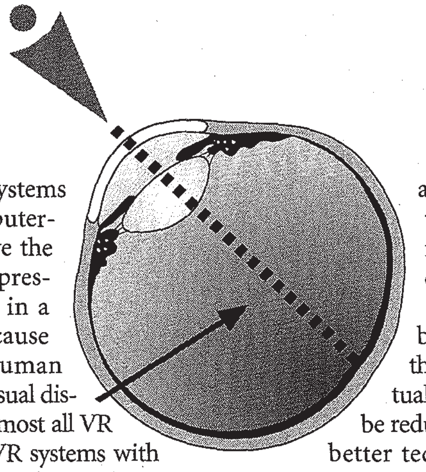
Real Vision & Virtual Reality

By Eli Peli

Snapshot: The effects of head-mounted displays on binocular vision are described.



Virtual reality (VR) systems are interactive computerized systems that give the user some sense of presence or immersion in a synthetic world. Because vision dominates human perception, it's not surprising that visual display systems play a central role in almost all VR systems, and most of us associate VR systems with head mounted displays (HMD). To enhance the sense of reality, many HMD systems are designed to provide stereoscopic depth cues and use head tracking to enable the virtual world to change in response to the users' movements.

If VR systems were successful in closely simulating reality, using them would be no more difficult than facing real life, which is tough enough. However, HMDs and other VR technologies cannot reproduce visual reality. The differences between the real world (for which the human visual system has had a few million years to adapt) and an HMD virtual world may require some adaptation. Some of these differences result in degradation of image quality, while others have been implicated as possible causes for discomfort and temporary visual changes. Concerns about possible harmful effects of using HMD systems are no different from those that accompanied the introduction of such technologies as television, computers, microwave ovens, and most recently, cellular phones.

There are 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 can be reduced or eliminated by proper designs and better technologies, while others appear to be inherent limitations of HMD which need to be considered by careful design of applications and software. This article reviews and discusses the current state of knowledge regarding HMD/visual system mismatches and points out their potential consequences for HMD users.

Head motion, vestibular effects, and image motion

Under normal viewing conditions, the vestibular ocular reflex (VOR) generates compensatory eye movements that counter the effects of head movement and 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. These eye movements are controlled in an open-loop mode, with residual error corrected by a visual tracking mechanism. This provides a stable reti-

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nal image of the world. The tracking mechanism also adapts the VOR response gain to changing situations.

The same vestibular mechanisms that serve to stabilize the retinal image in natural conditions may result in retinal slip and image degradation with an HMD. Because the HMD moves with the head, VOR eye movements that compensate for head motion, result in a moving retinal image. This causes apparent image motion and reduced clarity. HMDs used in VR systems frequently include head tracking capabilities that should compensate for these movements. However, in many devices, such compensation is not included or is very crude. Even with better head tracking, delays in the display update may result in the retinal image slipping and image jumpiness or blurring during motion.

Adaptation of the VOR to moderate changes, as those induced by eyeglass correction, is very rapid.[1] The eye, using an HMD, must completely eliminate the VOR gain to perceive it as stable. I am not aware of any study measuring the level and time course of VOR adaptation to HMD without head tracking, or of reports of image degradation in head tracking compensated systems.

Adaptation to unequal demands for the two eyes is almost impossible. The use of a monocular HMD presents such a situation. Image motion and text degradation in a monocular HMD (the Private Eye™—which displays an image that appears to float a few feet in front of the viewer's eyes) were noticeable only during acceleration and were more noticeable during active than passive motion. During constant-velocity phase, the display remained completely stable and legible.[2]

In military see-through helmet mounted display devices, the real world is seen simultaneously with the superimposed image. Obviously, no VOR adaptation for both stimuli is possible. It is not known which image would be stabilized by the visual system during motion with such devices. A see-through design HMD has been developed by Sony Inc.[3, 4] and by Virtual I-O Inc. The consumer devices, however, are designed to provide a see-through capability only when the video signal is muted. In this situation the high contrast image of the video signal will dominate when it is operated and the outside scene will dominate when the video is eliminated.

