Visual issues in the use of a head-mounted monocular display

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Abstract. A miniature display device, recently available commercially, is aimed at providing a portable, inexpensive means of visual information communication. The display is head mounted in front of one eye with the other eye's view of the environment unobstructed. Various visual phenomena are associated with this design. The consequences of these phenomena for visual safety, comfort, and efficiency of the user were evaluated: (1) The monocular, partially occluded mode of operation interrupts binocular vision. Presenting disparate images to each eye results in binocular rivalry. Most observers can use the display comfortably in this rivalrous mode. In many cases, it is easier to use the display in a peripheral position, slightly above or below the line of sight, thus permitting normal binocular vision of the environment. (2) As a head-mounted device, the displayed image is perceived to move during head movements due to the response of the vestibulo-ocular reflex. These movements affect the visibility of small letters during active head rotations and sharp accelerations. Adaptation is likely to reduce this perceived image motion. No evidence for postural instability or motion sickness was noted as a result of these conflicts between visual and vestibular inputs. (3) Small displacements of the image are noted even without head motion, resulting from eye movements and the virtual lack of display persistence. These movements are noticed spontaneously by few observers and are unlikely to interfere with the display use in most tasks.

Subject terms: electro-optical displays; monocular displays; head-mounted displays; eye movements; low persistence; rivalry.

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CONTENTS

1. INTRODUCTION

A miniature display device has recently been introduced.* The display creates a virtual image of a 12 in. monochrome monitor in a package of 1.1 × 1.2 × 3.2 in., weighing about 2 oz. It is designed to be used as head mounted in front of one eye, with the other eye's view of the environment uninterrupted (Fig. 1). The display provides high resolution [720 (H) × 280 (V) pixels, corresponding to 80 text characters by 25 lines with a 9 × 11 font] and a wide field (about 21° × 14°). The pixels are generated by red light-emitting diodes (LEDs) on a black background, resulting in a high-contrast image. The brightness is 2 fL nominal. The display is refreshed at 50 frames/s (noninterlaced). The

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*Private Eye™, Reflection Technology Inc., Waltham, Mass.

Fig. 1. The display is positioned in front of one eye using an adjustable headband. The other eye continues to view the environment.

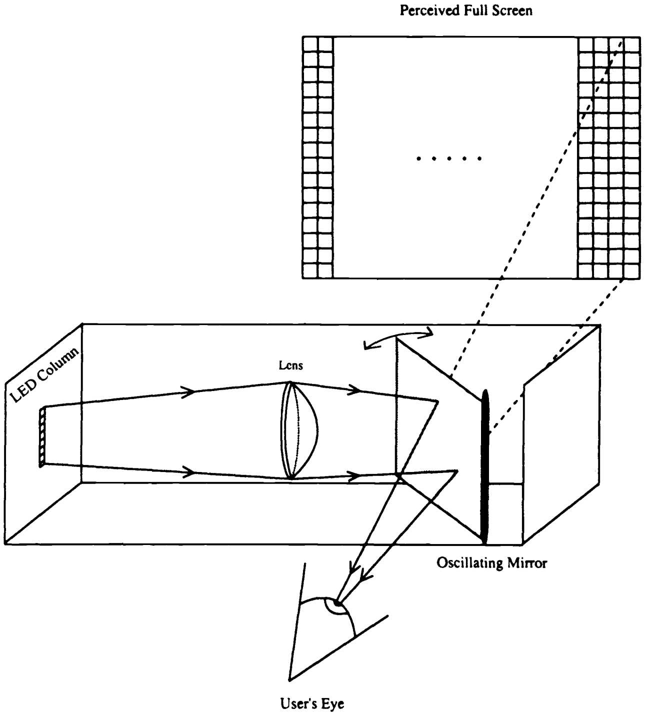


Fig. 2. Schematic of the display's design. A linear array of LEDs is driven with one column of imaged data at a time. The horizontally oscillating mirror (50 Hz) scans the column across the observer's retina. The focusing lens serves to create a virtual image of the display about 2 ft in front of the observer and to correct for the user's spherical refractive error.

headset is configured to enable use with either the right or left eye and can be located above, below, or directly in front of the wearer's line of sight.

Image data are sent as bit map graphics from a host computer to the display unit. The bit map information is loaded into a linear array of LEDs. A whole column is illuminated at once for about 6.25 μs. The image is displayed column by column, and the linear array is scanned horizontally by an oscillating mirror. The linear array is magnified by a lens system to form a virtual screen at user-adjustable distance between 9 in. and optical infinity (Fig. 2). To reduce the effect of nonlinear mirror motion, only a portion of the sinusoidal oscillating path of the mirror is used. Thus, the display is illuminated during only about 5 ms of the total 20 ms of frame period. Further linearization of the horizontal sweep is achieved by control of the display timing.

