Visual and Optometric Issues with Head-Mounted Displays

Eli Peli
The Schepens Eye Research Institute, Harvard Medical School
Boston, Massachusetts

Abstract

The differences between the real world for which the human visual system had a few million years to adapt, and the novel head-mounted display (HMD) may result in some perceptual changes. Some of these differences may result in degradation of image quality, while others have been suggested as possible causes for discomfort and temporary visual changes. This paper reviews a few of the possible mismatches between the visual system's response to real world and its response to the virtual world of the HMD. Many of these can be reduced or eliminated by proper designs and better technologies, while others appear to be inherent limitation of HMD, which need to be considered by careful design of applications and software. Understanding the phenomena based on current knowledge in visual science should lead to correcting measures or improved designs.

Introduction

When thinking about virtual reality (VR) systems the first image that comes to mind is that of a head-mounted display (HMD). To enhance the sense of reality many such systems are designed to provide stereo depth and are using head tracking to enable the virtual world to change in response to user's movements.

The current state of HMD and other VR technology is falling short of simulating real vision accurately. The differences between the real world and the novel HMD may result in some perceptual changes. Some of these differences may result in degradation of image quality, while others have been suggested as possible causes for discomfort and temporary visual changes. The concerns about possible harmful effects are reminiscent of such worries accompanying the introduction of almost any new wide-use technology. Such concerns were raised with the introduction of television, computers, microwave-ovens and most recently cellular-phones.

Published by The Society for Imaging Science and Technology, 1996

This paper describes a few possible mismatches between the visual system's response to real world and its response to the virtual world of the HMD. Some of the effects result in unwanted perceptual phenomena, which may or may not impact the acceptance of the technology. Other effects have been suggested to stress the visual system leading to discomfort and presumably even to some long term effects. Many of these can be reduced or eliminated by proper designs and better technologies, while others appear to be inherent limitation of HMD, which need to be considered by careful design of applications and software. The potential consequences of these mismatches and their effects are discussed and the state of knowledge to date reviewed. Preliminary recommendation for software were developed and their rationale is explained.

Understanding the phenomena discussed based on current knowledge in visual science should help us devise general rules for examining the possible effects, design correcting measures, or improved designs. The various parameters addressed in the literature are examined quantitatively to determine the magnitude of the various effects and place them in the context of similar challenges faced by the visual system in other situations. Preliminary recommendations for quality control tolerances were developed based on clinical practice guidelines.

Eye Movements Interactions with the Display

Both saccadic and smooth pursuit eye movement interact with various displays resulting in visual artifacts. Saccadic eye movements across an intermittently pulsating (non persistence displays) display such as the LED numerals used in digital alarm clocks, causes parts of the display occasionally to appear to jump or move in concert with the eye movement and in the same direction.[1,2] Similar effects have been reported with short persistence CRTs and in particular with sequential color displays.[3] In normal viewing of continuously illuminated targets, such occurrences are prevented by the phenomenon called saccadic suppression. When image jumpiness is very apparent, it may affect the control of eye movement.[4] 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 displays images are visually fused and if their illumination timing is out of phase, the integration of both eyes images may have the effect of visual persistence. Such design may reduce or eliminate the perception of image jumps.

The image degradation effects associated with saccadic eye movements have a counterpart in the pursuit eye movements that occurs while tracking smoothly moving targets. However, this effect occurs only when display update rates are lower than the display refresh rate. In the case of static imagery only the refresh rate matters. When motion video is presented the picture update rate is usually equal to the refresh rate. 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 refresh rate. When the update rate is half the refresh rate, for example, each frame can be presented twice.[5] When an image of a feature smoothly moved across such a display system and the movement is tracked by eye movements, the observer will see two moving features.[6,7] 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 1/3 the refresh rate, 3 features are seen. We have recently reported that the lower update rate results in reduced contrast detection even for fast (117Hz) refresh rate displays updated at a lower rate, and that temporal aliasing artifacts may results in unstable detection levels.[8] It is interesting to note that both the multiple images and temporal aliasing artifacts occure only for the cases where the direction of movements is orthogonal to the orientation of the moving Gabor patch (See Figure 1).

