulator sickness. Conflicts between vestibular and visual inputs are thought to be common causes of motion sickness with its unpleasant symptoms of ataxia (loss of balance) and nausea. For example, visual scene motion without a corresponding vestibular input, as is commonly found in a flight simulator, can result in simulator sickness (Uliano et al., 1986). Such motion sickness occurred in almost 50 percent of pilots tested on the first day of simulator training, but the magnitude of illness decreased on subsequent days, indicating that adaptation is possible (Uliano et al., 1986). It should be noted, however, that the vestibular-visual conflict encountered in many HMD applications is different. Vestibular input occurs without the corresponding visual movement (Howarth, 1996; Howarth and Costello, 1997). This is the inverse of what is found in flight simulators.

It is interesting to note that in early, extensive literature review on HMD devices (Hughes et al., 1973) there was no mention of image degradation due to motion and only one reference concerning motion sickness in relation to those devices in military applications. The paucity of such reports may indicate that the plasticity of the visual system enables quick adaptation to such changes in most of these applications. In one study Saito et al. (1984) evaluated vestibular-visual conflict with a helmet-mounted display in a flight simulator capable of rotating. The authors did not find any symptoms of motion sickness in any of the conditions where vestibular and visual motion conflicted. Similarly, none of the subjects I evaluated with the monocular Private Eye reported any symptoms of motion sickness; however, movement was limited and all subjects sat throughout the trials (except for those using the active rotation equipment) (Peli, 1990).

More recently, Kolasinski et al. (1995) reviewed the literature on simulator sickness with special emphasis on the possible impact on virtual reality systems. They classified factors affecting simulator sickness as those associated with the individual user, those associated with the simulator, and those associated with the task. Only a few of the many items reviewed there will be mentioned here. Motion sickness was reported to be strongly affected by age. Susceptibility was greatest between the ages of 2 and 12 y and decreased rapidly until age 21. After age 50, motion sickness was practically nonexistent. Adaptation to the simulation situation has been found to decrease sickness over time. However, it has been suggested (without evidence) that adaptation may lead to postimmersion symptoms [see Kolasinski et al. (1995) for references].

Experience with discomfort symptoms associated with new eyeglass prescriptions suggests that adaptation restores comfort in both the novel and the previous conditions within only a few days of adaptation (Carter, 1963; Miles, 1991). Presumably the symptoms associated with a change in prescription are also a result of the conflict between the visual and vestibular signals that occur during head movement due to the prismatic effect of the spectacle lenses (Miles, 1991).

In addition to vestibular-visual conflict, a wider field of view increases the incidence of simulator sickness. Perceived flicker appears to be associated with simulator sickness and other eye symptoms and is more likely to happen with wide-field systems due to the increased sensitivity of the peripheral retina to flicker. Thus, the drive for VR systems with wider fields of view may exacerbate the simulator sickness problem.

The complexity of the motion/simulation sickness situation is widely recognized. Still unknown are the requirements for a tracking system to reduce or eliminate the phenomenon, or even whether such an ideal tracking system can prevent motion sickness. Tracking errors cause conflict between the vestibular and visual signals and are presumed to cause sickness symptoms. While a good tracking system is likely to help with the visual-vestibular conflict that occurs when the head is physically moving but the visual scene is not, the vestibular-visual conflict that occurs when the body is stationary while the visual scene is changing (as in flight simulations) remains. The latter cannot be corrected by head tracking and is likely to continue to cause symptoms even with ideal head tracking. Piantanida et al. (1992) reported that in a search study using fields of view (varying sizes from 14 to 80°) and a head tracking system (which provided image update at 30 Hz and 100-ms lag) all subjects experienced some degree of simulator sickness. The greatest discomfort was felt when the edge of the display field was surrounded with a black border in high contrast to the white display screen. The task in that study required aggressive head movements. A more recent study showed that even playing a game such as chess, which requires little head movement with an HMD and no tracking, can cause significant motion sickness within 20 min due to this conflict (Howarth, 1996; Howarth and Costello, 1997)

Hettinger et al. (1990) reported that tracking error causing visual oscillations in the range of 0.2–0.25 Hz may be the most nauseogenic. While the required performance of a head tracker to limit symptoms is not known, the National Science Foundation (NSF) invitational workshop on virtual environments (Bishop and Fuchs, 1992) recommended developing systems with latency of less than 5 ms, resolution of 1 mm and 0.01°, and accuracy of 1 cm and 0.1° for non-registered (see-through) applications.

Eye movements and image motion. When the eye moves across a pulsating intermittent display, parts of the display occasionally appear to jump or move in the same direction as the eye movement. These apparent movements are the result of interaction between the rapid eye movements (saccades) and the intermittent nature of the display, and are particularly apparent on displays with short persistence. The effect has also been reported with CRT displays (Crookes, 1957; Neary and Wilkins, 1989), though it is limited to CRTs with short-persistence phosphors. HMDs frequently use non-CRT, short-persistence display technologies, and are more likely to be affected by this phenomenon.

If the display consists of only two dots, and saccadic eye movements are made from one dot to the other, an intermittent ghost image may be seen briefly just beyond the target. In normal viewing of continuously illuminated targets, such occurrences are prevented by saccadic suppression (Matin, 1974). At some point during a saccadic eye movement, the observer must shift the egocentric sense of direction (head-related coordinate system) from the initial target to the destination target (Fig. 6.11). This shift in egocentric direction occurs at the beginning of the saccade. At the moment of change in egocentric direction, the world should appear to jump in the other direction. If the visual scene remains visible during the saccade, it should also appear to move throughout the duration of one saccade (about 30 ms). Saccadic suppression prevents these potential fluctuations in perceived direction of targets. Saccadic suppression is not effective if the target is flashed for a short period during the saccade. Such targets will appear as an elongated smear of light and the length of the smear will be maximal when it is visible for 20 ms (Matin, 1974). Thus, if fixation is changed between two intermittently illuminated targets and the destination target is flashed during the saccade, it will become visible at a point in time at which it still projects on the retina away from the fovea and will be perceived beyond its actual position (Fig. 6.11). This phenomenon, commonly seen with LED-based alphanumeric displays (e.g., car clocks), was described by Peli (1990) for the LED-based Private Eye display and by Neary and Wilkins (1989) for CRT displays with short-persistence phosphors. On such CRTs, if a saccade crosses a displayed vertical line, the line appears to tilt in the direction of the eye movement, with the top of the line tilting further because the scan is from top to bottom [Fig. 6.12(*a*)]. In the Private Eye, the display mode differs from a standard raster scan. An entire vertical column is illuminated at once, rather than serially as on a normal raster display. The columns are swept horizontally; therefore a vertical line in this display appears to jump in parallel during a horizontal saccade rather than to tilt as is the case with a CRT display [Fig. 6.12(*b*)]. Horizontal lines in the Private Eye display appear to jump and to tilt only slightly in the direction of vertical saccadic movement [Fig. 6.12(*c*)]. The smaller tilt results from the shorter active display period of 5 ms, which allows

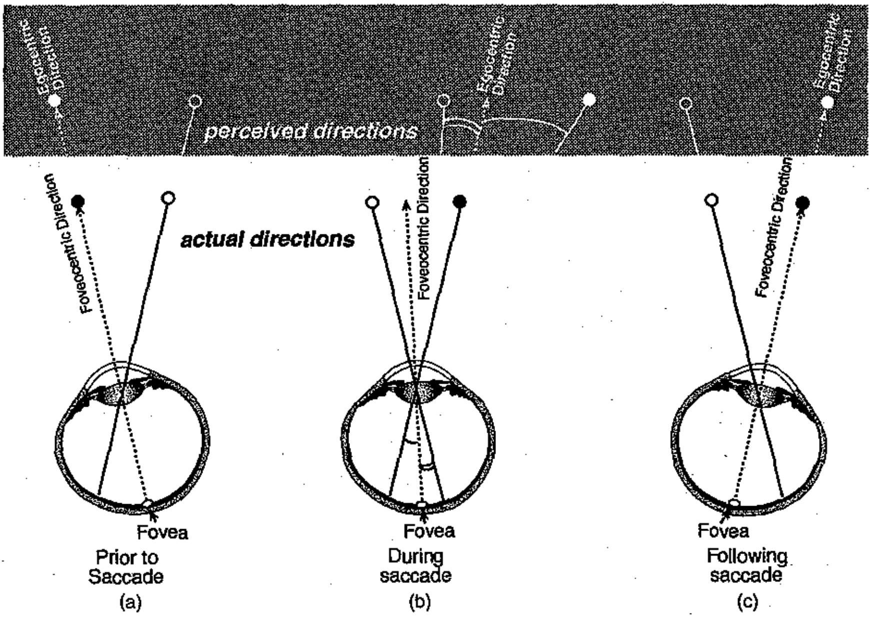


Figure 6.11 The appearance of an image jump during eye movements across an intermittent display. At some time during a saccadic eye movement, the observer must shift the egocentric sense of direction (head-related coordinate system) from the initial target (*a*) to the destination target. At the moment of change in egocentric direction, the world should appear to jump in the other direction. Saccadic suppression prevents these changes in perceived direction. Saccadic suppression, however, is not effective if a target is flashed during the saccade. If a subject changes fixation between two targets and the destination target is flashed during the saccade (*b*), it will become visible at a point in time at which it projects on the retina away from the fovea. Thus the destination target will be perceived beyond its actual position. Following the saccade, the veridical directions are restored (*c*).

