The impact of non-immersive head-mounted displays (HMDs) on the visual field

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Abstract — Binocular head-mounted displays (HMDs) that could be used non-immersively produced substantial interruption of the visual field. Monocular HMDs designed to be used non-immersively created minimal interruption of the visual fields. The scotomata are small enough to allow the HMD to be worn in mobile situations, but inattention associated with use of the HMD may cause safety concerns for some mobile situations. A small opaque display can be positioned to provide a see-through functionality.

Keywords — *Head-mounted displays, visual field, ergonomics.*

1 Objective and background

Non-immersive head-mounted displays (HMDs), those that allow the wearer to interact with their environment while using the HMD, have considerable potential for use in offices, industry, and medicine. For example, a worker could walk warehouse aisles collecting goods listed on a HMD that were transmitted from a central computer. In such circumstances the vision through and around the display are important for safety and orientation. While central vision is used to view an object of regard, peripheral (side) vision is critical for safe and efficient mobility.[1] The extent of peripheral vision is known as the visual field.[2]

While manufacturers provide the field of view of HMDs, the impact of HMDs on the visual field have been addressed only minimally in the literature. Most considerations given were to the trade-off between the field size and resolution and the effects of these trade-offs on target search.[3–5] The limitations of these trade-offs are important considerations in immersive HMDs but may be less important in non-immersive HMDs. In fact, as noted by Peli[6] and Davis,[5] a wide field of view in a HMD may be difficult to use as large eye movements are needed and no head movements can be used to reduce an eccentric eye position. Here we consider in addition to the field of view of the display itself the impact of the whole appliance on the visual fields of the user.

Vision through the HMD display may be reduced or obstructed by the veiling luminance of the display. Vision around the display may be limited by the supporting structure (the body) of the HMD. Between the display and the body is a region that we call the *clearance*,[7] as shown in Fig. 1. A HMD may obstruct the view of an object in a particular direction (a scotoma, as defined in the methods section). Non-immersive HMDs may be binocular or monocular, so we examined two examples of each. We show that the impact of the HMD on the visual field depends on a range of factors including HMD design and HMD placement. Interestingly, the scotoma caused by the display may be displaced from the direction of the display. These impacts on the visual field influence the relative safety of use of non-immersive HMDs when planned use requires interaction with the environment and should be considered in HMD design.

2 Methods

Visual fields (extent of vision) were measured on a small group of young (aged 20 to 30 years) normally sighted subjects using standard clinical procedures and instruments.[2] Subjects wore their own spectacles or contact lenses to correct any refractive error. Visual fields were measured without an HMD and with two binocular HMDs and with two monocular HMDs (Fig. 2). All evaluated HMDs were non-immersive designs. Care was taken to ensure that the HMDs did not move relative to the head during a measurement session. Visual fields were measured monocularly and binocularly.

Two perimeters were used to measure the visual fields. The left side of Fig. 1(a) shows a schematic view of the display surface on which targets are presented, and how the HMD elements may interfere with the view of the targets. The right side of Fig. 1(a) shows schematically how the visual fields are represented. The Auto-Plot perimeter (Bausch & Lomb, Rochester, NY) used for most measurements is a mechanical kinetic perimeter that allowed examination of the central 50° (diameter) of the visual field. Small circular spots of light (targets) were projected by the