The display is designed to operate as a monitor on any IBM-compatible PC, but it may be configured to operate with any other host device. It is aimed to provide a portable, private, inexpensive means of visual information and communication. Possible applications include miniature, private, lap-type computers and pocket fax machines that can be operated in conjunction with cellular telephones. When combined with CD ROM technology, it can provide access to voluminous graphic information as may be needed from technical manuals or other sources. We are also interested in the potential application of the display as visual aid for the visually impaired incorporating digital image-enhancement techniques.[1] For most currently envisioned applications, the display will be used as a monocular head-mounted display (HMD), setting it apart from any currently used visual display terminal (VDT). This design gives rise to many visual phenomena that are not encountered in normal desktop VDTs. This paper presents preliminary evaluation of some of these visual phenomena.

The ubiquity of computer VDTs has raised concerns regarding the safety and comfort of their use. The safety of the common cathode ray tube (CRT) display unit was questioned mostly in relation to emitted radiation. Although some questions remain regarding the safety of CRT-type VDTs used by pregnant women,[2] it is commonly accepted that the radiation emitted across the spectrum from these devices is too small to cause biological injury to the eye.[3]

Users of CRT-based VDTs frequently complain of ocular discomfort (asthenopia, i.e., eye strain) and visual disturbances.[4] The discomfort is similar to symptoms reported by people performing other, similar, near-visual tasks.[5] The effect of a full day's use of a VDT on various visual functions, such as acuity, accommodation, and convergence, is not different from the effect of non-VDT office work.[6] The asthenopic symptoms were found, in large portions of the population, to be associated with uncorrected visual defects such as presbyopia, extraocular muscle imbalance, and refractive errors.[3] Glare and improper lighting levels were also responsible for many of those complaints. Image quality, image polarity (white on black), image flicker, and other aspects of the displays have also been implicated in visual discomfort. A monocular HMD such as the Private Eye may share some problems with other VDTs; however, the emphasis of this paper is on the visual consequences of a monocular HMD as it differs from a typical desktop VDT.

HMDs have been in development and use for more than two decades. Most work in the field was restricted to helmet-mounted displays for various military applications.[7] In such applications short-term performance is of much greater importance than long-term effects and/or the comfort of the device. The Private Eye display differs from most helmet-mounted display devices in its use of LED technology rather than a CRT. Previously used LED helmet-mounted devices were limited to a small number of symbols presented with a few elements rather than a full alphanumeric and graphic display. Most current helmet-mounted displays use the see-through design, rather than the monocular occluding design of the Private Eye. The latter device is aimed at the civilian market, and attention should be paid to the possible visual consequences of extended, continuous, long-term use as it may affect the safety and comfort as well as the performance of the user. The civilian market also includes children. For this population, the use of a monocular display device is of special concern, since it may interrupt the normal development of binocular function.

We will first discuss the radiation emitted by the Private Eye in relation to ocular safety. Second, the effects of rivalry on the use of a monocular display device by users with normal and abnormal binocular visual function will be described, and the effect of monocular occlusion, complete and partial, will be reviewed. A HMD moves with every head movement. This may result in apparent image motion, reduction of image visibility, and possible disturbances of spatial orientation. The extent to which these phenomena affect the use of the Private Eye will be discussed. Finally, the visual interaction of a nonpersistent display with saccadic eye movement and the variable perceived size of the display will be explained.

2. RADIATION

In comparison with CRT devices, the Private Eye LED-based device emits limited radiations in both frequency range and magnitude. The radiance of the screen was measured as $R = 1.74\times10^{-5}$ W·sr^{-1}·cm^{-2}. The radiation is a narrow red light centered at 660 nm. The retinal irradiance may be calculated as

$$E\ [\mathrm{W\cdot cm^{-2}}] = \frac{n^2}{f^2}\mathrm{TRS}\ , \tag{1}$$

where n is the refractive index of the eye, f is the focal length of the eye in image space (in centimeters), T is the transmittance of the media, and S is the area of the pupil (in centimeters squared). Thus,

$$E \cong 0.28(\text{pupil diameter})^2R. \tag{2}$$

For pupil diameter of 0.4 cm, $E = 7.8\times10^{-7}$ W·cm^{-2}; for pupil diameter of 0.6 cm, $E = 1.8\times10^{-6}$ W·cm^{-2}. The American National Standards Institute (ANSI 136.1) recommends limiting continuous exposure of up to 12 h at 660 nm to retinal irradiance of 10^{-3} W·cm^{-2}. The light levels of the Private Eye are, therefore, about 500 times lower than the maximal permissible level.

Other radiations, including a possible 50 Hz electromagnetic radiation from the mirror-driving coil and the high-frequency data stream, have not been directly measured or evaluated. The radiation of these sources, however, cannot be significant considering the total power used in the system. In both cases the energy involved is substantially less than that of CRT devices.