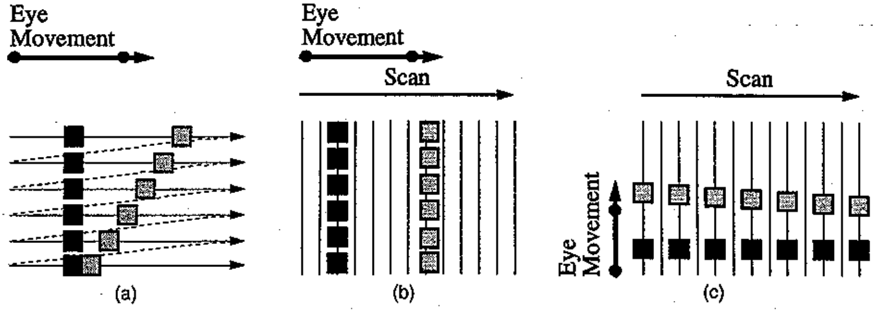


Figure 6.12 The appearance of a line on a pulsating display during saccadic eye movements. (*a*) A vertical line (dark pixels) presented on a standard raster (scanning left to right and top to bottom). If the saccade is across the line from left to right it will appear to tilt as illustrated (gray pixels). The top pixel is on early in the saccade and therefore is perceived to be shifted further in the direction of the eye movement than the bottom pixel. (*b*) In the nonstandard scan of the Private Eye display, each column of pixels is illuminated in turn and the horizontal mirror movement presents successive columns to the right or left (thin lines). A vertical line will appear to jump laterally and not tilt with the horizontal eye movement. (*c*) In the case of a horizontally displayed line and vertical eye movement, the line will appear to jump up and tilt only slightly, due to the shorter display time in this display.

only a small change of eye position to occur during the intrasaccadic display. Consequently, the appearance of line movement during eye movements can be used to determine the display raster organization.

When the phenomenon is very apparent, it may affect eye movement control (Kennedy and Murray, 1991; Wilkins, 1986), resulting in a significantly larger number of corrective saccades (Neary and Wilkins, 1989). This has been suggested as an explanation for the discomfort sometimes reported during reading from computer displays or even under fluorescent lights. The apparent movement of the display during a saccade may cause changes in the normal saccadic pattern via an adaptation process used to recalibrate the saccade systems when errors are noted (Albano and King, 1989). This recalibration ability is important in other situations in response to various optical mismatches that may occur in binocular HMDs.

Sequential color displays use temporal sequences of three-color illumination to generate a color image. In these displays, saccadic eye movements frequently cause a tearing of the display into its color components (Arend et al., 1994). When the eye is moving across such a display, one of the color components (e.g., the green image) seems to tear off the display and appear in space beside the display in the direction of the eye movement. This is a result of the same phenomena discussed above. Apparently, the effect is even easier to notice in sequential color displays since saccadic suppression is reduced for chromatic flickering stimuli even more than for luminance flickering stimuli (Uchikawa, 1995).

The phenomenon of image jump and color tearing during eye movements across the display can be controlled to some extent in binocular HMDs. If the temporal sequence of the two displays is out of phase, image jumps are reduced or eliminated (Chen, 1993). Presumably the out-of-phase display results in an effective increase in persistence for the visual system. It has been found that the critical fusion frequency (the lowest flickering frequency that is perceived as continuous light) in binocular displays is 8 percent higher when the flicker presented to both eyes is in phase than when it is out of phase (Perrin, 1954). Similar reduction may be noted when using the Nintendo Virtual Boy binocular display, which uses the same nonpersistence LED technology as the Private Eye.

Another related phenomenon that occurs during tracking of smooth target movement was recently reported (Nijhawan, 1997). When a smoothly moving target not tracked by eye movements has a briefly flashed secondary target superimposed on it, the two targets appear separate in space with the moving target seen ahead in the direction of its movement. The color of the secondary target is perceived as if it was presented alone rather than as the combination of its color with the primary color target. The effect is nullified if the observer tracks the target with eye movements. When the eye tracks a smoothly moving target, the eye movement is matched with the target to maintain its image on the fovea. In this case, there is no discrepancy between target position on the retina and its perceived position.

Effects of low update rates. Eye movements also affect the perceived image when the eyes are tracking a smoothly moving target in a system where the display's update rate is slower than its refresh rate. This situation is common to virtual environment systems where the computation speed is insufficient to update the displayed images at the full refresh rate of 50 or 60 frames per second. Systems in which the update rate is only 10–15 frames per second are commonplace. For example, the Bright Eye low-vision reading device refreshes at 50 frames per second and updates at only 15 frames per second (Peli, 1995), and the Zone Hunter game used by Rushton et al. (1994) on the Visette 2000 HMD updates at only 12 frames per second.

If the refresh rate is reduced to match the update rate, a constant flicker results. Thus it is common to maintain the higher refresh rate and repeat the nonupdated frames as needed. For static imagers, or for images that change abruptly, this solution is adequate. However, if the imagers include a smoothly moving object and the viewer tracks the object with eye movements, then a disturbing artifact may be noted. The tracked object in such a situation appears to split into multiple low-contrast images. The number of these images is equal to the ratio of the refresh rate to the update rate (Lindholm, 1992). The distance between the multiple images increases with target speed.

With a refresh rate that is faster than the update rate, the appearance of multiple images occurs with eye tracking in the condition just described; multiple images only occur without eye tracking in the case described in the previous section (Nijhawan, 1997). Reports of multiple images when the update rate is a fraction of the refresh rate were explained as a result of aliasing due to frequency domain replica detected within the observer's window of visibility (Lindholm, 1992). Chen (1993) suggested that eye tracking reorients the slower-frequency replicas, thus removing them from the window of visibility and resulting in the perception of multiple targets. However, an explanation based on the phenomenon described by Nijhawan (1997) does not imply a blurring of the images, consistent with observer reports and the fact that multiple images also occur at higher display rates. We have noted the phenomenon with a display operating at 117 Hz and update rates one-half and one-third of the refresh rate (Peli and Labianca, 1997).

As an alternative to the aliasing explanation, I offer the following account: When the update rate is half the refresh rate, let us assume that the display is updated on the odd frames and repeated on the even frames. Observers can easily track such targets at the correct speed. During tracking, predictive control capabilities are used to match both eye velocity and foveal position to those of the target. As in Nijhawan (1997), the target is then perceived at its correct location both during the odd frame, when it falls on the fovea, and the even frames, when it falls on the retina ahead of the fovea in the direction of motion. It thus appears, during the odd frame, as a separate target trailing the target seen during the even frame. If any point between the even and odd frames is tracked, the effect will be the same. This accounts for the perception of multiple targets during tracking.

If attention is directed to the target but no eye movements are initiated to track the target, its perceived position leads the actual position, accounting for neural processing delay (Nijhawan, 1997). If the position of the repeated frames is tracked by attention (but not eye movements), the position of the following nonrepeated frame target in space will exactly coincide with the predicted location. Observers report a single target under these conditions. If the nonrepeated target position is tracked, the same analysis will lead to the perception of two targets with a wide spatial separation. It appears that the visual system selects the position for tracking that leads to the perception of a single target.

This effect may have important implications for the use of sequential color systems to display moving targets. A sequential color display is described as a system with a 180-Hz refresh rate and an update rate of

60 Hz in which a different color is presented in each of the three update cycles (Baron et al., 1996). If there are moving targets in such a display, they result in the same artifacts when tracked by eye movements: multiple, low-contrast images of the three colors. When the image is computer-generated graphics, it may be possible to correct for the effect by calculating the three color images at their respective display locations with image motion taken into account. Baron et al. (1996) simulated the effect and found a large attenuation of the artifact when the position of each color was updated separately during a target tracking task. When no tracking was employed, such compensation was less effective. The data show that with no tracking, the uncompensated condition had less breakup than in the tracking condition.

Another method to avoid the image tearing associated with low update rates is to reduce the refresh rate to match the update rate. Although this completely eliminates the doubling artifact, the resulting noticeable image flicker is usually more disturbing, and consequently this method is rarely used.

In a binocular HMD it is possible to use a hybrid method where each update frame is presented once to the right eye and once to left eye. This eliminates the image doubling artifact and causes less noticeable flicker due to the integration of images between the eyes (Chen, 1993).

6.3.2 Binocular rivalry effects in monocular HMDs

Monocular HMDs present a unique problem for the user. Looking at such a display for the first time, observers usually perceive a superimposition or even merging of the display image with the ambient image seen with the other eye. Merging of the images from both eyes, called *fusion,* is possible only under strictly controlled conditions when the two images are fairly similar. Even small differences will prevent fusion of the images. Superimposition of two nonsimilar images, presented to each eye, usually results in alternating periods of monocular dominance during which only one of the images is visible (Wheatstone, 1838). This phenomenon is called *binocular rivalry.* Alternation does not necessarily include the entire visual field: the observer may perceive parts of one image interwoven with the complementary parts of the other image, giving the appearance of a patchwork composite (Fig. 6.13). Different parts of this patchwork alternate periodically. The brightness, contrast, content, and motion of the displayed images and the ambient scene may all play a role in the ability of observers to use such rivalry inclusion displays for different tasks. The user's eye dominance, inequality of visual acuity of the two eyes, and state of binocu-

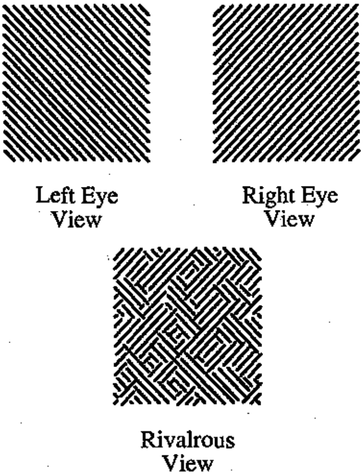


Figure 6.13 Binocular rivalry occurs when different images are presented to each eye, as illustrated. In cases of strong eye dominance, only one eye's view will be perceived. If the eyes are similar and the images are similar in contrast, brightness, movement, and so on, a composite patchwork appearance would appear with parts of the image contributed by one eye's view and the complementary parts by the other eye's view.

lar function may also affect rivalry. Although it was commonly believed to represent competition between the images from the two eyes, recent findings (Kovacs et al., 1996; Sengpiel, 1997) show that rivalry occurs between two competing percepts, irrespective of the eye of origin. This new understanding also accounts for the ability of an observer to control rivalry to some extent by (voluntary) attention.