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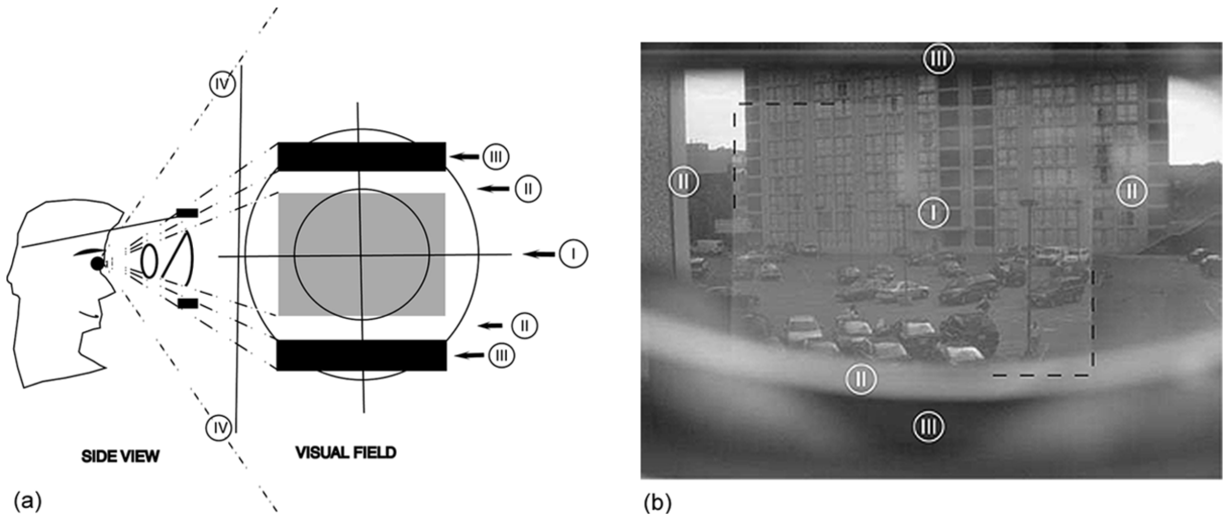

FIGURE 1 — (a) Schematic view of an HMD wearer and the visual field restrictions of a non-immersive HMD. The areas of the visual field of interest are (I) the gray area is the image of the display projected onto the test screen; (II) clearance is the part of the visual field that surrounds the display and is not blocked by the HMD body; (III) the areas of the visual field that are blocked by the body, and (IV) the natural limits of the visual field, *e.g.,* brows. (b) A photograph taken through the Sony Glasstron HMD of a parking lot and nearby buildings. In this black and white image, it is difficult to see all of the characteristics of the view through the HMD. The central, apparently lighter, rectangle is seen through the display, and appeared blue. So that this area can be distinguished we added dashed lines in two corners. There is an absolute scotoma at the top and the bottom due to the body of the device. There is a relative scotoma both in the display zone and in the clearance zone (*i.e.,* many things are visible, but not a tree to the right of the large building, or some of the lane markings in the parking lot).

perimeter onto a screen 1 m from the subject. Target sizes used were 0.5, 1, 2, 3, 6, and 12 mm. Measurements were conducted in a dimly lit room (0.26 lux: Minolta Illuminance meter TL-1), with a screen luminance of 0.021 cd/m^2 and a target luminance of 7.0 cd/m^2 (Minolta LS 110 spot photometer). While the subject maintained a steady gaze at a bright red spot (laser pointer directed at screen) white targets were moved on the screen and the subject reported when the target appeared (or disappeared). The Auto-Plot projects a bright (white) target on the screen. Targets vary in size and are specified as to their diameter in millimeters on the screen. From the observation distance of 1 m, a