3. MONOCULAR OCCLUDING DISPLAY

When using the display for the first time, an observer usually perceives a superimposition or even merging of the image seen on the screen with the ambient scene image seen with the other eye. Merging of the images from both eyes, called fusion, is possible only under strict conditions where the two images are fairly similar. Even small differences, such as a few percent difference in magnification, will prevent fusion of the images. Superimposition of two nonsimilar images presented to both eyes usually does not result in a stable perception; rather, alternating periods of monocular dominance occur during which only one of the images is visible.[8] This phenomenon is called binocular rivalry. The alternation does not have to be complete over the whole 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. Different parts of this patchwork alternate periodically between the two eyes' dominance. 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 rivalrous display for different tasks. The user's eye dominance, inequality of visual acuity of the two eyes, and state of binocular function may also affect rivalry.

3.1. Binocular rivalry

The effects of various stimulus parameters on rivalry in helmet-mounted displays were reviewed by Hughes et al.[7] Experiments investigating many of the parameters in a simulated helmet-mounted display were carried out by Hershberger et al.[9] Under conditions of rivalry, the brighter field will dominate.[10] A number of papers reported in Hughes et al.[7] indicated that contrast sensitivity, speed of reading, and performance of counting or search tasks were better binocularly, or when the illumination for the nonutilized eye equaled that of the monocular display. Hershberger et al.[9] found that the ambient scene luminance had the largest effect on the rivalry. With no filtering of light to the open eye, rivalry was too great to make the helmet-mounted display useful for flying under full-sun conditions.[11] Control of the ambient luminance or complexity may be achieved in many cases by simple movement of the head and eyes toward a less complex, dimly lit portion of the environment.[9] However, under the ambient illumination common in most offices and industrial environments, the brightness disparity is lower and does not represent problems in the use of the display.

We have tested the Private Eye outdoors on a sunny August day around noontime in Boston. The bright ambient light and reflections of brightly illuminated objects in the environment off the display's screen reduced the display's contrast substantially. The contrast could be increased by proper shielding of the ambient light. With the shielded display, rivalry effect was minimal and the display was usable with both eyes open with no need for adaptation. Without shielding the display, 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.

During rivalry the field with the higher contrast will dominate,[11] contours will dominate over plain fields, and the more interesting contour or the higher contour density image will dominate when both are contoured.[10] Luminance and complexity of the display and the ambient scene are the key parameters that determine the incidence of the binocular rivalry and which view predominates. Display resolution and contrast were found to be of secondary importance for rivalry. The field of view, color, framing, and accommodation had negligible effect on controlling binocular rivalry.[11] It is clear that substantial information acquisition deficit occurs with regard to the suppressed eye during rivalry. This deficit encompasses form recognition, target detection, and tracking performance. Despite this decrease in performance relating to tasks presented to the suppressed eye, there is evidence that rivalry did not prohibit perception of both sets of information.[11] Since the Private Eye's contrast is usually higher than the ambient scene contrast, the displayed information will usually be dominant.

The rate of alternation between the two eyes' views increases as the difference in the size of items in the two fields increases; alternation is not under complete voluntary control. Increased time spent actively on the task reduces the alternation rate.[11] The alternation rate between the two eyes may be influenced by instructions[12] and fixation movements.[13] Thus, voluntary control could be demonstrated in rivalry, but it has never been demonstrated that any procedure or practice can result in total control over the alternation of rivaling visual fields.[7]

A temporal change in the suppressed stimulus, such as changing contrast, phase, or spatial frequency, causes it to reappear within 20 ms (Ref. 14). This shows suppression to be selective and enables the presentation of important information to the observer during rivalry even if it occurs during the suppression phase. However, if the dominant target is of much higher contrast, it may not be possible to regain the appearance of the suppressed low-contrast target.[15] The high contrast of the Private Eye may prevent suppression of its image even during movements in the environment.

Rivalry is considered complete if the targets are perceived as alternating in their entirety rather than blending into a composite. With long periods of adaptation, the completeness of rivalry declines.[16] Exclusive visibility of only one target falls from about 30% of the time to less than 10% of the time after adaptation of 30 min. Thus, in continuous use one should have incomplete rivalry most of the time if the contrast and brightness of the display and the ambient scene are not too disparate.

Three subjects (ages 22 through 35) with normal binocular function (normal stereo acuity) evaluated the use of the display in a word-processing task. Each typed from a printed text for 30 min. The subjects deliberately inserted typographical errors during this time. Following the typing session, they searched for and corrected the typographical errors and re-edited the text for 15 min. All subjects could perform the task with little difficulty. All subjects noticed active, incomplete rivalry especially when attending to the paper copy. It was easier to suppress the paper copy than the display. 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 in this mode. The third preferred to position the copy to one side to reduce rivalry. The subjects did not notice any image movement due to head or eye movements. One subject noticed a faint afterimage following the task. No subject reported diplopia, blur, or discomfort following the word-processing session.