The effects of various stimulus parameters on rivalry in HMDs were reviewed by Hughes et al. (1973); experiments investigating many of these parameters in a simulated HMD were carried out by Hershberger (1975), and additional discussion of the parameters affecting rivalry may be found in Blake (1995) and Peli (1990). I have tested the Private Eye monocular display outdoors on a sunny day. The bright ambient light and reflections of brightly illuminated objects in the environment substantially reduced the display's contrast. When the display was shielded, rivalry effects were minimal, and the display was usable with both eyes open without adaptation. Without shielding, it was difficult to read the low-contrast screen even with the other eye covered. Rivalry made this dim display impossible to use with the other eye uncovered. The effect of rivalry in bright environments should be considered in the design of monocular displays. Although closing one eye easily resolves the problem of rivalry, many people have difficulties closing one eye and most are very uncomfortable keeping one eye closed for any length of time. It is therefore advisable to design into the product a shield that can be placed in front of the other eye to prevent rivalry.

In some HMD applications, such as personal computer screens, alternating access to the display image and the outside world view is necessary, and blocking the other eye's view is not possible. When typing from a printed page onto a computer using the Private Eye, subjects with normal binocular function (normal stereo acuity) could perform the task with little difficulty, but all noticed active, incomplete rivalry, especially when attending to the paper copy (Peli, 1990). One subject found copying to be very comfortable when the screen view was superimposed on the paper copy, while another found it very uncomfortable and complained of asthenopia (eyestrain) in this mode. The third subject preferred to position the copy to one side to reduce rivalry. These findings illustrate the variability in response and tolerance to rivalrous conditions among users, and suggest that maximal flexibility should be designed into the display head mount to permit individual adjustment. One of the most important individual adjustments needed is the selection of the dominant eye for use.

Most observers show a preference of one eye over the other for various tasks (Miles, 1930). When a person points a finger at a distant target, the images of the target and the fingertip can coincide on the fovea of only one eye (sighting dominance). Sighting dominance (Fig. 6.14) differs from eye dominance in binocular rivalry, which is usually defined as the eye whose image is perceived a larger proportion of the time. Under laboratory conditions, when two rivalrous stimuli are equal in most important parameters (e.g., brightness, motion, spatial frequency, etc.), the sighting-dominant eye shows a small but significant dominance in binocular rivalry. That dominance may be reduced by short training periods (Porac and Coren, 1975).

Individuals with abnormal binocular vision have strong ocular dominance and therefore may have difficulties using a monocular display. Persons with an eye deviation acquired in childhood, or with a so-called lazy eye (amblyopia), are included in this category. The incidence of eye

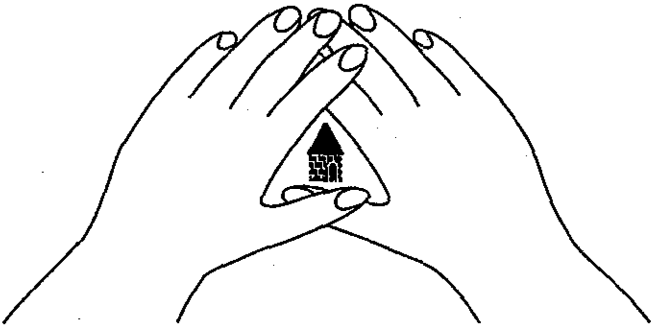


Figure 6.14 Sighting eye dominance can be easily determined. View a far target with both eyes open while looking through an opening formed between both hands as illustrated. Close each eye in turn. The eye that continues to see the target is the sighting-dominant eye.

deviation in the U.S. population has been estimated at 3–4 percent. The incidence of amblyopia in the U.S. population is estimated at 2–2.5 percent (Gitschlag and Scott, 1982), and there is a large overlap between these populations. It has been reported that people with eye deviation can use a monocular display, but they have more difficulties than people with normal binocular vision (Peli, 1990).

Placement of the monocular HMD. In most tasks there is no need to superimpose a display image on the ambient or outside scene. For such applications the display may be placed above (bioptic position) or below (bifocular position) the straight-ahead position of the eyes. When placing the display in one of these peripheral positions, the user has binocular vision when viewing the outside world and thus may avoid the problem of binocular rivalry. An observer's ability to see the world outside the display was found to be greatly superior in bifocular display. Occurrence of binocular rivalry was considerably lower and more easily controlled with the bifocular configuration than with a central position (Brooks, 1987; Hershberger, 1975; Katsuyama et al., 1989). The bifocular position may limit field of view for users wearing bifocal spectacles (see Sec. 6.4.1). The bioptic position may be preferred if the user is mobile (which is generally unsafe and thus not recommended) (Peli, 1997a). Peripheral positioning of the display may also permit comfortable use by people with abnormal binocular vision.

6.3.3 Size perception

Perceived object size is determined by the combination of retinal image size and the perceived distance (Wetzel et al., 1996). Thus a toy car in one's hands and a real car on the road may span the same retinal image, but their size is perceived correctly because the observer correctly interprets their relative distance. With HMDs, the retinal image size is fixed by the display, but the distance to a displayed object may be improperly estimated, leading to inaccurate perception of size.

With monocular HMDs, the displayed image may appear to be projected on the surface seen with the other eye, and the observer will estimate the distance based on information from the wrong eye. Changing from a distant surface to a near one (such as looking at one's own hand) makes the image on the HMD screen appear nearer and smaller. This relationship is described by Emmert's law (Gregory, 1978; Yeh, 1993), and is linear (i.e., perceived size doubles with each doubling of the apparent distance). Peli (1990) reported that the magnitude of the effect on perceived size with monocular HMD depends on the contrast and texture of the surface seen with the other eye. For high-contrast surfaces, the full effect, as predicted by Emmert's law, is perceived.

However, if the surface seen the with other eye is a bland, low-contrast surface (such as a white wall), a relatively smaller change in perceived size takes place with change in distance. Presumably this is due to an inaccurate estimate of the projection distance.

The same phenomenon is seen during use of see-through displays. The perceived size of the displayed images changes with the distance of the surface on which the image appears to be projected. Here too, the contrast, texture, and detail of the outside surface affect the magnitude of the change.

In binocular stereo displays, the estimated image distance may be affected by the convergence of the eyes. This leads to a change in perceived size known by the acronym SILO (small in, large out). This is typically demonstrated by free fusion of two coins. If fusion of the two coins is achieved by crossing one's eyes, getting the left coin to fall on the fovea of the right eye and vice versa, the fused coin appears smaller. The reason for this misperception is that the convergence effort causes the observer to perceive the coin to be closer than it really is, and the small retinal image is interpreted to arise from a smaller-than-normal coin. If the coins are fused by diverging the eyes, the fused coin appears larger than normal because it is misperceived to be farther away. The same effects take place in a stereo display.

Morita and Hiruma (1996) and Nagata (1997) have shown that in a stereo display the perceived size of a target presented in cross-disparity (appearing in front of the screen) is larger than that of a similar target presented with no disparity when it is corrected in size for the effect of the different display distances. Similarly, targets presented in depth behind the screen appeared smaller than they should have.

When targets are generated in depth on a stereo display, target size is usually changed to match the expected change in retinal image size associated with the change in distance. The ratio of the size S_d of the right and left eye images on the display to the size S_v of the closer (or farther) virtual image can be calculated as

$$\frac{S_v}{S_d} = \frac{\text{IPD}}{\text{IPD} - d} \tag{6.3}$$

where d is the disparity on the screen in the same units as the IPD and is positive for crossed disparity. However, due to the convergence and accommodation conflict that occurs in this situation (just as it occurs in the simple coin demonstration), the observer's accommodation is somewhere between the screen and the calculated depth once a fixed value of accommodation demand is exceeded (Hiruma and Fukuda, 1993; Okuyama et al., 1996). Presumably, the observer's distance estimate, which is based in part on accommodation, is also between the two.

Since the computations used to determine image size assume an accurate distance estimation, the computed size overcorrects for the SILO effect, resulting in an inversion of the direction of the observed effect. Morita and Hiruma (1996) showed that the convergence of both eyes is about halfway between the screen and the simulated distance for large disparity. Yeh (1993) reported such deviations from size constancy to vary between individuals, some strictly equating retinal image and some accounting for perceived distance. Ellis et al. (1995) also reported changes in perceived distance to virtual objects to be affected by convergence. In particular, they demonstrated that the perceived distance to a virtual object displayed on a see-through display was affected by the convergence to the physical object on which the virtual object was superimposed.

A different phenomenon apparently occurs during dynamic changes in disparity. Mon-Williams (1997, personal communication) reported that if a target is continuously moving in depth due to changes in binocular disparities, but the target's physical size on the stereo display remains constant, no change in perceived size occurs, as would be predicted by Emmert's law. Changes in perceived size take place only when the stimuli stop moving.

Size constancy in depth. In addition to a perceived distance from the observer—which determines its size—a displayed 3 D object also has a dimension of its own in depth. The validity of the perceived size in the depth dimension is a more complicated issue. Displayed disparity must be scaled by perceived distance before a perception of linear depth can be obtained. This measure is important for telerobotics applications, where a pair of cameras would provide a stereo HMD user with images of objects to be manipulated with a remote robot. A complete discussion of this issue is beyond the scope of this chapter, but a good discussion can be found in a paper by Smith (1994).