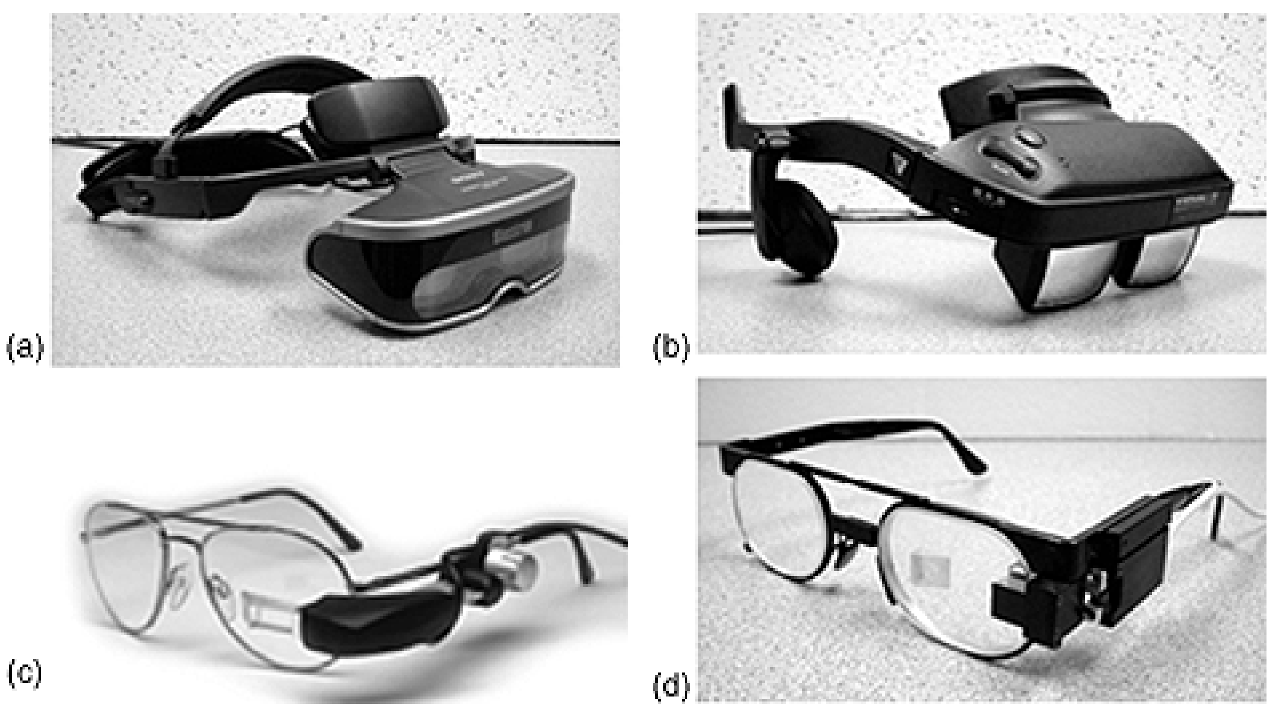

FIGURE 2 — The four non-immersive HMDs that were evaluated: (a) Sony Glasstron PLM-50; (b) Virtual I-O Iglasses; (c) MicroOptical Clip-On CO-1; and (d) a prototype MicroOptical Integrated EyeGlass.

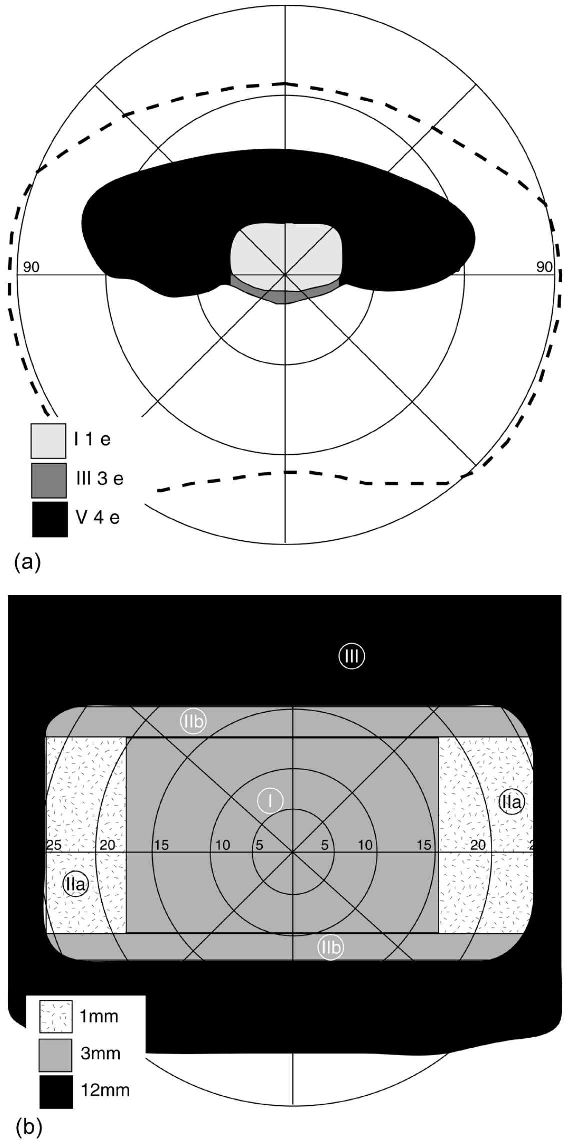

FIGURE 3 — Binocular visual field with a Sony Glasstron PLM-50. (a) Measured with display off, to ±90° with a Goldmann perimeter. The extent of the normally sighted subject's binocular visual field is shown as the dashed line (V4e target). (b) Measured with blue screen on, to ±25° with the B&L Auto-Plot perimeter. The areas of interest are: (I) the relative scotoma caused by the display, 3-mm targets were not seen in this region; (IIa) a relative scotoma in the clearance on each side of the display, 1-mm targets were not visible; (IIb) a relative scotoma in the clearance above and below the display, 3-mm targets were not visible; and (III) an absolute scotoma caused by the HMD body that extended more than 60° to either side.