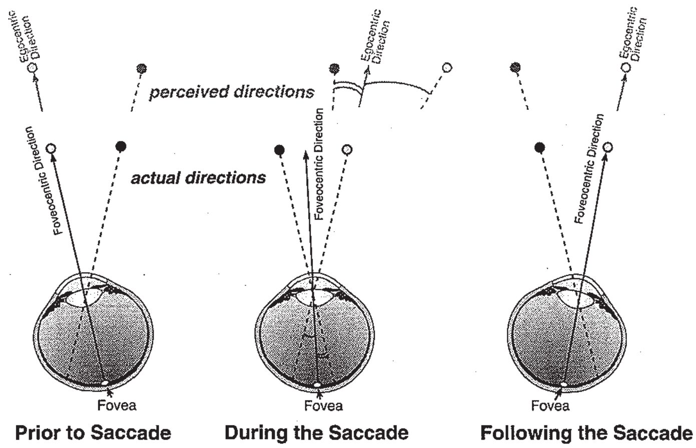

Figure 1. The appearance of an image jump during eye movements across an intermittent display. a) During a saccadic eye movement, the observer must shift the egocentric sense of direction (head-related coordination system) from the initial target to the destination. At the moment of change in egocentric 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 the target is flashed during the saccade. b) If one changes fixation between two targets and the targets are flashed during the saccade, they will become visible at a point in time where both projects on the retina away from the fovea and thus the destination target will be perceived beyond its actual position. c) Following the saccade, the veridical directions are restored.

In addition to their potential effects on image quality, conflicts between vestibular and visual inputs are considered common causes of motion sickness. Visual scene motion (indicating strong and fast self motion) without corresponding vestibular input, as is commonly the case in flight simulators, can result in motion sickness. Such illness was reported to occur in almost 50% of pilots tested on the first day of training, but the magnitude of illness decreased on subsequent days.[5]

It is surprising that an extensive literature review of HMD devices,[6] and a further computer literature search, resulted in no mention of image degradation due to motion. The same search found only one reference concerning motion sickness.[7] More recently a full issue of the *Journal Presence* (Vol. 1, No. 3, 1992) was dedicated to articles on simulator sickness. As noted by Piantanida[8] the articles "... were mainly limited to speculations on the simulator effects that will be seen in the general public with the emergence of VR systems." The paucity of reports on motion sickness may indicate that the plasticity of the visual system enables quick adaptation to such changes. None of the subjects evaluated with the monocular Private Eye™ display[2] reported any symptoms of motion sickness.

Eye movements and image motion

When the eye moves across an intermittently pulsating display such as the LED numerals used in digital alarm clocks, parts of the display occasionally appear to jump or move in concert with the eye movement. These apparent movements result from an interaction between the rapid eye movements (saccades) and the intermittent nature of the display. Similar effects have been reported with short persistence CRTs[9, 10] and other short persistence display devices.[11] The effects are particularly easy to note in non-persistence displays such as the LED based Private Eye.[2] If the displayed image consists of only two dots and saccades are made from one to another, an intermittent ghost image may be seen briefly just beyond the target (see Fig. 1). In normal viewing of continuously illuminated targets, such occurrences are prevented by the phenomenon called saccadic suppression.[12] When image jumpiness is very apparent, it may affect the control of eye movement.[10,13] It has been hypothesized that these effects may account for the frequent complaints of visual discomfort associated with reading from electronic displays.

In binocular HMDs, the two display images are visually fused, and if their illumination timing is out of phase, the integration of images for both eyes may have the effect of visual persistence. Such a design may reduce or eliminate the perception of image jumps.[14]

Effects of low update rates

The image degradation effects associated with saccadic eye movements have a counterpart in the pursuit eye movements that occur while tracking smoothly moving targets. However, this effect occurs only with low update rates. Display devices are usually refreshed at a rate of 60 Hz (or 30 Hz interlaced). In the case of static imagery this is the only rate that matters. When motion video is presented, the picture update rate is also 60 Hz. In VR systems the updated images have to be calculated in response to the user's movement. This could cause an update rate slower than the 60 Hz refresh rate.