6.4 Design Considerations

The vision science considerations just discussed should be included in making decisions and choices necessary in the design of an HMD system. The following sections will discuss a number of the parameters and the options to be considered during design, as well as bring examples from existing commercial systems.

6.4.1 Resolution and field of view

The field of view of a simple magnifier display system is determined by the size of the display screen and the focal distance of the lens used to magnify it. The nominal field of view in such a system (expressed in degrees of visual angle) is:

$$\alpha = 2 \arctan\left(\frac{m}{2F}\right) \tag{6.4}$$

where m is the dimension of the screen and F is the focal distance of the lens in the same units. The complete field of view is available only if the user is close enough to the lens to provide a complete view. If the lens diameter D is too small, or the distance of the eye from the lens L is too large such that $D/L < m/F$, then the entire scene is not visible and the actual field of view, α', is limited by the lens diameter:

$$\alpha' = 2 \arctan\left(\frac{D}{2L}\right) \tag{6.5}$$

A well-designed HMD should have both a large enough lens diameter and a small enough eye-to-lens distance (eye relief) to permit the whole screen to be visible.

The resolution of the visual system is about 1 minarc (20/20), corresponding to 60 pixels per degree of visual angle. For a typical 20° (horizontal field of view) display, this corresponds to 1200 horizontal pixels, much more than most current systems provide. In fact, a typical system now has only about half of that resolution. Since the system resolution is substantially worse than that of the visual system, the pixelated structure of the display is visible, and various optical tricks are implemented to reduce its visibility. The resolution of a display limits the practical field of view because the two are inversely related. Figure 6.15 shows the relationship for various numbers of pixels. It can be easily appreciated that with current display modules the field of view possible at a reasonable resolution is limited. Even the next generation of high-resolution HMD systems for entertainment will not provide a field of view larger than 44° (Matsui and Kawamura, 1995).

Bolas et al. (1995) determined that immersive viewing requires an 80° or greater field of view and resolution of at least 1 million pixels. Wells et al. (1990) investigated the effect of field size on performance in a gamelike activity and found benefits only up to 60°. Piantanida et al. (1992) studied search time for a target with and without distractors and found an increase in performance with increasing field size from 28 to 100°, while Padmos and Milders (1992) reported that a 50 × 40° field is adequate for takeoffs and landings in flight simulators and for lane changing in driving simulators. Sony tested a prototype HMD with a wide field of view and low-resolution displays and found that users became very tired. The difficulty their subjects reported may be a result of a need to monitor the whole field with eye movements

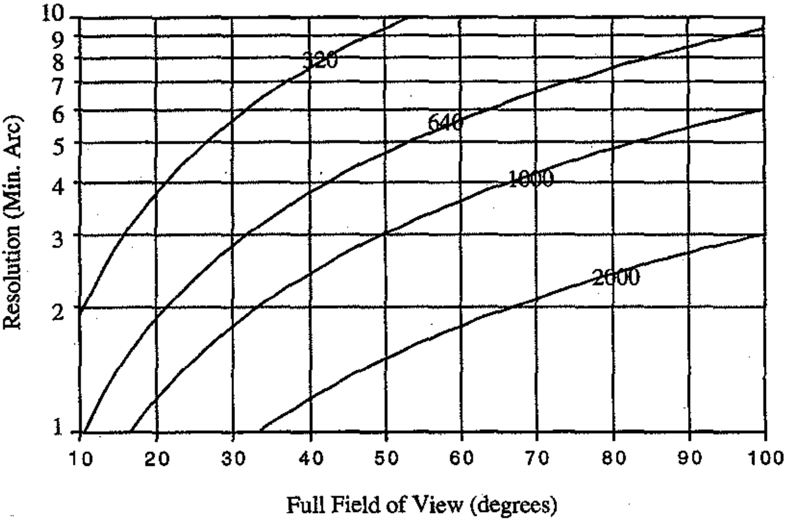


Figure 6.15 The relationship between the field of view and resolution for displays of varying number of horizontal pixels (insets) illustrates the limited capabilities of current technologies to meet both needs simultaneously (Adapted from Fischer, 1994).

instead of being able to use head movements to examine peripheral targets.

In normal free viewing, people use coordinated movements of eyes and head to scan scenes and track moving targets. When scanning a scene from one static target to another, the eyes move first, reaching the target in a very short time (~250 ms). The head begins to turn toward the target shortly thereafter. As the head turns, the eyes make slow compensatory movements so that the fovea remains on the target (Leigh and Zee, 1983). After about 1 s, the head is turned toward the target and the eyes are back close to the primary position of gaze (the straight-ahead position where it is comfortable). Uemura et al. (1980) reported that for horizontal movements of 10°, the head's final amplitude was 93 percent of the target eccentricity. For angles of more than 30°, the head movement is initiated before the eyes reach the target. Fixation can be as accurate with the head immobilized (Bizzi, 1981). If a target is moving smoothly, it is usually tracked by a combination of eye and head movements. Here too accurate tracking is possible without head movements (Bizzi, 1981). However, when the head is free to move, the eyes tend to stay in the primary position of gaze and most of the tracking is done by head movements. It is important to note that for self-directed saccades, the head begins to move before the eyes.

In an HMD it is impossible to move the head, so all gaze changes must be accomplished by eye movements, and continuous fixation at or near the edge of the screen may be required in some applications. Maintaining such fixation without head movement is likely to be very uncomfortable and may cause asthenopic symptoms. The problem should be larger with a larger field of view. With HMDs, consideration of eye movements would suggest limiting the field to about 30° (Davis, 1997).

As discussed in the next section, some HMD systems are designed to be used with spectacle correction. Systems designs of computer terminals may incorporate a short focal distance, which may require older users to read the screen through the bifocal segments of their spectacles. This limits the field of view, and may limit the practical field of view to 20 or 22° horizontally.

The problem is more severe with progressive addition lenses. According to Wittenberg and Borish (1990), the width of the reading area (defined as a range with less than 0.50 diopter cylinder of error) is small. If centered on the screen, the width of the reading area at the top of a 20° screen will be only 6–9°. This suggests that serious consideration should be given to field of view design for systems to be used by persons over 45 years of age.

6.4.2 Focal position

Focal position is the distance between the user and the display screen. A fixed focal distance represents the simplest design and manufacturing option. It also offers advantages in the stability and reliability of the final product. The fixed focal display system cannot be misadjusted by the untrained user, nor can it be used with the improper adjustment. The fixed focal system necessarily requires that users provide their own refractive correction (spectacles or contact lenses). Therefore, the design should permit sufficient eye-to-lens distance (eye relief) to allow comfortable use of the display with spectacles.

The requirement for eye relief of about 25 mm (sufficient to allow spectacle use) is not simple to meet. Field of view and the diameter of the optical elements needed to achieve a given eye relief interact. To maintain a constant field of view with a fixed eye relief requires that the diameter of the lens increase proportionately. This may increase both the cost and weight of the display. Alternately, providing adjustable focus to permit use without spectacles may result in even higher cost and weight.

If a fixed focal system is to be used, the distance of the virtual screen must be selected. As explained above, an image distance reduces the difficulties one may encounter with matching the convergence demand to the accomodation demand and also reduces the effect of user IPD on the convergence demand. To meet these considerations, a distance of more than 1 m is preferred. Most systems on the market with fixed focus have been designed with such larger focal distances (e.g., Virtual I/O ≈ 4 m; Optics 1 ≈ 6 m).

A shorter distance (1 m or less) takes into account the user's tendency to accommodate excessively when using an optical instrument. A shorter focal distance has usually been incorporated into adjustable focal system designs (e.g., Nintendo's Virtual Boy, Sony's Visortron). The Sony Visortron was first designed with a 60-cm image distance, but following preliminary tests the design was modified to incorporate a 1.2-m image distance. The Edinburgh Virtual Environment Laboratory report pointed out that many early HMD systems were designed with an image distance of 50 cm, but later designs included larger image distances (Wann et al., 1993). Consideration should also be given to whether the system is used in a see-through or opaque configuration. In a see-through design, the user would optimally have both the displayed image and the outside view at the same focal distance to enable clear visibility of both simultaneously. Such considerations are also important to the design of monocular HMDs.

Most systems on the market are designed with only a limited range of focus adjustment. These systems require that the necessary spectacle or contact lens refractive correction be in place. Although the focus range of some systems (e.g., The Private Eye) can be extended to permit use without spectacles, this is undesirable for a binocular display because of the potential interaction between focal point and convergence distance. Indeed, the Nintendo Virtual Boy, which uses two Private Eye-type displays, permits a much smaller range of focus and is designed for use with spectacle correction. Sony's later Visortron prototype permitted adjustment over a wide range of refractive correction, but it was found that some users misadjusted the focal distance, resulting in the wrong convergence setting (NikkeiElectronics, 1993). Consequently, the Glasstron (marketed in Japan only) is designed with a fixed focal distance. Hiruma and Fukuda (1993) studied the decoupling of the convergence and accommodation in stereo displays with different focal distances. Since they found that decoupling occurred at the same disparity level (in degrees) irrespective of the distance, they recommended a large viewing distance to reduce the effects of decoupling.

6.4.3 Convergence

A fixed convergence setting at the same distance as the virtual image is the option selected by most manufacturers (e.g., Optics 1 and Sony). As discussed previously, the convergence can be achieved in a number of optically equivalent ways.

Adjustable convergence has been implemented in a number of systems, and may be needed to compensate for the different convergence angle associated with a change in user's IPD. Although the effect is very small for systems with large focal distances, some correction may be needed for systems with shorter distances. The Nintendo Virtual Boy appears to have just such an adjustment, where a change in the system IPD changes the convergence slightly as well. Such adjustment is easier to implement in a convergence system [Fig. 6.4(*b*)] such as the Virtual Boy.