1-mm target spans 0.057° or 3.44 arcmin of visual angle. As smaller targets (*e.g.*, 0.5 mm the smallest target available) are more difficult to see than larger targets (*e.g.*, 6 mm) measured scotomata may vary with target size. In dynamic perimetry the target is moved in slowly (about 2 deg/sec) from the area where it is not seen towards the area where it is seen. When the subjects indicate spotting the target the position is marked. On a visual field plot, scotomata (regions in which a target are not seen) are outlined by isopters (lines joining the points that define the scotoma edge) and are commonly hatched or shaded (*e.g.*, Fig. 3). A region in which no target can be seen is known as an absolute scotoma and a region in which one target can be seen, but a smaller target cannot be seen is known as a relative scotoma. Note that due to the observer's finite-size pupil, vingetting causes relative scotomata at the edges of opaque obstructions in front of the eye.

The Goldmann perimeter (Haag-Streit, Berne, Switzerland) is a spherical projection kinetic perimeter that allowed wider examination of the visual field (180° diameter). Targets varying in size from I (about 0.3 mm) to V (about 9 mm) and in intensity from 1e (20 cd/m^2) to 4e (328 cd/m^2) are projected onto the inner surface of a bowl of radius 300 mm (10 cd/m^2). As can be seen in Figs. 3 and 4, the normal binocular visual field extends more than 90° to either side, and more than 60° above and below for large targets.

The (NTSC) Sony Glasstron PLM-50 (Sony, Tokyo, Japan) and the (NTSC) Virtual I-O Iglasses (i-O Display Systems, LLC, Sacramento, CA) are binocular HMDs with an open (non-immersive) design [Figs. 2(a) and 2(b)]. The (QVGA) MicroOptical Clip-on CO-1 and a prototype VGA MicroOptical Integrated EyeGlass (MicroOptical Corp., Westwood, MA) are monocular HMDs [Figs. 2(c) and 2(d)]. All four HMDs were used in a see-through mode, and visual field measurements were taken with either a black (no power) or with a blank blue screen displayed on the display. Visibility of objects seen through the display may decrease when there is an active display (*e.g.*, patterned, moving) compared to those described here. Except for the MicroOptical Eyeglass, all monocular measurements were of the right eye.

3 Results

Binocular HMDs (Sony Glasstron PLM-50 and Virtual I-0) had a more significant impact on the visual field than monocular HMDs (MicroOptical Clip-on and MicroOptical Eyeglass). Both binocular HMDs blocked some parts of the monocular and binocular visual field (*i.e.*, absolute scotomata), whereas the MicroOptical Clip-On blocked some of the monocular visual field but not the binocular visual field (Figs. 3–6).

The body of the Sony Glasstron PLM-50 caused a large absolute scotoma that extended lower in the visual field (Fig. 3) than the scotoma created by the body of the Virtual I-O (Fig. 4). The body scotoma found in the lower part of the monocular visual field was minimal in the binocular visual field of the Virtual I-0 [Fig. 4(b)], while the body scotoma in the binocular visual field of the Sony HMD remained, and was denser [Fig. 3(b)]. The body scotomata in the upper visual field of both binocular HMDs was larger for the Virtual I-0 than the Sony Glasstron. Slightly surprisingly, changing to binocular viewing did not substantially reduce those scotomata found monocularly, with either binocular HMD. The body of the Virtual I-0 had little effect along the lateral visual field, while the body of the Sony