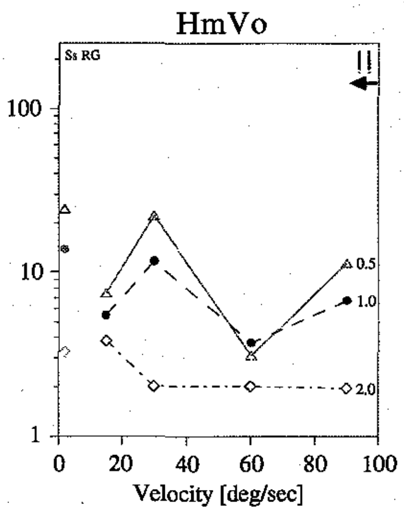

Figure 1. Contrast sensitivity of peripheral retina (recorded from a patient with a large central scotoma) for horizontally moving vertical Gabor patches (spatial frequencies, in c/deg, as noted) presented with an update rate of every third frame on a 117Hz non interlaced display. The results demonstrate alternating increases and decreases in sensitivity with increased velocity resulting from temporal aliasing. Normally sighted observers using foveal vision demonstrate the same effect for low spatial frequencies but of smaller magnitude.

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,[7] but a visible flicker remains. Due to the integration of both eyes' images, the flicker is less noticeable.

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 the residual error corrected by a visual tracking mechanism. This provides a stable retinal 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 which compensate for head motion result in a moving retinal image. This causes apparent image motion and reduced clarity.[1] 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 due to computing speed limitation may result in the retinal image slipping and image jumpiness or blurring during motion.

The eye using an HMD, must completely eliminate the VOR to perceive a stable image. Adaptation of the VOR gain to moderate changes, as those induced by spectacle correction, is very rapid, but it is not known if VOR adaptation to HMD is possible. Monocular HMD require adaptation from only one eye. Such adaptation to unequal demands for the two eyes is almost impossible. Therefore, image motion and degradation in monocular HMD are noticeable during acceleration and are more noticeable during active than passive motion.[1]

In see-through HMDs the real world is seen simultaneously with the superimposed image. Obviously, VOR adaptation for both simultaneously is impossible. It is not known which image would be stabilized by the visual system in such devices. Military see-through devices are frequently used in this mode and the discomfort generated by this conflict has been demonstrated. See-through HMD developed for the consumer market, however, are designed to provide a see-through capability only when the video signal is muted. Thus, the high contrast image of the video signal will dominate when it is operated, and the outside scene will drive VOR when the video is eliminated.

In addition to their potential effect on image quality, conflicts between vestibular and visual inputs are considered common causes of motion sickness. Visual scene motion without a corresponding vestibular input, as commonly found in flight simulators can result in simulator sickness. Such motion sickness was reported to occur in almost 50% of pilots tested on the first day of testing, but the magnitude of illness decreased on subsequent days.[9] A full issue of the Journal Presence (Vol. 1, number 3, 1992) was dedicated to articles on simulator sickness. As noted by Piantanida[10] 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". A recent review of simulator sickness in virtual environment was prepared by Kolasinski et al.[11] and can be found on the internet at http://www.cyberedge.com/4a7a.html. A recent study of a number of consumer market HMD did find significant increases in levels of motion sickness symptoms such as disorientation, nausea, and dizziness with HMDs based games (including head tracking) but not with desk top control games.[12]

Convergence and Accommodation in Binocular HMD

The virtual images' distance sets the accommodative (focusing) demand for the HMD user. The physical convergence of the two optical channels sets the convergence demand, although it can be changed by software control in some systems.[13] The visual system would be most comfortable with the natural relationship that exist for physical real world targets, such correspondence is therefore, a basic consideration in the design of HMDs. Thus it is important to consider the magnitude and consequence of deviating from the natural relationship.

With small levels of misalignment, prism adaptation[14] will result in 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 system may have various symptoms such as blur, eye strain or double vision.[15] Double vision for more than a fraction of a second may be unpleasant and disorienting. There are no reports of double vision persisting after using a HMD, although short term blur, eye strain and head aches were reported in recent studies of VR systems.[12,16]

Various approaches to adjusting the convergence and accommodative demands in HMD have been suggested. A different optical channels convergence is needed for the same focus setting for users with differing inter pupillary distance (IPDs). If the image distance is large (≥ 1 meter) however, the difference is fairly small.[2] 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 HMD's will look through the inner parts of both lenses creating a prismatic effect. The prismatic effect of the lenses has been identified in the literature as a major problem for HMD use.[15,17] The mismatched between user IPD and system IPD was implicated also in large proportion of discomfort reported following short term use of HMD.[18] The magnitude of the prismatic effect, however, is very small. For a large image distance (i.e. 2 meters), 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 10mm deviation.[2] Note that prism imbalance of 0.5 prism diopters is permitted for spectacles under the international standard for ophthalmic prescription ANSI Z80.1-1972. It is important to note also that although positive lenses are used in the system the effective prismatic effect due to the IPD mismatch is equivalent to that generated by a negative lens with focal length equal to the virtual image distance (Figure 2).