Another reason to provide adjustable convergence is that it is needed for a system with adjustable focal distance. As the focal distance is varied, the convergence demand should be varied as well to maintain the natural relation between the two. Such a system was proposed for the Sony Visortron (Onishi et al., 1994), but it is not clear if it was ever implemented in a commercial product. The system illustrated in Fig. 6.16 provides a very simple and elegant solution for the problem. It is based on the design option depicted in Fig. 6.4(*c*), but it uses a mechanical connection to covary the convergence appropriately with the changes in the focal distance. Peli (1995) offered a minor correction to the original design (Onishi et al., 1994) by setting the point toward which the two tracks converge on the line connecting the two centers of rotation of the eyes and not the line connecting the system's lenses as

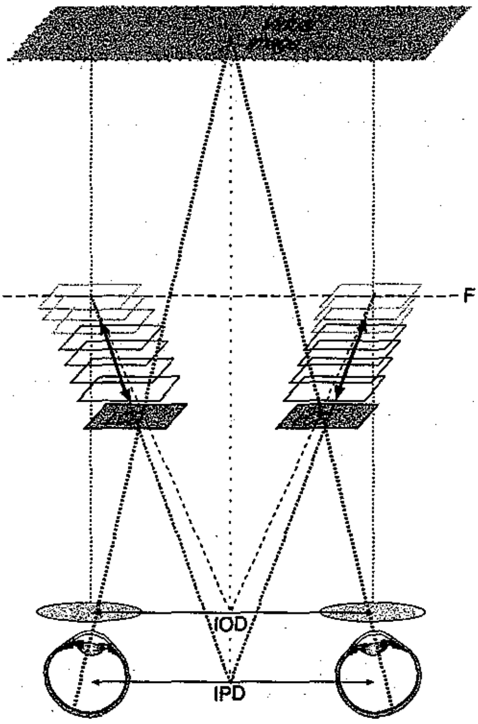


Figure 6.16 Schematic of the mechanical coupling of focus and convergence in Sony's Visortron permitting automatic adjustment of convergence with change in accommodation demand. (Adapted from Onishi et al., 1994.) Note the change of the reference line from the original—connecting the display lenses—to the line connecting eye's centers of rotation.

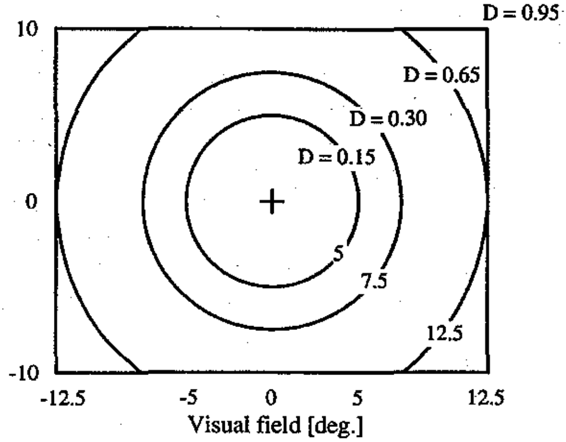


Figure 6.17 Typical field curvature for HMD optics. Each circle with a given eccentricity in degrees illustrates the deviation from nominal focal power at the center. The values given are the average of the sagittal and transverse power values. Note that the corner of the screen in this case is about 1 D away from the focal distance of the center.

Figure 6.17 illustrates the level of field curvature in a typical design. In such a system, more accommodation is required at the periphery of the field than in the center. While designing the system with minimal field curvature is preferable, knowing what can be tolerated in various systems simplifies the design. The effect of field curvature is different for different HMD designs. In a monocular HMD, the only concern is the user's ability to comfortably view the full field without blur. Katz and Zikos (1994) found that for frequently used optical stand magnifiers, field curvatures of up to 2 D are common. They further noted that this range of curvature presents little difficulty for young, accommodating users. If older, presbyopic users are anticipated, field curvature should be limited to about 1 D. The amount of field curvature acceptable in any display is related to the intended use. For instance, displays used for watching movies may be acceptable with a higher level of field curvature than displays intended for use with a laptop computer. Computer use requires sharp imagery to the edges and corners, while in movies, most of the action takes place at the center of the screen and sharp details are rarely presented near the edge.

Field curvature disparity. If the user's IPD does not match the IOD of the system, both eyes will be looking at the screen through off-center portions of the lenses, resulting in asymmetrical field curvatures. This asymmetry leads to *anisoaccommodative demand,* where one eye needs in the original design. This design should be considered appropriate only if the user's IPD is similar to the system's IPD and if the user is corrected properly for distance vision with spectacles or contact lenses. If the user adjusts the focus to correct some refractive error, the convergence distance should not be changed. (The correction in this case is applied to the user's eye and not to the image distances). For this reason, the design should be used only with systems that work with spectacle correction and have limited focal adjustment range.

In view of these limitations, it appears that the fixed convergence solution is probably the most attractive, even for systems with adjustable focus and/or IPD.

6.4.4 IOD

The question of IPD or IOD adjustment has been addressed in full earlier in this chapter. Many systems provide IOD adjustment to enable use by people with different IPDs. The importance of adjustment is not the prismatic effect that can result from a mismatch of user and system IPD. Rather, IOD adjustment is necessary because of the limitations imposed by the exit pupil. With a small exit pupil, a user with an IPD very different from that of the system will not be able to view both screens at the same time (de Wit and Beek, 1997). Such adjustment is needed with the Nintendo Virtual Boy, and software is provided to help the user adjust the system's IOD to the position permitting a full view of both screens. Systems with wide exit pupils, such as the Virtual I-O i-glasses, can be viewed without adjustment by almost all users.

There are some secondary considerations for the determination of fixed IOD separations. For example, the prismatic effects in HMD are equivalent to the effect of a negative lens. For users with wider IPDs, the prismatic effect increases convergence demand (BO effect). For users with narrower IPDs, a divergence demand is induced (BI effect). Since it is easier to respond to a convergence demand than to a divergence demand, this suggests a preference for smaller system IOD. Changes in vertical vergence demand also occur when the user's IPD does not match the system's IOD. The changes are fairly small even at the corners (0.03 Δ for the field curvature shown in Fig. 6.17; see explanation below) and thus are easily compensated. Other issues are discussed in the next section.

6.4.5 Field curvature

In most systems, flat-field optics are not used to image the display. As a result, a flat display is imaged on a curved surface. This requires a change in accommodation as the user's gaze moves across the screen.

to accommodate more than the other. When the user's IPD is wider than system's IOD, the direction of the differential in accommodative demand mirrors the demands that occur under natural viewing conditions when looking at a target close to the face and closer to one eye. About 0.5 D of difference can exist in a system, as shown in Fig. 6.17. As shown in Fig. 6.18, a similar level of unequal accommodative demand may be present in free viewing, implying that the visual system can function with this difference. If the user's IPD is smaller than system's IOD, however, the accommodation demand is higher on the side opposite the direction of gaze. This is opposite to the natural situation and consequently may be harder to adapt to. To minimize the effect of field curvature disparity, it is better to design toward the smaller IPD.

6.4.6 Multiple accommodation stimuli in see-through devices

A special accommodative demand is faced by users of see-through devices. Real objects appear at varying distances, while the images on the display are at a fixed optical distance. Conflict between the two will cause one or the other to be blurred.

Norman and Ehrlich (1986) examined distance target detection and recognition performance with a see-through system while varying the optical distance of the near virtual image. They found that the focal distance of the virtual images affected performance on the distant target task. A closer virtual image (0.5 m) significantly reduced detection and recognition of distant targets relative to a farther (2-m) virtual image distance. Norman and Ehrlich also found that individual subjects' resting positions of accommodation were correlated with the reduction in performance under this conflict situation.

Schor (1995) proposed a number of approaches that could be implemented to help in these situations. The first and most practical approach

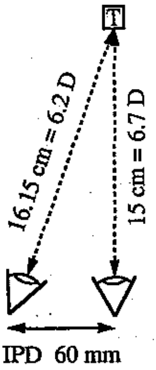


Figure 6.18 Accommodation demand disparity of 0.5 D is illustrated for the natural condition of viewing an object aligned with the right eye at a distance of 15 cm.

is to make judicious use of the depth of focus (DOF), which is larger with low-resolution systems. For example, in a driving simulator with real car controls and a virtual road, placing the virtual plane 1 DOF from the farthest real object may enable both the simulated road and the car control to be seen clearly simultaneously.

Schor's other suggestions involve more complex designs. For example, pinhole optics increase DOF, but reduce the amount of light reaching the retina, and maxwellian view (where the light source is imaged at the observer's pupil) is therefore needed to maintain image brightness. Such design is typically too complex, heavy, and expensive for most applications. In a recent study de Wit and Beek (1997) reported that the use of a small exit pupil in an HMD is possible only if eye tracking is used to shift the exit pupil following eye movements. Without such tracking, only a very small field of view will be accessible.

Monovision is the optometric name for the use of one eye for near viewing and the other for distance viewing. Unequal focal distance could be intentionally induced for both images in the display, thus increasing the range of clear vision for see-through objects. The monovision method is known to work as a contact lens correction for some presbyopes. However, it is not known if it works with prepresbyopes who may be able to respond with unequal accommodation to the unequal demand.

The chromatic "bifocal" approach makes use of the eyes' longitudinal chromatic aberration (up to 2 D). Assuming that near objects are usually found in the lower field, red images could be used for the lower field and blue images for the upper field. This may not be useful in many of the service and maintenance applications envisioned with see-through HMD. In these situations, the near real objects may be found in the upper field just as often as in the lower field. A simpler approach would place a bifocal lens segment in the lower portion of the see-through window, bringing near real objects to the same focal distance as the images seen on the display.