3.1.1. *Eye dominance in rivalry*

Most observers show a preference of one eye over another for various tasks.[17] The most common eye dominance is sighting dominance. 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. The disparate images on the other retina are suppressed by the brain. Eye dominance in binocular rivalry is usually defined as the eye whose image is perceived a larger proportion of the time. The relationship between sighting dominance and rivalry dominance may be important, since sighting dominance can be determined easily. Initial reports regarding the relations were ambiguous. Some suggested the sighting dominance and the binocular rivalry to be independent.[18] Others found some degree of association between the two types of dominance.[19] The same group found, in a later investigation, that the sighting eye tends to display a longer total viewing time in binocular rivalry and that asymmetry remains even after increased experience. Porac and Coren[20] found that the rivalry dominance of the sighted eye actually increased with training. On the other hand, Lack[12] found a significant reduction of ocular dominance while his subject attempted actively to control the rivalry stimulus. However, even in this case the change in ocular dominance was on the order of 5% of the total time. Thus, it appears that under laboratory conditions, when the two rivalry stimuli are equal in most important parameters such as brightness, motion, spatial frequency, etc., the sighting eye shows a small but significant dominance in the rivalry, and that dominance may be reduced by short training periods[19] but cannot be shifted to the other eye. In using the high-contrast Private Eye, the effect of display and ambient scene brightness and complexity may be much more important than eye dominance.

3.1.2. *Users with abnormal binocular function*

Individuals with an eye turn (strabismus or squint) suffer simultaneously from two visual disturbances, diplopia and confusion. Both may be reduced or eliminated by suppression of the central vision of the deviating eye. These individuals have strong ocular dominance[21] and therefore may have difficulties using a monocular display.

An eye deviation acquired in childhood and left untreated usually results in substantial reduction of vision in the deviating eye; this condition is called lazy eye (amblyopia). With proper treatment, however, many patients with amblyopia regain good acuity in both eyes. The incidence of strabismus in the U.S. population has been estimated at 3% to 4% (Ref. 22). Strabismus is hereditary in many cases, estimated at 41% and 50% by Scobee[23] and Keiner,[24] respectively. Onset of strabismus is usually before the age of eight years.[25] The incidence of amblyopia in the general U.S. population is estimated at 2% to 2.5% (Ref. 22). Flom and Newmaier[26] found amblyopia in 1% to 1.8% of children and 1.7% in persons aged 10 and older; Woo,[27] with lower inclusion criteria, found 3.2% amblyopes among Canadian grade-school children. Not all amblyopes are strabismic.

Schor[28] evaluated the pattern of rivalry in strabismus patients with good visual acuity and found that strabismus subjects had normal binocular rivalry when presented with stimuli that were highly different. Suppression of the deviating eye occurred only with similar stimuli under conditions that would normally stimulate stereopsis and sensory fusion. The binocular rivalry of the strabismic observers is not completely normal since it did not demonstrate the spectral sensitivity changes that occur during the suppression phase of rivalry in normal binocular vision.[29] It appears, therefore, that strabismic observers with good visual acuity in both eyes should be able to use a rivalrous-mode display.

Two strabismic observers we tested (one accommodative esotrope and one alternating exotrope) were able to use the Private Eye successfully. For both, the rivalry appearance and the apparent superimposition of the screen over the ambient scene were similar to those described by observers with normal binocular vision. Both observers were able to type into a word-processing document using a paper copy seen in the other eye with little difficulty. The esotropic subject had strong eye dominancy and could use the display in the rivalrous mode better when the display was in front of the nondominant eye. Suppression of the display when seen by the dominant eye was difficult. Therefore, this subject preferred to position the display above the line of sight.

3.2. Peripheral placement of the display

In most tasks, there is no need to superimpose a display image on the ambient scene or outside scene. When placing the display below the straight-ahead position of the eyes, the user has binocular vision when viewing the outside world and may avoid the problem of binocular rivalry. This position below the line of sight was referred to as a bifocular HMD.[9] Observers' ability to see the world outside the display was greatly superior in bifocular display. Occurrence of binocular rivalry was considerably less and more easily controlled with this bifocular configuration.[9] The bifocular HMD produced results equivalent to control conditions in which no ambient scene was presented to the other eye. Brooks[30] found that tank commanders experimenting with helmet-mounted displays attempted on their own to use the display in the bifocular position. Katsuyama et al.[31] evaluated the effects of various display positions on performance of task related to this display and on user's comfort. They found better performance and decreased discomfort in the bifocular position (15° below the line of sight) in comparison to the bioptic position (15° above the line of sight).

Patients with amblyopia whose visual acuity in the deviating eye is greatly reduced (less than 20/50) will be unable to use the Private Eye in a binocular rivalry mode.[32] Such users as well as other observers with only one functional eye will be able to use the device only in a peripheral position. With the display positioned slightly above (bioptic position) or below (bifocular position) the line of sight, they can shift their fixation with the same eye from looking into the display's screen and then out of the screen for outside targets.

3.3. Monocular occlusion and binocular function

3.3.1. Monocular occlusion in children

Normal development of visual function in each eye is dependent on 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 eye will also lose visual acuity and may be severely impaired. Normal binocular function can be interrupted by misalignment of the eyes (strabismus), or by significantly different refractive error causing blurring of the image in one eye (anisometropia). Binocular function also can be interrupted by occlusion of 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. Visual acuity loss due to amblyopia may be severe even beyond the level of legal blindness. The loss of visual function in the occluded eye occurs mainly through maldevelopment of cortical connections from the eye.