Most systems permit adjustment of at least one of the three parameters (IPD, focus, and convergence), few permit adjustment of two (usually the focus and IPD), and one system offers a mechanically yoked system which set the system convergence based on user selected screen distance (for a fixed IPD value).[19] Because of the interdependence of the parameters it would be very difficult for most users to adjust all three satisfactorily.

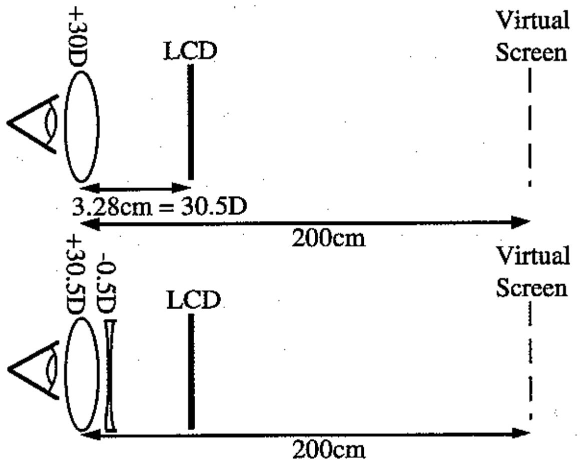

Figure 2. The prismatic effect of IPD mismatch in a +30 D lens system set for virtual image distance of 2m (0.5 D). The lens can be decomposed into a +30.5 D lens, which will place the virtual image at infinity and will have no prismatic effect, and a -0.5 D lens, correcting for the myopic observer generated that way. Only the latter lens contributes to the prismatic effect.

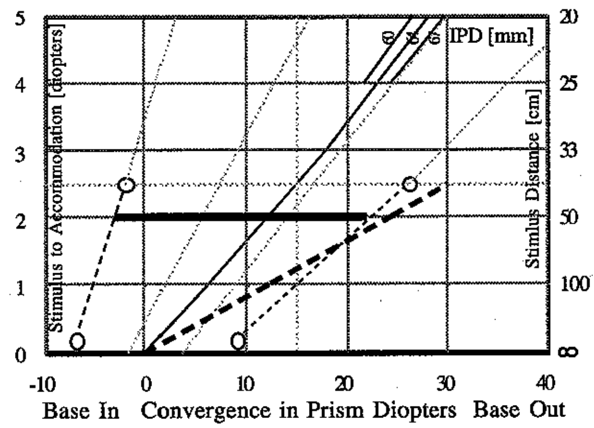

Figure 3. The demand line representing the relations of accommodation demand and convergence demand in real world (thin solid line for observer with IPD = 64 mm) is compared with the demand line in a stereo HMD set to 50 cm image distance (thick horizontal line). The demand line imposed by a laterally, displacing periscopic spectacles with IPD = 128 mm (dashed thick line) is intermediate to the two others. The thin gray lines represent the zone of single binocular vision (outer lines) and the comfort zone for single clear binocular vision (inner lines).

Convergence and Accommodation Mismatch with Stereo Images

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 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 towards 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. It has been suggested that this may lead to eye strain and head aches since it is a prolonged state of a situation that cannot be relieved by prism adaptation. A few studies reported small temporary changes in the accommodation or convergence systems after stereo display use.[20] No evidence was presented that these changes are meaningful or differ from changes occurring with many other tasks such as desk top VDT use.[12] That study comparing various systems found that small changes in the accommodative convergence to convergence ratio (AC/A) occurred with some systems but not with others. Similar changes in AC/A ratio were noted in studies using optical decoupling between the convergence and accommodation.[21] They found that with laterally displacing periscopic spectacles (which artificially increase the user's IPD) cause an increase in the AC/A. Such periscopic spectacles break the natural relations between accommodation and convergence imbedded in the AC/A ratio although to a smaller extent than the presentation of stereo images on an HMD (see Figure 3).