6.5 Tolerances for Quality Control

Once a design approach has been established and an HMD system is to be constructed, the question of quality control and standards quickly follows. No standard exists as yet, and it is probably premature to try to establish one before more is known about the consequences of various parameter settings. In the meantime, manufacturers need some guidance. This section tries to derive some preliminary guidelines from what is known in other, related areas. The relevant information was derived from various sources about displays, binocular optical devices, and optometric standards and practices for the construction of spectacles.

The International Standard (ISO, 1992) specifies the requirements for desktop workstation displays used for presenting text and other alphanumeric information. It specifically excludes other display applications [e.g., computer-aided drafting (CAD)]. Thus, it is not directly transferable to issues of HMDs. Nevertheless, we can use it to try to learn what kinds of requirements were considered to assure performance and comfort when viewing such displays. Some of these considerations may be directly applicable to the HMD situation, while others can only serve as general pointers for issues that need consideration.

The standard specifies that "A good work system should meet the needs of the individual. In a specific situation this can be accomplished by custom design or by providing appropriate adjustability." This general rule should be considered in the design of HMD and may involve many details as discussed earlier. Adjustability has its limitations, since a system that can be easily adjusted can also be easily misadjusted. As Morse et al. (1994) showed, even highly trained and sophisticated users can easily misadjust their HMDs, although with minimal training the misadjustment was reduced to acceptable levels. The current trend is toward a broadly adjustable system that can meet most users' needs with minimal or one-time adjustment.

A viewing distance of no less than 400 mm was recommended in the standard for desktop displays. This lower bound probably applies for HMDs as well, although for binocular systems a much larger image distance is recommended (see earlier discussion). For example, the Virtual I-O i-glasses have an image distance of 4 m.

A number of tolerances specified by the ISO for desktop displays may be used as initial guidelines for setting the requirements for HMD. However, differences in image type and intended use should be considered before any of these are adopted for HMDs. For example, raster modulation not to exceed a contrast of 0.4 was recommended for CRT displays. The requirements for modern flat-panel displays need to be specified in terms of pixel boundary size. Clearly a contrast of 0.4 represents a very visible raster structure. Alternately, some of the ISO tolerances do apply to HMDs. For example, the recommendations for luminance uniformity are: (*1*) the average luminance difference from the center to the edge shall not exceed 1.7:1; (*2*) the variation of nearby pixels shall not exceed 1.5:1; and (*3*) the image shall be free of flicker to at least 90 percent of the user population. These recommendations probably apply to HMDs just as they do for desktop displays.

Since the HMD is an optical device worn on the face in front of both eyes, it could be treated as a type of spectacles. ANSI Z80.1-1972 is the American standard for spectacle manufacturing tolerances. This standard could be applied to determine the requirements for HMDs, though it may be too stringent since spectacles are worn continuously while HMD use is intermittent and lasts for (relatively) short periods at a time. Nevertheless, some guidance can be derived from this standard as well.

Self (1986) reviewed the available literature for tolerances for binocular HMDs. Although he found sources that addressed such tolerances (mostly in military reports), he noted that in most cases the recommendations were given without any reference to the way they were derived. In the few cases where such information was provided, it was based on testing of very few subjects. Furthermore, much of the data was derived from standards developed for optical field binoculars that are not necessarily transferable to HMDs. In the following discussion I have referred to Self's sources where appropriate. Table 6.2 gives the various tolerances cited by Self, as well as my own preliminary recommendations discussed in more detail later in this chapter.

6.5.1 Vertical alignment

The Z80 ANSI standard for vertical misalignment of spectacles is 0.25 Δ = 8.6 arcmin. This standard is appropriate for constant use (e.g., distance spectacles). Similar levels of tolerance (5–10 arcmin) were recommended by Farrell and Booth (1984) and by Jacobs (1943) (8 arcmin).

TABLE 6.2 Tolerance Limits for Binocular Instruments Cited in Technical Literature

Author/source	Vertical misalignment	Convergence error	Divergence error	Magnification difference	Rotation (cyclotation)
MIL-STD 1472C (1981)				<5%	
Gold and Hyman (1970)	0.1 Δ	0.25 Δ	0.1 Δ		Keep to a minimum
Gold (1971)	0.1 Δ	0.25 Δ	0.1 Δ		
Genco (1983)		0.25 Δ	0.13 Δ		
Jacobs (1943)	~0.25 Δ	0.66 Δ	~0.2 Δ		
Farrell and Booth (1984)	~0.34 Δ	~4.7 Δ	0	<0.8% (40° field)	<30 arcmin (40° field)
NRC Vision Cmt. (1946)	0.4 Δ	0.8 Δ	0.4 Δ		
MIL-HDBK-141 (1962)	0.5 Δ			<2% (<0.5%)	
Johnson (1948)	1 Δ	4 Δ	2 Δ		Cannot be tolerated
Peli (This chapter)	0.75 Δ	1 Δ	1 Δ	<1%	<6% of field diameter

Adapted from Self (1986).

Larger tolerances of 17 and 34 arcmin, respectively, were recommended by MIL-HDBK-141 (1962) and Johnson (1948) for binoculars, which are used much more sparingly than HMDs. If these tolerances are valid, the tolerances for HMDs should fall within this range.

The amount of time spent using HMDs is more like that of reading with bifocals: intermittent, but for longer periods of time than binoculars are used. For bifocals, Midler and Rubin (1991) recommend correcting only errors larger than 1.5–2 Δ of vertical misalignment, and those errors need only be partially corrected (by 0.5–0.75 percent of the error). HMDs should stay within a tighter tolerance because a person wearing bifocals with such vertical deviation has time to get used to the deviation and adapt to it. A value of 0.75 Δ therefore seems appropriate.

Sony found that a vertical misalignment of peripheral targets of as little as 0.25° caused discomfort, and misalignments of more than 0.5° caused diplopia (S. Onishi, 1996, personal communication). However, only the peripheral targets were misaligned (competing with a binocularly fused fixation target and the aligned screen borders). Thus these results do not directly apply to the case of LCD screen manufacturing misalignment.

Since the vertical alignment is probably the most important tolerance, it might be wise to include software to enable the user to confirm that the HMD has not been knocked out of alignment. Figure 6.19 shows such vertical alignment targets. For these targets to work, a


Vertical alignment targets

Left Eye View

Right Eye View


Binocular view of targets by user with no phoria in vertically aligned HMD

Binocular view of target in vertically misaligned device or by phoric user

Figure 6.19 Software targets to be used for checking and possibly correcting vertical misalignment of the screens (phoria measurement targets). Note the small break in the middle of the vertical line.

black screen with no frame visible is needed. This is not practical with current liquid crystal display (LCD) devices due to light leakage, but can be used with displays that are completely black when off (e.g., LED-based displays).

Shift in vertical alignment as a result of direction of gaze. When the user's IPD does not match the system's IOD, changes in vertical prismatic effects can occur for different positions of gaze. These changes in vertical binocular image disparity may appear to be a problem, but the visual system is familiar with such changes in natural viewing and can compensate for them quite easily (Ygge and Zee, 1995). When looking at a target that is closer to one eye, the difference in image size in the two eyes leads to vertical misalignment of the targets. For a 20° vertical target there can be as much as 2° of vertical misalignment when the target is held closer to one eye. When changing fixations between such targets, most of the misalignment is taken up by eye movements; only 10–20 percent of the difference is corrected by sensory fusion. Better tolerance for downward eye movements than for upward movements and some capacity to adapt within a few hours has been reported. The adaptation is disparity-driven, but the actual movement is preprogrammed. The effects take place during a saccadic shift that helps speed the vertical convergence, just as it does for horizontal vergence (Peli and McCormack, 1983).

6.5.2 Horizontal alignment

People have a much wider range of horizontal vergence eye movements than vertical vergence and more tolerance for horizontal than vertical misalignment. Yet the ANSI standard limits horizontal prismatic error to 0.5 Δ (17 arcmin) measured at the user's IPD. This very strict tolerance is designed for the constant use of spectacles, but it is easy to meet. (For HMDs with a fixed or adjustable IPD, the worst case due to wide or narrow IPD should be added up to the production misalignment.) Using the same considerations just presented regarding reading bifocals, we can probably relax it by a factor of 2, to about 1 Δ. Jones (1992) recommended 1 Δ on the basis of different considerations. Self (1986) cited a wide range of recommendations for tolerances, mostly derived from the alignment of field binoculars (see Table 6.2). It should be noted that a misalignment in binoculars also results in a different field of view.

6.5.3 Magnification difference

Aniseikonia—unequal image size between the eyes—represents a problem for binocular vision. Naturally occurring aniseikonia is usually the result of the difference in magnification of corrective lenses for persons with different refractive error in each eye (anisometropia). The clinical literature (e.g., Midler and Rubin, 1991) reports that aniseikonia may result in eyestrain and headache unless properly compensated. Aniseikonia of 1 percent or less is not considered a problem, whereas more than 5 percent is not compatible with binocular vision and usually results in diplopia or suppression. Aniseikonia of 1–5 percent typically causes discomfort symptoms for people with naturally occurring aniseikonia (Ogle, 1964). Based on clinical experience, aniseikonia should be limited to less than 1 percent. There are no data on the level of aniseikonia in HMDs that causes discomfort or difficulty in fusion.

Induced or acute aniseikonia of the same degree is very common both with lens implants and with contact lens correction after cataract surgery. Katsumi et al. (1992) report aniseikonia of more than 2 percent in 20 percent of pseudophakic patients. Such acute aniseikonia seems to be much less bothersome than naturally occurring aniseikonia (Crone and Leuridan, 1975).