The critical period during which amblyopia may be induced by interruption of binocular function is estimated to end at age eight[33] or nine.[34] Sensitivity to monocular visual deprivation is high during the years up to age five and decreases until after the age of nine, when the system matures.[34] The Private Eye does not actually occlude the eye and form vision is maintained in both eyes; however, it clearly interrupts normal binocular function. Therefore, further information is needed on the effect of such interruption of binocular vision before continuous use of the device by children six years or younger is recommended.

3.3.2. Monocular occlusion in adults

Continuous monocular occlusion may affect the visual system of adults as well. Marlow[35] found that patients with asthenopic symptoms had substantially increased phoria following complete, continuous occlusion of one eye for about a week. Smaller effects were noticed in cases in which the occlusion was interrupted occasionally. Phoria is the latent tendency of the eye to deviate when the stimulus for binocular fusion is removed, for example, by covering one eye. Sethi[36] reported, for normal observers, large changes in phoria position following only 4 h of monocular occlusion. She found that when binocular vision was restored, the recovery was very fast, following an exponential time course with a time constant of about 1 min. Ellerbrock and Loran[37] found significant changes in vertical phoria in less than 2 h of occlusion and measurable changes in less than half an hour. They explained their results with the use of a measurement technique that eliminated all possibility of fusion stimuli before or during the measurements, suggesting again that the recovery of the system is very rapid once binocular vision is reestablished. Brown el al.[38] reported that after eight days of continuous occlusion, all subjects developed large phorias both lateral and vertical, noted severe diplopia, failed all tests of stereopsis, and had slightly reduced contrast sensitivity. All of these effects persisted for several hours, but all capacities returned to normal within 24 h. Changes in phoria posture occur when normal binocular vision is interrupted without occlusion, such as in the use of night vision goggles,[39] but the changes are much smaller in this case.

Lateral phoria was measured for our three normal subjects before and after 45 min of active use of the Private Eye in a word-processing task. The phoria was measured, using an alternating cover test and a prism bar, both at a distance (6 ft) and near (16 in.). Only one of the three had a small, measurable increase in exophoria (Table I). As a control, phoria changes were also evaluated for these subjects following 4 h of complete occlusion of one eye. Here, two of the three subjects had measurable change in phoria. None reported diplopia or any symptoms of visual discomfort following occlusion or use of the Private Eye.

3.3.3. Peripheral fusion

In normal use the Private Eye does not completely interrupt binocular vision. Substantial parts of the peripheral field remain unobstructed (Fig. 3). Most of this peripheral field overlaps with parts of the visual field of the other eye and therefore can serve to maintain alignment of both eyes. The literature suggests that such a peripheral field may be sufficient to maintain binocular fusion and proper alignment of the eyes.

Burian,[40] the first to study the role of peripheral vision in binocular fusion, found that fusion can be driven by strictly peripheral stimuli. A surprising result of this study was that peripheral fusion is strong enough to disrupt central fusion when the disparate peripheral targets are large enough. Winkelman[41] confirmed those results and extended them to horizontal fusion using similar techniques with targets located up to 27° lateral to the fovea. He also noted that the larger and brighter the target,

TABLE I. Lateral phoria measured at distance/near after 4 h of complete occlusion of one eye and 45 min of word-processing task with the Private Eye.

	Subject 1	Subject 2	Subject 3
Baseline phoria	4^{Δ}BI/8^{Δ}BI	1^{Δ}BO/2^{Δ}BO	2^{Δ}BI/6^{Δ}BI
Phoria after occlusion	7^{Δ}BI/10^{Δ}BI	1^{Δ}BO/2^{Δ}BO	4^{Δ}BI/8^{Δ}BI
Phoria after word processing	7^{Δ}BI/10^{Δ}BI	1^{Δ}BO/2^{Δ}BO	2^{Δ}BI/6^{Δ}BI

BI, Base In (exophoria); BO, Base Out (esophoria) , Δ, prism diopters.

the stronger is its effect on fusion. Hampton and Kertesz[42] showed that the motor part (eye movements) of the fusional response (horizontal and vertical) to localized peripheral disparity stimuli decreases with the eccentricity. Kertesz[43] found a systematic increase in fusional response with increased stimulus size. Kertesz and Hampton[44] also studied the effect of central scotoma (blind spot) on fusional vergence. Using a wide-angle stimulus with an artificial, stabilized central scotoma of 10° diameter centered around the fovea of one eye, they found an asymmetric fusional response with the scotoma eye moving less than the other eye. The fact that extrafoveal stimulation was sufficient to generate fusional response is not surprising to clinicians, since many patients with macular degeneration can maintain ocular alignment. Sullivan and Kertesz[45] showed that peripheral stimulation may be sufficient to induce cyclofusional movement. Furthermore, under suitable conditions (i.e., large peripheral targets), peripheral stimulation may influence cyclofusional motor response more than does an opposing central stimulation. Thus, under normal use of the Private Eye, users with a normal binocular system may be expected to maintain peripheral fusion and ocular alignment.