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.[23] Yet the mismatch of convergence and accommodation demands in the stereo systems is still a cause for concern. There have been some proposals to design systems which record user's eye movement to determine the locus of fixation and adjust the focus to matched the distance of the stereoscopically depicted feature.[22] It is not clear that such system can function effectively but it is sure to be more expensive. In order to reduce the possible harmful effects of the de-coupling of convergence and accommodation care should be exercised in the design of software to be used in such systems. Proper software design should limit the disparities induced in the device to within safe limits for either long or short term exposure, to assure the comfort and safety of the users. A preliminary guideline for software design can be derived from existing knowledge in the ophthalmic literature regarding tolerances in the population to various levels of mismatch.

Software Guidelines

The consideration of software guidelines should assume some basic details on the system used. I have assumed a standard display of 320 pixels across spanning 20 degrees of visual angle. Thus each pixel is 3.75 arc min. Since 98% of the population have stereo acuity thresholds of 2 min. or less, all users with normal stereo vision will be able to see disparities as small as one pixel. If we further assume users IPD of 60 mm and virtual screen distance of 200 cm The convergence angle of the eyes is: 1.7 deg. to the baseline screen. We should avoid image depth set beyond infinity or beyond parallel eyes, thus, uncrossed disparity should be always of less than 1.7 deg or 27 pixels.

The bounds on the disparity presented under the HMD condition of fixed accommodative demand can be derived from Morgan's data[23] on the limit of convergence under such conditions. For a screen distance of 1 meter this analysis indicate that single binocular vision is possible within a wide range of 6.8 degrees of uncrossed disparity and 11.5 degrees of crossed disparity. These numbers represent the absolute range of operation possible. They also represent conditions of break of binocular vision when applied once and therefore obviously should not be used for continuous time. Using Percival's comfort zone,[23] defined as the middle third of the width of the zone of single clear binocular vision, we get 2 degrees of uncrossed disparity (32 pixels) and 2.3 degrees crossed disparity (36 pixels). These numbers are a fairly conservative estimate of comfort zone as they were developed for continuous use as in spectacle lenses.

Small levels of disparity do not necessarily trigger any vergence and are addressed by sensory fusional capabilities within the so called Panum's area. In the central fovea Panum's area are about 15 arc min. This means that 4-5 pixels of disparity could be used without eliciting vergence and thus avoiding stress from the mismatch of vergence and accommodation. Higher values of disparity usually stimulate vergence eye movement except if the change is too brief in time to be responded with eye movement (0.25 sec). In such a case depth up to 2 deg (30 pixels) of disparity may be perceived even though fusion may not take place and double vision is perceived Panum's area become larger for peripheral vision and for larger targets. Thus, a figure of large size (more than 20 pixels) especially if it moves in the peripheral part of the screen (away from were the main action is) can easily have 10 pixels of disparities without stimulating vergence.

Tolerances for Quality Control

In addition to the various design aspects that require consideration of the variability of dimensions and capabilities of various users there is a need to develop some tolerances for the manufacturing of HMD. Once a design option has been chosen it is important to consider what level of manufacturing accuracy is needed to assure comfortable and safe use for most of the potential users population. No Standard exist yet. Self[24] has reviewed the literature and developed recommendations for tolerances for the alignment (horizontal, vertical, and rotational) and for the magnification and luminance differences between the displays. Many of this were taken from literature addressing field binoculars. He noted in his review that most tolerances cited in the literature he reviewed were given without any sources or justifications. I have attempted to derive preliminary recommendations based on the ophthalmic literature and in consideration of the ANSI Z80.1-1972 standard for spectacle tolerances. That standard may be too stringent since spectacles are worn continuously, while HMD use is intermittent and for short (relatively) periods at a time, thus, proper adjustment had to be made.[25]

Conclusion

In view of the variability of experimental results to date, and the relative lack of information on the affects of many design parameters on the user, it appears to be most appropriate to test each system separately. This will enable the developer to determine for each design that comfortable and safe use, by the target population and the intended use, is achievable. Once a number of such studies are completed the information will enable a refinement and modifications of the preliminary tolerances proposed here. It is clear that the current level of knowledge is insufficient to support a development of a reasonable standard at this point in time.

Acknowledgment

Supported in part by grant R01 EY 05957 from the NIH. The author has been a consultant to a number of HMD manufacturers.