When the update rate is half the refresh rate, each frame can be presented twice. When an image of a feature smoothly moves across such a display system and the movement is tracked, the observer will see two moving features.[14, 15] The tracking visual system analyzes the motion and predicts the anticipated position of the feature along the same trajectory. When the feature is displayed at its previous position on the repeated frame, it is perceived as a second feature. If the update rate is one-third the refresh rate, three features are seen. The multiple images also have lower contrast. This approach was applied by Optelec Inc. in their Bright Eye™ low vision head mounted electronic magnifier.

If the refresh rate is lowered to match the update rate, the double feature artifact disappears, but a disturbing flicker becomes noticeable. Therefore, this method is rarely used. With a binocular display, every updated frame can be presented once to the right eye display and once to the left. This technique, which is a hybrid of the two methods described above, eliminates the doubling artifact,[14] but a flicker remains. Due to the integration of both eyes' images, the flicker is less noticeable.

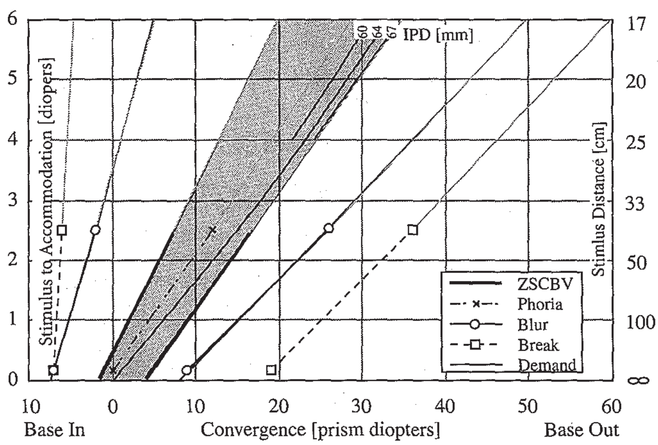

Figure 2. The graphic representation of accommodation and convergence demands and the zones of single clear binocular vision (ZSCBV) in an average person. A demand line is associated with the person's IPD. The ZSCBV and the comfort zone representing the middle third of the zone are illustrated. Operating outside of the comfort zone may cause eye strain and/or headaches. The range outside the ZSCBV is the zone where single vision is maintained by changes in accommodation resulting in blurred vision.

Convergence and accommodation

When operating in the real world the observer's eyes move between targets at different distances. For each target, the eye's lens is focused to obtain a clear image, and the eyes converge on the target. The distance of the target determines the focusing or accommodation *demand* in diopters. The convergence *demand* is measured in degrees or prism diopters and is determined by both the distance to the target and the distance between the eyes (interpupillary distance or IPD). A prism diopter is the angle subtended by one centimeter from a distance of one meter (also called meter angle).

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 (see Fig. 2). For an observer to see a target clearly and singly with both eyes, both demands should be met. If for some reason the response difference from the demand is larger than the tolerance permitted, either a blurred image or double vision will result.

To simultaneously satisfy these joint convergence and accommodation demands, the visual system has evolved a coupled control system for both mechanisms. When the eyes accommodate, they converge even without convergence stimuli (*i.e.*, when one eye is covered). When both eyes are open, a small correction in convergence may be needed for perfect alignment. The difference between this open loop convergence angle and the convergence demand is called heterophoria.

Accommodation and convergence demand for an observer can be changed by using lenses or prisms. Placing convex lenses in front of the eyes reduces accommodation demand, while convergence demand is unchanged. Similarly, convergence demand can be changed using prisms. A base-out prism (prism base toward the ear) increases the convergence demand, while a base-in prism reduces it, moving the demand line right and left, respectively. When tested under these unnatural conditions, the visual system demonstrates some flexibility. Using such prisms and lenses, the range over which the demand can be changed while the observer is able to maintain single clear binocular vision can be mapped (see Fig. 2). Outside the zone of single clear binocular vision (ZSCBV), the observer will have blurred or double vision. If an observer operates for any length of time close to the edge of his ZSCBV,

Glossary

Accommodation: The focusing of the eye's lens to create a clear image, on the retina, of objects at different distances.

Convergence: The turning-in of both eyes to bring the image of a near object onto corresponding points of each retina.