Only one of the three subjects tested reported occasional diplopia of the ambient scene in the periphery. The diplopia was noted only during periods of attention to the screen and was resolved immediately when attention was shifted back to the ambient scene. In most cases the peripheral field around the display should be sufficient to maintain peripheral fusion and alignment of the eyes.

4. HEAD-MOUNTED DISPLAY

4.1. Image motion due to head motion

A stable retinal image is required for clear and sharp vision. Retinal image motion of 15°/s to 25°/s may reduce visual acuity almost fivefold.[46] Eye movements that compensate for an ordinary 90° head turn could exceed 100°/s and thus reduce visual acuity of normally sighted persons to the level of legal blindness.[47] During normal viewing conditions, two separate mechanisms, the vestibular ocular reflex (VOR) and the visual tracking mechanism (pursuit and optikinetic), generate compensatory eye movements that counter the effect 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 movements have very short latency and are controlled in an open-loop mode. The gain of this loop is on the order of 0.7 to 0.8 for passive motion[48] and 0.96 for active head motion.[49] The difference between passive and active is not due to neck proprioception since this system has low gain and inappropriate phase for compensation.[49] The residual error is corrected by the tracking visual mechanism, which operates with long delays and relatively slow movement, but accurately. The joint operation of the two mechanisms, called the visual vestibular ocular reflex, adequately compensates for all image motion during head motion, providing a stable retinal image of the world.

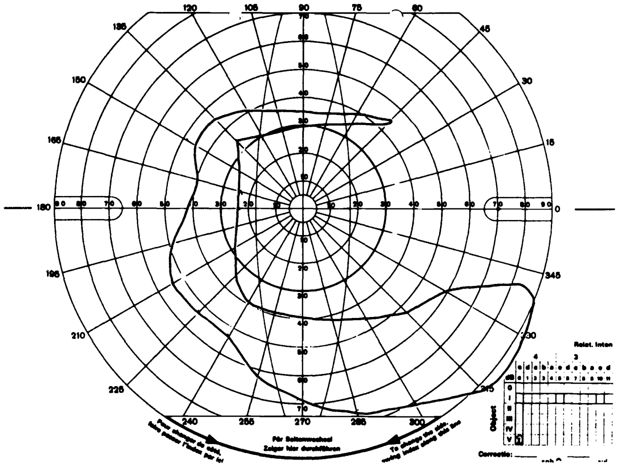


Fig. 3. The unobstructed peripheral field with the Private Eye in front of the right eye measured with a Goldmann perimeter. Most of the nasal (left) and lower field overlap with the left eye field and may be used for peripheral fusion and maintenance of binocular alignment.

The same mechanisms that serve to stabilize the retinal image in natural conditions may result in retinal slip and image degradation when the HMD is used. Eye movements driven by the vestibular mechanism during head motion will cause the HMD image to slip across the retina and will result in reduced acuity and apparent image motion (oscillopsia). HMDs used in flight simulation generally include head motion measurement and display that compensate for these movements and present a normal stable environment. The VOR may be inhibited or suppressed by the visual fixation mechanisms.[50] Thus, when a target is moving with the head, as with the HMD, the visual mechanism may completely suppress the vestibular response. This compensation is instantaneous in many cases, and thus, the adaptation of the VOR, as measured without visual input, serves only to shift the burden of compensation from visual pursuit to the vestibular system. With head-mounted, low-vision telescopes with magnification of 2.0 ×, Demer et al.[51] found no effect on acuity up to 30°/s velocities, although higher magnification resulted in decreased dynamic visual acuity with increased velocity.

4.1.1. Adaptation

VOR is strictly reflexive and not under voluntary control. However, being 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 those induced by moderate spectacle correction, is very rapid and is completed in 4 to 20 min (Ref. 49). Adaptation of the VOR gain to the extreme demands imposed by reversing prisms[52] or 2.1 × telescopic spectacles[53] and by the higher magnification of low-vision telescopes[54] is limited in range and never complete. Adaptation to reversing prisms may take days. Gonshor and Melvill-Jones[52] reported a VOR gain decrease by 75% after many days of adaptation to reversing prisms. Another study found a decrease of 36% in VOR gain after only 1 h of wearing reversing prisms. Significant adaptation to telescopic spectacles may be recorded after 15 min of wear.[47] I am not aware of any study evaluating the level of adaptation and time course for a HMD, except imaginary target (Barr, 1926, cited in Collewijin et al.[49]).

Adaptation to unequal 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.[49] The use of a monocular HMD presents such a 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.

We have evaluated the effects of rotary and linear motion on perceived image motion and the ability to read the display. Rotary movement was evaluated for active and passive movements for two subjects. 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. Image motion was noted by both subjects throughout the rotation but was greatest at the two extremes of the range at which acceleration is increased due to change in direction. At these instances the small print became illegible due to the motion. With a short adaptation period the image motion could be reduced for most of the range, except for the points of direction reversal.