References

1. E. Peli, Visual issues in the use of a head mounted monocular display. *Optical Engineering* **29**, 1990, 883-892.
2. E. Peli, Real vision and virtual reality. *Optics and Photonics News July*, 1995, 28-34.
3. L. Arend, L. Lubin, J. Gille, and J. Larimer, Color breakup in sequentially scanned LCDs. *SID 94 Digest* **welcome datacomp**, 201.
4. C. Neary and A. J. Wilkins, Effects of phosphor persistence of perception and the control of eye movements. *Perception* **18**, 1989, 257-264.
5. E. Peli, Head mounted display as a low vision aid, in *Proceedings of the Second International Conference on Virtual Reality and Persons with Disabilities*, (Center on Disabilities, California State Univ., Northridge, Northridge, CA, 1994), pp. 115-122.
6. J. M. Lindholm, Perceptual effects of spatiotemporal sampling., in *Electro-Optical Displays*, M. Karim, ed. Vol (Marcel Dekker, New York, 1992),
7. J. S. Chen, A study of the effects of low update rate on visual displays. *SID Digest of Technical Papers* ***XXIV***, 1993, 510-513.
8. E. M. Fine and E. Peli, Orientation and direction of motion of Gabor patches do not interact in a detection task. *Invest Ophthalmol Vis Sci (ARVO Suppl)* **37**, 1996, s233.
9. K. C. Uliano, E. Y. Lambert, R. S. Kennedy, and D. J. Sheppard, *The effects of asynchronous visual delays on simulator flight performance and the development of simulator sickness symptomatology*, Naval Training Systems Center, Orlando, 1986), Chap. , p. 1-74.
10. T. Piantanida, Low-cost virtual-reality head-mounted displays and vision, (SRI International, Menlo Park, CA, 1995).
11. E. M. Kolasinski, S. L. Goldberg, and J. H. Hiller, Simulator sickness in virtual environments., (U.S. Army Research Institute for the Behavior and Social Sciences, Alexandria, Virginia, 1995).
12. P. A. Howarth and P. J. Costello, Visual effects of immersion in virtual environments: Interim results from the U.K. Health and Safety Executive Study, in *Society for Information Display*, J. Morreale, ed., Vol. **27**, (SID, San Diego, CA, 1996), pp. 885-888.
13. J. P. Wann, S. Rushton, and M. Mon-Williams, Natural problems for stereoscopic depth perception in virtual envirnments. *Vision Res* **35**, 1995, 2731-2736.
14. R. C. Carter, Gray scale and achromatic color difference. *J Opt Soc Am A* **10**, 1993, 1380-1391.

15. T. Piantanida, Another look at HMD safety. *CyberEdge Nov/Dec*, 1993, 9-12.
16. M. Mon-Williams, J. P. Wann, and S. Rushton, Binocular vision in a virtual world: visual deficits following the wearing of a head-mounted display. *Ophthal Physiol Opt* **13**, 1993, 387-391.
17. J. Melzer, Tech:HMDs and oculo-motor changes., (Newsgroups:sci.virtual-worlds (on the internet), 1994 (Nov 14).
18. D. Regan and K. I. Beverley, Visual fields described by contrast sensitivity, by acuity, and by relative sensitivity to different orientations. *Invest Ophthalmol Vis Sci* **24**, 1983, 754-759.
19. S. Onishi, H. Yoshimatsu, A. Kawamura, and K. Ashizaki, An approach to natural vision using a novel head-mounted dispaly. *SID 94 Digest* 1994, 28-31.
20. M. A. Mon-Williams and E. Pascal, Virtual reality displays: Implications for optometrists. *Optometry Today* 1995, 30-33.
21. F. A. Miles, S. J. Judge, and L. M. Optican, Optically induced changes in the couplings between vergence and accommodation. *Journal of Neuroscience* **7**, 1987, 2576-2589.
22. K. Omura, S. Shiwa, and F. Kishino, 3-D Display with accommodative compensation (3DDAC) employing real-time gaze direction. *SID 96 Digest* 1996, 889-892.
23. A. D. Goss, *Ocular Accommodation, Convergence, and Fixation Disparity: A Manual of Clinical Analysis*, (Butterworth-Heinemann, Boston, 1986).
24. H. C. Self, Optical tolerances for alignment and image differences for binocular helmet-mounted displays, (Armstrong Aerospace Medicla Research Laboratory, Wright-Patterson AFB, OH, 1986), 39 pages.
25. E. Peli, Visual, perceptual, and optometric issues with head-mounted displays (HMD), in *Society for Information Display*, Vol. **I**, (Seminar Lecture Notes, Palaya del Ray, CA, 1996), pp. M-10/1 - M-10/29.