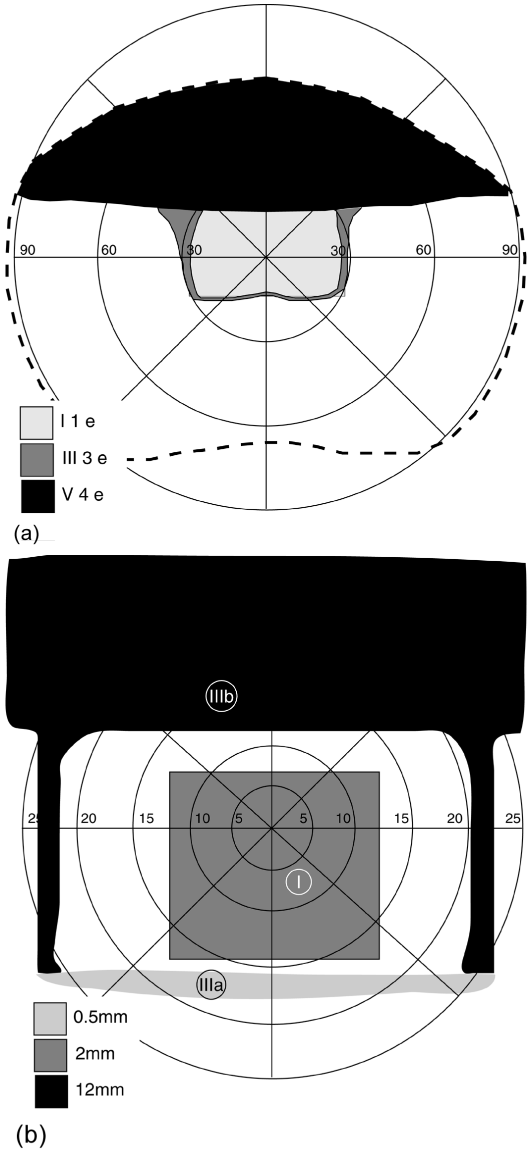

FIGURE 4 — Binocular visual field with the Virtual I-O Iglasses. (a) Measured with display off, to ±90° with a Goldmann perimeter. The extent of the normally sighted subject's binocular visual field is shown as the dashed line (V4e target). (b) Measured with blue screen on, to ±25° with the B&L Auto-Plot perimeter. The areas of interest are: (I) the relative scotoma caused by the display, 2-mm targets were not seen in this region; (IIIa) a relative scotoma in the inferior visual field caused by the HMD body, 0.5-mm targets were not visible; and (IIIb) an absolute scotoma (12-mm targets) caused by the HMD body that covered all of the superior visual field (±90°).

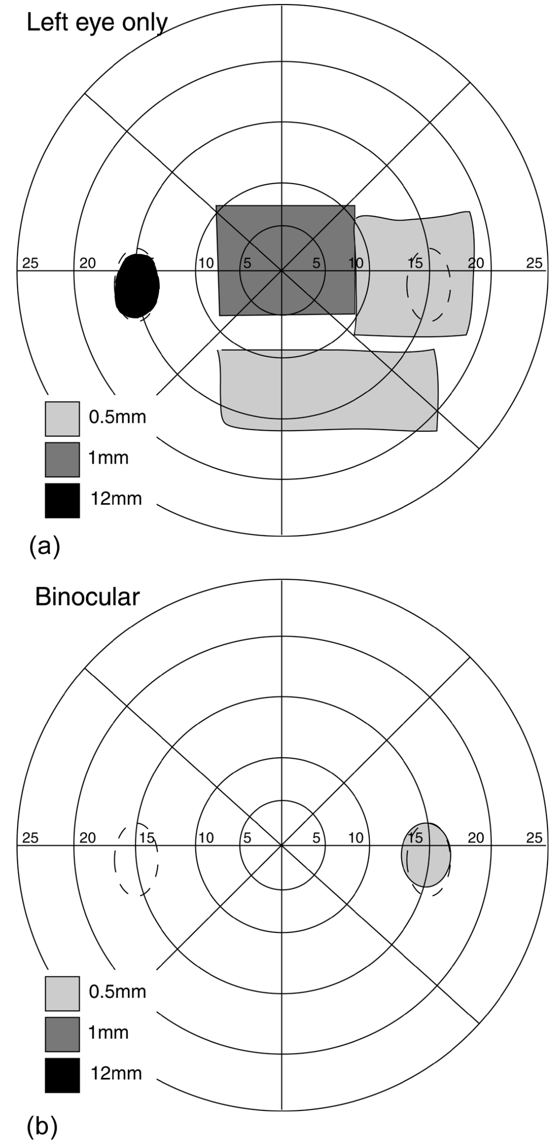

FIGURE 5 — Central visual fields with the MicroOptical Eyeglass worn over the left eye. (a) The monocular visual field (left eye) showed the physiological blind spot and relative scotomata from the display and from the optics of the device. (b) There was a relative scotoma in the binocular visual field due to the overlap of an "optics" scotoma and the physiological blind spot of the other (right) eye. The dashed ellipses represent the typical locations of the two physiological blind spots.

blocked most of the horizontal meridian beyond the central 42°. The body of MicroOptical Clip-On caused a small scotoma in the visual field (Fig. 6) that was not found in the binocular visual field, as the visual field of the other eye was unobstructed. The MicroOptical Eyeglass did not cause a body scotoma.