Active rotations were obtained by the subjects standing up and rotating their head with the body trunk stable or by sitting in a rotating chair with their feet on the ground. In both cases, induced image motion increased, compared with the passive condition, and text legibility decreased throughout the range of movement.

Linear motion was induced by pushing the subject sitting in a wheelchair for about 2.5 m as permitted by the Private Eye wire and then stopping abruptly. Image motion and text degradation were noticeable only during the initial acceleration and final deceleration of the movement. During the constant-velocity phase, the display remained completely stable and legible. During all of these testing situations, attention was directed strictly to the display. Subjects did not report noticing any unusual movement of the environment nor any tendency for rivalrous dominance to shift to the eye not using the display.

4.1.2. Motion sickness

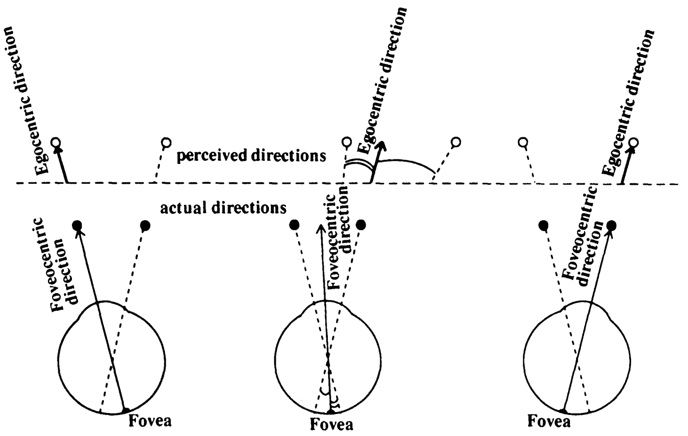
Conflicts between vestibular and visual inputs are considered common causes for motion sickness with its unpleasant symptoms of ataxia (loss of balance) and nausea. Visual scene motion without a corresponding vestibular input as commonly found in a flight simulator can result in simulator sickness.[55] These types of motion sickness occurred in almost 50% of pilots tested on the first day of testing, but the magnitude of illness decreased on subsequent days, indicating that adaptation is possible.[55] It should be noted, however, that the vestibular-visual conflict encountered in the Private Eye is different, i.e., vestibular input without the corresponding visual movement as compared with the inverse situation in flight simulation. In addition, the other eye and the peripheral view provide proper visual input that corresponds to the vestibular stimulation.

Woods and White[56] found body sways to be larger when the retinal image motion was inconsistent with vestibular input. For one of these conditions the image "follows" the subject head motion; however, their stimulus included a wide field and was applied to both eyes. It is surprising that an extensive literature review on HMD devices,[7] both occluding and nonoccluding, and a further computer literature search resulted in no mention of image degradation due to motion and only one reference concerning motion sickness in relation to those devices that are used to fly jet fighters and helicopters and to drive tanks. 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. The one study[57] we found evaluated vestibular-visual conflict with a helmet-mounted display in a simulator capable of rotating. They did not find any symptoms of motion sickness in all of the conditions where bodily and visual motion conflicted. None of our subjects reported any symptoms of motion sickness; however, movement was limited and all subjects sat throughout the trials.

5. OTHER VISUAL PHENOMENA

5.1. Eye movements and image motion

When the eye moves across the Private Eye display, parts of the display occasionally appear to jump or move in concert with the eye movement. These apparent movements are the result of interaction between the rapid eye movements (saccades) and the intermittent nature of the display, coupled with the fact that unlike most CRT displays, the Private Eye has no persistence. If the display 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. In normal viewing of continuously illuminated targets, such occurrences are prevented by the phenomenon called saccadic suppression.[58] 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 (Fig. 4). This shift in egocentric direction occurs some time 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 saccadic duration (30 ms). Saccadic suppression prevents these potential fluctuations in perceived direction of targets. Saccadic suppression, however, 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 (Ref. 59). Thus, if one changes fixation 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 thus will be perceived beyond its actual position (Fig. 4). This phenomenon was recently described by Neary and Wilkins[60] for CRT displays with short phosphor persistence. On such CRTs, if a saccade crosses a vertical line, the line appears to tilt in the direction of the eye movement. When the phenomenon is very apparent, it may affect the control of eye movement,[61] resulting in a significantly larger number of corrective saccades.[60] The apparent movement



Prior to the Saccade Duringthe Saccade Following the Saccade

Fig. 4. Actual and perceived directions of intermittently illuminated targets before, during, and following saccadic eye movement. The mislocalization during the saccade gives rise to the image motion that may be noted during eye movements.

of the display during saccade may cause the changes in saccadic pattern via an adaptation process used to recalibrate the saccadic system when errors are noted.[62]

The Private Eye display mode differs from a standard raster scan. Although the display rate is 50 Hz and every point gets reilluminated every 20 ms, an entire vertical column is illuminated at once, rather than serially as would occur in a normal raster display. The columns are swept horizontally; therefore, a vertical line in this display appears to jump in parallel during horizontal saccade, rather than tilt as is the case with a regular CRT display. Horizontal lines in the display appear to jump and to tilt only slightly in the direction of vertical saccadic movement. The smaller tilt results from the shorter active display period of 5 ms, which allows only a small change of eye position to occur during the intersaccadic display. The effects of these image motions on eye movements and reading rates have not yet been evaluated.