Aniseikonia in HMDs can occur due to screen position differences between the two channels. It is important to remember that it is the retinal image size (in degrees) that matters, not virtual image size (in centimeters). For example, a +30-D lens system designed for a 2-m image distance is shown in Fig. 6.20. An error of 0.3 mm in LCD position will send the image to 4 m, magnifying it by a factor of 2. The retinal image will be only 0.4 percent smaller (assuming a 20-mm lens to eye distance), which is not expected to cause any problem. It may be possible to use software targets to test for such aniseikonia (McCormack et al., 1992) in the HMD. This is best done in quality control and not by the user.

Meridional aniseikonia occurs when magnification differences between the eyes are different in different meridia (e.g., more difference

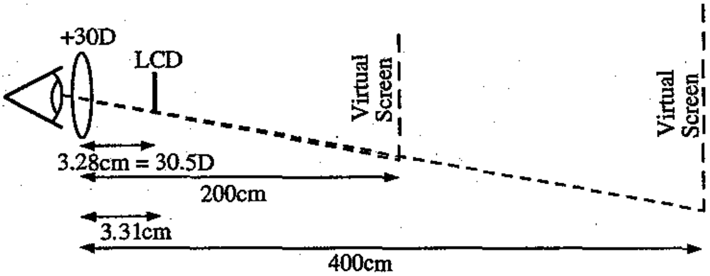


Figure 6.20 The difference in retinal image size due to differences in lens-to-LCD distance in the two channels. Although the virtual image distance and size is greatly affected by a small (0.3-mm) error, the retinal image size is only slightly affected.

for horizontal than vertical). Such meridional aniseikonia is not likely to occur due to lens or screen position error, but it may be found in scanning systems such as the Private Eye or CRT-based systems. Meridional aniseikonia is more difficult for the users to sustain and causes more discomfort symptoms. Meridional aniseikonia also results in an apparent tilt of the image plane. Such tilt may be bothersome in some applications and dangerous in others (e.g., remote control operations).

6.5.4 Focus difference

A slight error in the distance of the screen to the lens, as discussed previously, causes only a small change in retinal image size but can cause a large change in accommodative demand (e.g., 1.7 D for a 1-mm change in a 40-D system). A difference in the accommodative demands between the two channels presents a problem to the visual system. Under ideal conditions, it has been demonstrated that people can respond to anisoaccommodative stimuli with unequal response. The average anisoaccommodative response was found to be 1.0 D (Marran and Schor, 1994). However, it is not clear how long such a response can be maintained, and it is certainly uncomfortable. At the moment, there are no clear guidelines on the level of focus difference that is safe or comfortable. The 0.25-D difference derived from the ophthalmic standard for refractive error correction refers to the acceptable blur limit and does not necessarily apply to this situation, although it is likely that error as small as this will be acceptable.

6.5.5 Cyclotorsion

Rotation of one screen relative to the other is another possible outcome of production error. Fusion of the two rotated images requires cyclotosion of the user's eyes. Any asymmetry in the rotation between the screens should be represented as vertical misalignment. There are no standards in the ophthalmic industry for image rotation, since spectacles cannot cause such an effect (although slight image rotation can result from rotation of cylindrical lenses (Borish, 1970). The standard for the axis of rotation of cylindrical lens is probably specified because of blur. The ANSI standard requires less than 2° of axis rotation for cylindrical power above 1.12 D.

Fusion of rotated images and cyclotortional eye movements are possible over a surprisingly wide range. For a large field (50°), 40–70 percent of the rotational disparity is accomodated by cyclotorsional eye movements and the rest by sensory fusion (Sullivan and Kertesz, 1978). Fusional responses to rotational disparities as large as 10° have been demonstrated. The response is slow and there is initial diplopia reported before fusion for disparities of 5° or larger, while instantaneous fusion is perceived with 2° of disparity. Sullivan and Kertesz did not report how long fusion could be sustained without any symptoms or difficulties.

The threshold of cyclofusion was reported to be about 7 percent of the eccentricity of the target, expressed in degrees of visual angle (e.g., 3.5° for a 40° field) (Crone and Leuridan, 1975). For the 12.5° half-field of a typical HMD that threshold would be 52 minarc, corresponding to a misregistration of about 10 pixels at the edge. This tolerance may not be acceptable for constant, long-term use. If we apply the middle third of the comfort range used for horizontal vergence, we will get 3.5 pixels as the acceptable range of cyclofusion. Sony found that image rotation as large as 5° was possible without discomfort for low-frequency images and slightly smaller angles of rotation were possible for sharp images (Onishi, 1996, personal communication).

Human observers are able to respond to image rotation over a wide range. This flexibility must be a result of some previous exposure. As shown in Fig. 6.21, the observation of a vertical line on a slanted plane will cause such image rotation and will require cyclotorsional eye movements for fusion. Note that the effect is more complicated for images with horizontal details. However, experience with vertical features may prove sufficient to explain our ability to make the appropriate eye movements.

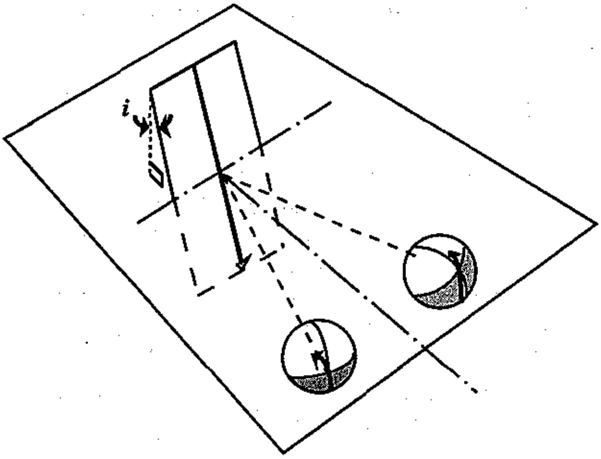


Figure 6.21 Image rotation difference between the eyes is actually very common in the real world. Whenever a line on an inclined (*i*, angle of incline) plane is viewed binocularly, its image is rotated on one retina relative to the other and requires rotational (also called cyclotorsional) eye movements. In the case of the incline direction illustrated here, excyclotorsion eye movements are needed.

6.6 Stereo Software Guidelines

Guidelines for software developers are no less important than those for the design and quality control of the hardware. This section discusses the underlying principles that should be used to develop guidelines for the disparity limits in software that promote longer, more comfortable use. The discussion is framed around the design of a typical computer game, but can be applied to any other application. In addition, although we are discussing HMDs in particular, most of the considerations apply, with little modification, to any other binocular stereoscopic display. To simplify the discussion and the notation, we assume that all depth changes occur along the midline at eye level. In other directions, disparity is reduced by the cosine of the angle.

6.6.1 Definitions

We define a background image or scene as one that is conceptually static but may actually be moving on the screen. Within the scene we recognize figures, or game characters, that are dynamic. The baseline depth is represented with no disparity. Image features presented at that depth are at the same distance as the virtual screen, which is defined by the focal distance of the display. Features presented in crossed disparity (i.e., the left eye's image is presented to the right of the right eye's image) appear in front, or closer than baseline. Features presented with uncrossed disparity appear behind the baseline or farther away. Specifically, if a feature is located at coordinates (X_L, Y) on the left eye's screen and at coordinate (X_R, Y) on the right eye's screen (Fig. 6.22), then the feature is presented in crossed disparity if

$$X_L - X_R > 0 \tag{6.6}$$

and in uncrossed disparity if

$$X_L - X_R < 0 \tag{6.7}$$

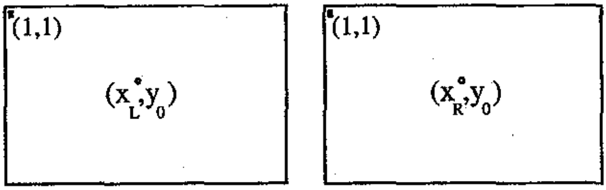


Figure 6.22 The definitions of pixels variables used in the software guideline.

6.6.2 Absolute bounds on disparity

Ninety-eight percent of the population have stereo acuity thresholds of 2 minarc or less. In common (¼ VGA) displays with 320 pixels spanning 20°, a single pixel is 3.75 minarc. For a full VGA display, a single pixel is just under 2 minarc. All users with normal stereo vision will be able to see disparities as small as one pixel. Yeh and Silverstein (1982) reported a mean error of 2.2 minarc in judging depth using disparity. This also suggests that, except for very unusual applications, there is no need to try to present disparities of subpixel magnitude. Such disparities can be displayed using gray scale and are implemented, for example, in the VisionWorks system by Vision Research Graphics, Durham, NH.

Since it is generally advisable to avoid depth beyond infinity, or divergence beyond parallel eyes, uncrossed disparity should always be less than the convergence angle of the baseline frame. Assuming, for example, a user IPD of 60 mm and a virtual screen distance of 200 cm, the convergence angle of the baseline screen is 1.7°.

The upper bound on crossed disparity is determined by the user's ability to converge his or her eyes—called the near point of convergence—which is usually at 15 cm. Users should not be challenged to converge at a shorter distance for any length of time. For the same 20° display at 200 cm, this corresponds to a disparity of 22°, which cannot be presented on a typical display.

6.6.3 Bounds on disparity determined by Morgan's data

The range of disparities could be determined from the population norms on vergence test measurements. In this clinical test, the disparity between images is varied using a variable prism, while the accommodation stimuli remain the same. The results could be used to determine the range of disparities that could be presented and still permit single and clear binocular vision, though not necessarily comfortable long-term viewing.

To make such a calculation virtual screen distance has to be assumed. Population norms for clinical tests, such as Morgan's norms (Borish, 1970) are typically given for distances of 6 and 40 cm. The data for any other distance can be calculated using the graphical analysis chart (Fig. 6.3). For a distance of 1 m we get 5.1° for blur and 6.8° for break (i.e., loss of fusion, or double vision) for uncrossed disparity, and 8 and 11.5°, respectively, for crossed disparity. These numbers are very large. They represent conditions of break of binocular vision when applied once and therefore obviously should not be applied for continuous use. More reasonable values could be obtained by looking at the comfort zone.