The optics within the spectacle lens of the MicroOptical Eyeglass caused relative scotomata, as it reduced the see-through contrast in the clearance area (MicroOptical are working to remove this effect). In the binocular field these scotomata may overlap with the physiological blind spot of the other eye in which case a relative scotoma was noted (Fig. 5). The blind spot that corresponds with the part of the retina where the optic nerve attaches to the eye (the optic disk), and there are no photoreceptors overlying the optic disk. Internal reflections were also noted with the MicroOptical Clip-On, though they were smaller and less noticeable than those of the Eyeglass.

As shown in Table 1, the measured angular size of the HMD displays compared reasonably well with the nominal field of view (*i.e.*, as specified by the manufacturers). Notably, the displays of the binocular HMDs were larger than those of the monocular HMDs. The Sony Glasstron had the largest display; however, it was difficult for most wearers to

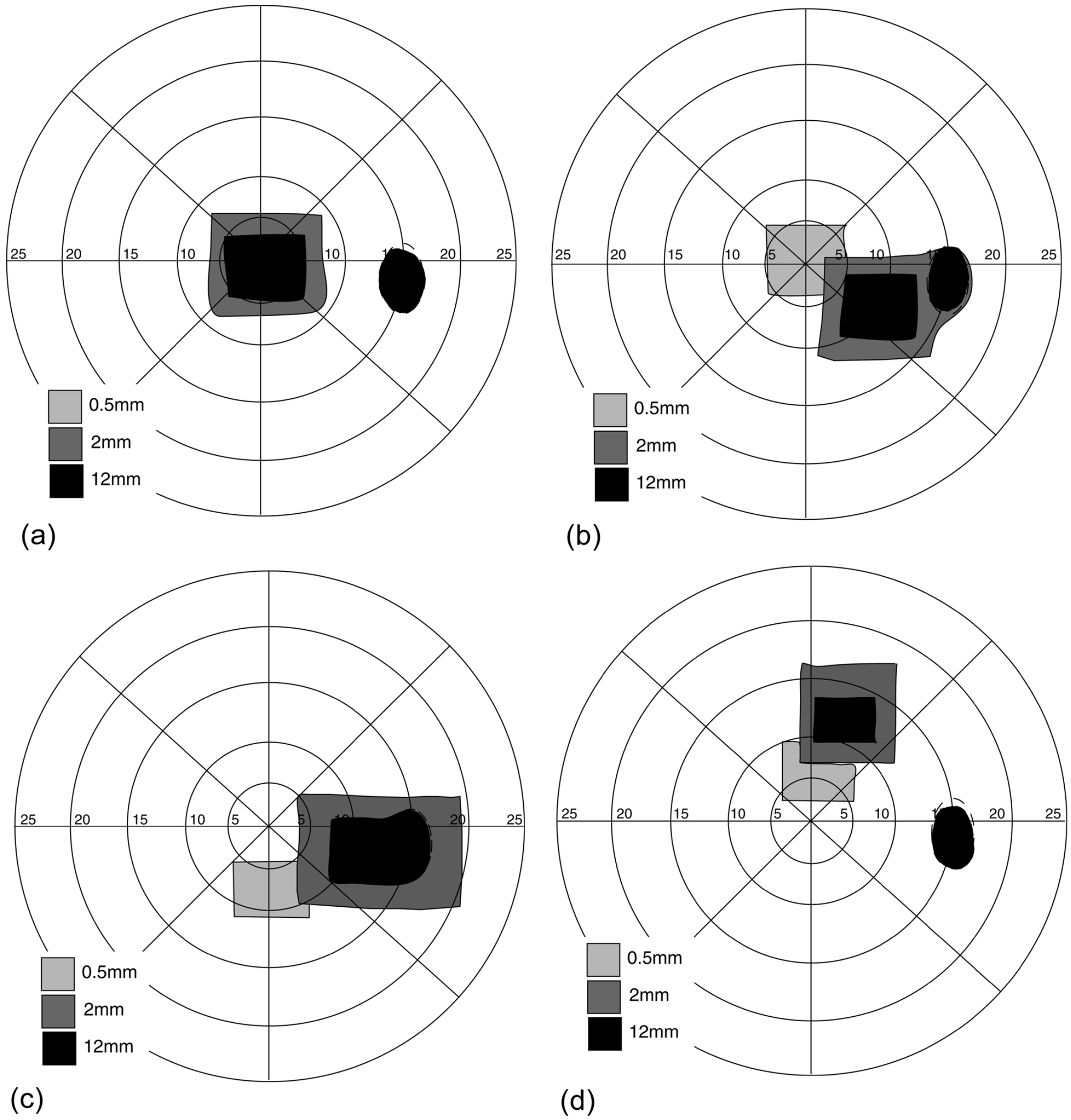

FIGURE 6 — Monocular visual fields of the right eyes of subjects wearing the MicroOptical Clip-On HMD over the right eye. (a) The display and the absolute scotoma created by the mirror were in the same direction at the center of the visual field (opaque display). The physiological blind spot is apparent on the right. (b) The display remained centered, but the "mirror scotoma" was displaced to the right (creating a see-through display). (c) The subject viewed above the display, and the mirror scotoma was displaced to the right. (d) The subject viewed below the display, and the mirror scotoma was displaced above the display. Other visual field measurements were taken, where the display and the mirror scotoma had different relative positions. Note that the MicroOptical Clip-On did not produce a binocular scotoma.

see the entire display at once. Only when the HMD was close to the eyes were all edges of the Sony display visible at once. Subjects wearing glasses could not see all corners of the display at the same time, either the upper or the lower edges being strongly vignetted [as is apparent in Fig. 1(b)]. Thus, the larger field of view of the Sony was usually not fully usable.

The distance between the eye and the HMD (vertex distance) affects the size of the scotoma. This distance is a consequence of facial physiognomy and, where available, adjustments of the HMD. For example, in the four visual fields of the MicroOptical Clip-On shown in Fig. 6, the vertex distances for subjects varied between 26 and 34 mm, resulting in scotomata of different sizes when wearing the same HMD.