A study evaluating a night-vision, helmet-mounted display for helicopter pilots found the long persistence of P-I phosphor unacceptable and replaced it with short-persistence P-43 (Ref. 63); no difficulties were reported with the short-persistence phosphor at either day or night use.

5.2. Size constancy

Once the focusing lens of the Private Eye has been adjusted, the size of the screen's image on the retina remains fixed. The image usually does not appear to be suspended in space but rather projected onto the surface seen with the other eye. When changing one's view from a distant surface to a near one, the image of the screen appears correspondingly near and will look smaller. If a high-contrast pattern surface is placed in front of the other eye and moved backward and forward, the image of the screen will appear to expand and shrink as the surface is moved. This effect is an illustration of the visual phenomenon called size constancy, where the brain changes the scaling of an image as its perceived distance is altered. The size of the Private Eye screen appears to nearly double in size with each doubling of the screen's distance. This is Emmert's law.[64] If the background surface on which the image is projected is a bland, low-contrast surface, the effect of size constancy is much smaller. Of course, changes in the perceived size do not change the resolution in any way.

6. DISCUSSION

This preliminary evaluation suggests that, for the short periods tested, the display is comfortable for use in the rivalrous mode both by subjects with normal ocular vision and by strabismic subjects with good acuity in both eyes. Similar conclusions were drawn by another recent study in which 17 individuals of varying age and technical experience used the device for about 20 min in a data input mode.[65] (The subjects entered simulated flight strip information displayed in the Private Eye into another microcomputer and performed similar tasks using a paper printout as well.) The subjective rating on the characteristics of the display ranged from neutral to slightly favorable. Input rate and error rate were not significantly different between the display and printed material. Although four subjects noted the flickering appearance of ghost images, no visual problems were reported by any of the subjects.

In many cases, it would be more comfortable to use the display in peripheral position, enabling normal binocular vision for the ambient scene. Even when the central, monocular occluding position is used, the residual peripheral field can serve binocular fusion and maintenance of alignment of the eyes.

As with other displays, extended use of the monocular display may result in changes in the phoria posture and cause asthenopic symptoms. However, it appears that changes in phoria and fixation disparity[66] are more likely in people who are already symptomatic or who have various uncorrected visual deficits. Appearance of asthenopic visual discomfort symptoms in a user may be regarded a protective-screening effect, since it appears to uncover existing latent problems. Asthenopic symptoms can be viewed as the visual system's method of preventing abuse. If such symptoms appear, use of the display should be discontinued and the user should be checked by an eye-care provider. Even if, for various reasons, one neglects to take care of these problems, the chances of serious, long-term effects are small, since it appears from the reviewed literature that the visual system tends to recover quickly when the monocular occlusion is removed. This is true only for adults; the effects of long-term rivalrous condition on the visual system of children under the age of six should be further investigated.

Although awareness of the environment is maintained when using the display, it is obviously unsafe to attempt to use a monocular display of this type while driving. Since the rivalry is never completely under voluntary control, situations in which the screen image is dominant may cause accidents.

Image motion that can be noticed during head motion due to the conflict between the vestibular and visual inputs may be reduced with adaptation. Even after long adaptation, this image motion is likely to reduce display visibility during active head rotation or sharp acceleration. For applications that may require visibility during these conditions, larger fonts may resolve the problem. During our experimentation with the device we have seen no evidence of motion sickness or loss of postural stability in any of the users, standing or sitting. Further studies of body sway, nevertheless, may be indicated.

The image motion noted during saccades is small and usually not noticeable spontaneously by most users. These motions may affect reading of short-persistence flickering displays through their effect on control of eye movement as well as text visibility. However, any effect on the reading rate that may be found with further studies is likely to be small. The comfort level during extended reading may be more affected by these phenomena.

A number of other visual issues have not been addressed here at all. These include the role of accommodation using a monocular HMD, with regard to instrument myopia or spasm of accommodation associated with the use of optical instruments in general, and the effect on accommodation facility when one changes accommodation between the display and the environment. Similar to the changes in accommodation, changes in pupil diameter may also occur and affect the user. The current design of the head mount partially blocks peripheral lateral field. A different design using overhead mount or transparent side mount would leave the peripheral field unobstructed and make for a safer instrument. The ability to perform various tasks using one eye are generally reduced only for tasks that require depth perception.[39] However, task performance under rivalrous conditions may differ from the performance with one eye occluded. Since this kind of display is becoming more common and is used more extensively, studies regarding these other effects will be required as well.

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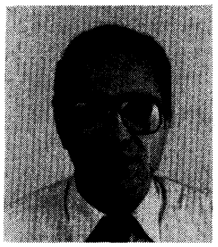

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