6.6.4 Disparity bounds within the comfort zone

Percival's criterion for determining the comfort zone within the zone of single clear binocular vision (ZSCBV) is defined as the middle third of the ZSCBV's total width. Using Morgan's population norms we get 2° of uncrossed disparity and 2.3° of crossed disparity. For a screen distance of 1 m, this represents about half the perceived distance of the baseline frame for the extreme point of convergence.

It should be noted here that Morgan's norms and other similar values in the literature were obtained with gradual increases of disparity, similar to those represented by a game feature slowly moving in depth toward or away from the observer. In many cases, however, the changes in disparity imposed in a game or other software may be sudden. Abrupt changes also occur when the user changes fixation from one feature to another at a different disparity. Yeh and Silverstein (1982) measured the limits of fusion for such abrupt changes in a CRT stereo display. With a short display duration of 200 ms, thresholds of 27 and 24 minarc were found for crossed and uncrossed disparities, respectively. For longer exposures of 2 s, Yeh and Silverstein found that larger disparities could be fused using convergence eye movements of 4.93° (crossed) and 1.57° (uncrossed). These findings suggest that brief instances of disparity can work with smaller disparities than steady-state stimuli. This is the case only if the ability to achieve and maintain fusion for a short period is the criterion applied. In most cases we are more interested in what level of disparity is compatible with comfortable, longer-term viewing. Here the situation is probably reversed. Steady-state conditions within the comfort zone are probably acceptable over long periods, as this criterion was developed to address constant use of spectacles. Fast (a few seconds) intrusions beyond these disparity limits for big depth effects should not pose a problem for either comfort or safety. Even if the fusion limit is exceeded, and diplopia occurs briefly, the perception of depth is still possible and the apparent fleeting diplopia is not very bothersome.

Hiruma and Fukuda (1993) based their recommendation on the level of disparity they found to be accompanied by accommodative response. They found that for targets in front of the screen, crossed disparity of up to 9 percent of the screen width was acceptable (1.8° for a typical 20° screen). For uncrossed disparity, they recommended restricting the disparity to the distance between the pupils. Hiruma (1991) measured the accommodative response to disparity in stereoscopic displays, and found that despite the fact that accommodation *demand* was fixed at the screen, observers *responded* with accommodation to the convergence stimuli. The CA/C ratio of about 1.0 was maintained until the accommodation exceeded the depth of focus of the subjects' eyes, resulting in the saturation of the accommodation response and, consequently, blur. From various control experiments, Hiruma concluded that for a screen viewed at the standard observation distance (6 times the height of the display) the saturation limit was found when convergence disparity exceeded 9 percent of the display width (about 1.8° for a 20° display). This is in agreement with the values calculated from other considerations, as described earlier.

In a recent study (Peli, 1998), the comfort and visual function effects of playing a computer game on a desktop CRT were compared to playing the same game with the Virtual I-O i-glasses HMD in both bi-ocular and stereo modes. The game used (Ascent, by Gravity Inc., San Francisco, CA) had all the disparities within the comfort zone (see Fig. 1 in Peli, 1998). A small but statistically significant difference in comfort between the CRT and the stereo mode was found, but no difference was found between the stereo and bi-ocular modes of the HMD. Furthermore, no statistically significant differences were found among the three conditions for any of the visual functions tested. Many of the previous studies that did find changes in visual function did not report the magnitude of the disparities used and usually included a repeated tracking task over a long period of time (Inoue and Ohzu, 1990a; Iwasaki et al., 1994).

6.6.5 Range of disparity without vergence eye movements

Small levels of disparity do not necessarily trigger any vergence if the fusional demand is kept within Panum's area (the retinal area within which fusion of disparate targets is possible). In the fovea, Panum's area is about 15 minarc horizontally. This means that disparity of this magnitude could be used without eliciting vergence, thus avoiding stress from the decoupling of vergence and accommodation.

Higher values of disparity usually stimulate vergence eye movements unless the change is too brief to permit eye movements (~0.25 s). In such cases, depth with up to 2° of disparity may be perceived even though fusion does not take place and a double image is seen. Panum's area becomes larger for peripheral vision and for larger targets. Therefore, a large figure can easily have 30 minarc of disparity without stimulating vergence, especially if it moves in the peripheral area of the screen (away from the center of fixation).

In designing moving targets, it is important to provide an increase in size with looming (targets getting closer). Increases in size require less accommodative effort to keep details clear. This permits larger disparity to be uncompensated by convergence, which reduces the binocular stress of decoupling. This rule works well for crossed disparity only. For uncrossed disparity, we would expect the target to become smaller.

6.6.6 Eye tracking option

The range of disparity that can be fused (Nagata, 1996) and the range of disparity that is comfortable (Wöpking, 1995) depend on the appearance of the background scene. The ranges of disparity may be increased if the background, or out-of-fixation details, are low-pass filtered or blurred. One paper has proposed the blurring of background objects displayed at different depths (Omura et al., 1996) in addition to changing the focal distance of the fixated target to match its depth by disparity (Shiwa et al., 1996). A preliminary guideline for the level of blur needed can be derived from the results of Wöpking (1995). With a sharp image, disparities of up to 35 arcmin could be viewed comfortably. Disparities of 70 arcmin created an annoying sensation, and a large amount of blurring was needed to avoid eyestrain. All of this, of course, assumes that it is possible to predict which objects will be fixated by the user. It has been suggested that this is possible by online tracking of the user's eye position.

6.6.7 Alignment software

Software targets can be used to check the alignment of a device and to enable the user to adjust and correct misalignments. Wann et al. (1995) recommended using alignment targets embedded within a complex 3 D image. Their proposed targets were designed to measure fixation disparity (with central and peripheral locks). Eliminating the disparity by shifting the whole screen laterally is equivalent to measuring the associated phoria and correcting for it with prisms, a technique not recommended in clinical practice for horizontal disparities (although it is considered a proper approach to correcting vertical fixation disparity in symptomatic patients). The associated phoria may be large—a few prism diopters or a few degrees—and any screen shift to compensate for it will result in loss of the corresponding magnitude from the available field of view.

Similar targets could indicate to the user that the device is misaligned (e.g., focus or IOD is not correct). Alternatively, the misalignment may represent a fault in the device itself that would need repair or adjustment; or it could mean that the response of the user's binocular visual system is outside the norm and should be checked before further use of the device is attempted. The alignment target can be included in an alignment task that would be a prerequisite for playing the game. This would permit continuous game play only if alignment is within some predetermined level.

6.7 Product Liability

A number of publications have made dramatic reports about the looming possibility of lawsuits related to HMD use, especially in VR applications (Gross et al., 1995; Strauss, 1995). To a large extent the accounts in these reports were based on rumors regarding the outcomes of studies conducted by HMD manufacturers. Media reports also cited concerns about use causing mysterious LSD-type flashbacks as well as emotional and mental illness (Strauss, 1995). These terrible effects were considered by these newspaper accounts to bear the potential for a flood of liability litigation, but the published information in the scientific literature fails to support most of these claims and no lawsuits have been reported as of yet.

The concerns did affect the companies involved. Sega Corporation reportedly canceled its HMD game system after research conducted by SRI indicated that a significant number of users complained of significant side effects (Gross et al., 1995), including 40 percent who experienced cybersickness (Strauss, 1995). Sony's Visortron was first presented in 1991; the advanced prototype was introduced for limited application as a personal viewing device on first-class flights of Japan Air Lines. However, concerns regarding the device's possible side effects limited its use to 2 h (NikkeiElectronics, 1993). Even the much improved recent model, Glasstron, is not marketed in the United States yet, presumably because of concerns about unresolved issues regarding safety and comfort.

Wilson (1995) reviewed the possible side effects suggested or reported in the literature. He classified them as: (1) effects on visual system performance (e.g., reduced acuity or stereo vision, changes in phoria posture or fixation disparity); (2) strabismus; (3) subjective reports of visual discomfort (i.e., asthenopia); (4) physical discomfort (head, neck, or back); (5) disorientation, nausea, motion sickness, or simulation sickness; (6) lowered cognitive and psychomotor performance; and (7) long-term effects including hallucinations, flashbacks, and addiction. Wilson concluded that some of these effects were indeed found. Specifically, nausea and disorientation similar to motion sickness occur in some users during performance of some activities. The causes were speculated to be either tracking system lag or optical effects, and Wilson argued that the consequences appear no more serious than carsickness. Other effects result from known technical shortcomings of HMDs. Asthenopia presumably resulted from the mismatch between accommodation and convergence demands, which exist in all stereo systems and may occur in bi-ocular systems not properly fitted to individual users. No data were available on long-term consequences or on the length and magnitude of exposure that can cause asthenopia. Wilson attributed some of the effects to early-generation systems, which were typically heavy and thus led to physical discomfort in the back and neck. However, I have found postural discomfort with much lighter and better-fitting systems such as the i-glasses (Peli, 1998). Earlier-generation systems had a close focal distance, which has been blamed for some of the binocular vision symptoms reported.

Wilson (1995) also found that many of the serious effects reported in the media had no known supportive evidence. In particular, the reports on LSD-like experiences, presumably due to a permanently corrupted vestibular system response, were based on no supporting evidence.

6.8 Conclusions

With the current state of knowledge, it appears that there are some concerns about possible discomfort or cumulative harmful effects stemming from extensive use of HMD systems. However, the concerns expressed in the literature and the media clearly exceed any scientific evidence. Product liability is a legal issue more than a scientific issue. As such, it is likely to be affected by articles in trade magazines just as much as by scientific publications. Until much more information becomes available regarding the effects of HMD use, it appears to be most appropriate to test each system separately to determine for each design whether comfortable and safe use by the target population is achievable.

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