Inter-pupillary distance (IPD): The distance between the two pupils. Serves as an estimate of the distance between the centers of rotation of both eyes.

Zone of Single Clear Binocular Vision (ZSCBV): An area in the accommodation versus convergence plan. Outside this zone, vision is either blurred or doubled.

he is likely to feel eye strain, develop headaches, and even lose temporarily his clear or single vision. The middle third of the zone is referred to as the zone of comfortable single clear binocular vision.

Alignment of convergence and accommodation in HMD

In HMD virtual images of the screens are created. The virtual images' distance sets the accommodative demand for the user. The physical convergence of the two optical channels sets the convergence demand. Since the visual system would be most comfortable with the natural relationships that exist for real-world targets, such correspondence is a basic consideration in the design of VR systems. Achieving it for all observers is theoretically possible only for one point on the screens and without stereo-depth variations in the images. Even for this limited case, design considerations must account for different users' capabilities in adjusting the system. Thus, it is important to consider the magnitude and consequence of deviating from the natural relationship.

What happens if the convergence demand is not matched to the accommodative demand (*e.g.*, if one places a base out prism in front of one eye)? With small misalignment, prism adaptation[16] will result in a clear image with little eye strain. If adaptation is incomplete, eye strain may persist. For a person with an intact binocular system, adaptation reverts to baseline after a short period away from the display. However, it was suggested that some users with borderline functioning visual systems may have various symptoms such as blur, eye strain, or double vision.[17] Double vision for more than a fraction of a second may be unpleasant and disorienting. It should be emphasized that there are no reports of double vision persisting after using a HMD, although short-term blur, eye strain, and headaches were reported in one study,[18] in which fixed IPD, convergence, and short focus conditions were used.

Various manufacturers have taken different approaches to adjusting the convergence and accommodative demands in HMD. One difficulty in finding a simple solution rests with the fact that the demand line depends on the observer's IPD. In principle, a different optical channels convergence is needed for the same focus setting for users with differing

IPDs. If the image distance is large (1 m), the demand difference is fairly small (see Fig. 2).

The simplest approach, therefore, is to set the focus at a fixed level and assume a normal user's IPD (*i.e.*, 65 mm). The required convergence can then be calculated and fixed as well. An observer with an IPD smaller than the HMD will look through the inner parts of both lenses. This situation is equivalent to having an additional base-out prism in front of the eyes. The prismatic effect of the lenses has been identified in the literature as a major problem for HMD use.[17, 19] The magnitude of the prismatic effect, however, has not been discussed. In fact, it is very small. In spectacle fabrication, Prentice's rule is applied, in which for every 1 diopter of lens power and for every 1 mm of decentration we get 0.1 prism diopters of deviation. HMDs usually use very strong lenses. However, the prismatic effect in HMDs can be shown to be a function of the virtual image distance. For a large image distance (*i.e.*, two m), the effective lens associated with the prismatic effect will be −0.5 diopters, leading to a small 0.5 prism diopter effect for a full 10 mm deviation. Note that prism imbalance of 0.5 prism diopters is permitted for spectacles under the international standard for ophthalmic prescription ANSI Z80.1-1972.

A fixed IPD and large virtual image distance was used by Virtual I-O Inc. in the design of their i-glasses™. A similar approach was taken by Sony in their recent update of the design of the Visortron™. In this system a mechanical connection couples the system convergence with the focus adjustment, which can be set by the user (see Fig. 3). The user can choose the preferred virtual image's distance and set the accommodation level. The convergence demand is then automatically adjusted for observers with an IPD equal to that of the system.

A fixed IPD, convergence, and focus condition was tested by Mon-Williams *et al.* in their first study,[18] where they reported significant visual changes. However, the Eyephone™ LX system they used had a virtual image distance of less than 50 cm, potentially leading to a prismatic effect four times as large. In a second study by the same group, using a Visette™2000 (Virtuality Entertainment Ltd.), none of these potentially worrisome results were found.[20] The discomfort symptoms reported were much fewer and milder, and disappeared in less than 5 min. The Visette™2000 has adjustable focus and IPD settings. With this design, the prismatic effect of the lenses can be used by the observer to modify the vergence demand by setting the IPD of the unit.[20] The user can set the system to the position that feels most comfortable, or use software targets to adjust the system.

I was unable to identify a system that permits adjustment of all three parameters (IPD, focus, and convergence). Because of the interdependence it would be very difficult for most users to adjust all three satisfactorily.

Decoupling of convergence and accommodation

Shifting the fixation from one object to another at a different distance requires a change in both convergence and accommodation. In a binocular stereo display (HMD or otherwise) this is not the case. Since the image is always displayed on the screen, accommodation should be maintained at that distance to provide a clear image. When disparity is introduced, the convergence should change toward the simulated distance of the target. This has the same effect as introducing prisms in front of the eye, but the situation in this case is dynamic. Either the depth in the image is changing with time or the user is fixating static objects at different apparent depths. The dynamic nature of the situation prevents prism adaptation, discussed above, from taking place. It has been suggested that this may lead to eye strain and headaches since it is a prolonged state of a situation that cannot be relieved by prism adaptation. One study did report subjects' discomfort with even very short exposure.[18] However the effect of de-coupling was not established, since in the second study conducted by the same group without stereo depth, a different system was used and many other parameters were modified as well.[20] A few other studies reported small temporary changes in the accommodation or convergence systems after non-head-mounted stereo display use. No evidence was presented that these changes are meaningful or differ from changes occurring with many other tasks, such as reading.

The only other condition that requires such decoupling of accommodation and convergence is the practice of visual training or eye exercises used to treat binocular disorders. Many of the training exercises use the same type of changes in convergence while maintaining a fixed accommodation. It has been shown that such training, although typically uncomfortable at first, can increase the ZSCBV for normal observers, as well as patients with various binocular and accommodative disorders. The increased range increases the comfort zone and thus ultimately may reduce symptoms for a patient. It is possible that the adaptation that could be expected from stereo HMDs will be an increase in the ZSCBV with improved binocular function. Positive or negative effects of stereo-depth changes in various entertainment systems have not been published.

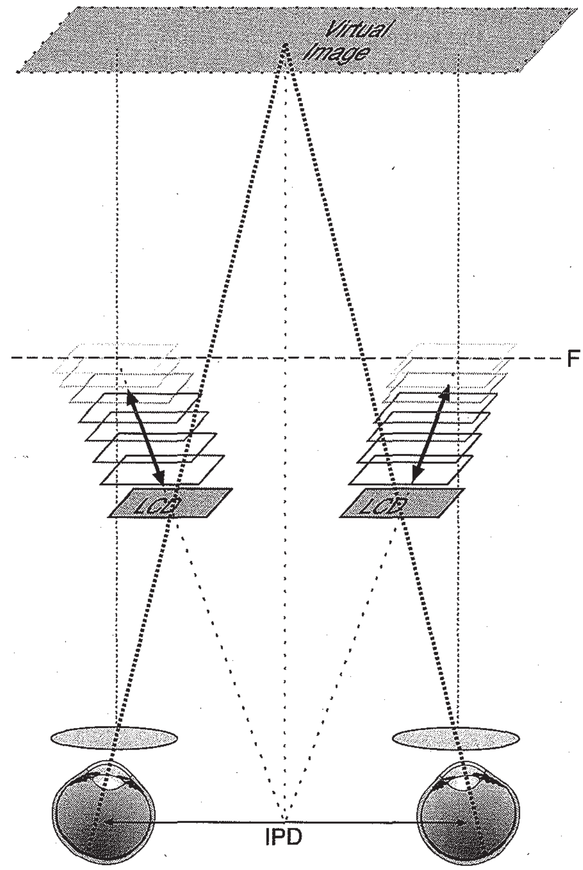

Figure 3. Schematic of the mechanical coupling of focus and convergence in Sony's Visortron permitting automatic adjustment of convergence with change in accommodation demand. Adapted from Onishi *et al.* (1994).

Final vision

Despite much discussion of the possible harmful or disturbing effects of HMD on binocular vision, the research published to date provides little evidence that such effects occur.[21] In view of the variability of previous results, it appears to be most appropriate to test each system separately to determine for each design that comfortable and safe use by the target population is achievable.

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