Clearance, a see-through part of the visual field visible between the HMD body and the display, was found with both binocular HMDs but not with either monocular HMD. As shown in Fig. 3(b), clearance may be a relative scotoma (due to reduced transmittance). As targets larger than 2 mm were visible in the clearance of the Sony Glasstron, the relative scotoma was less dense than that of the display.

An important feature of a non-immersive HMD is see-through transmittance (the relative brightness of the environment seen through the display). See-through transmittance affects display contrast; however, a low see-through trans-

TABLE 1 — The measured field of view of the display was consistent with the nominal field of view as reported by the manufacturer. The depth of the relative scotoma created by the display was greater when the display was illuminated (with-power) than when without power. A relative scotoma defined by a 0.5-mm target is minimal as this was our smallest target. For the monocular HMDs, these measurements were made monocularly.

	Horizontal field of view (°)		Smallest white target visible through the display (mm)	
	Nominal	Measured	Without power	With power
Sony Glasstron (PLM-50)	30	33	1	6
Virtual I-O (I-glasses)	27	25	0.5	3
MicroOptical Clip-On (CO-1)	10	10	0.5	12/0.5*
MicroOptical Integrated EyeGlass	16	17	0.5	0.5

*For the MicroOptical Clip-On, the visibility through the display depended on the positioning of the HMD as described in the text.

mittance brightness may cause relative scotomata, such that objects that are small or have a low luminance may be not visible. The see-through transmittance of the two binocular HMDs depended strongly on whether the display was powered, but this was not true of the monocular HMDs (Table 1), though see the discussion below about the Micro-Optical Clip-On. Without power, very small targets were visible through all displays except the Sony Glasstron which required targets 2 mm or larger. With power (*i.e.*, displaying a blue screen), again the Sony Glasstron required larger targets (6 mm or larger) than the Virtual I-O. Even at the highest see-through transmittance of the Sony Glasstron, the environment seen through the display was dimmer than through the (fixed transmittance) Virtual I-O display. Though we found no measurable difference between with- and without-power for the two monocular HMDs the environment viewed through the MicroOptical Eyeglass was dimmer than through the MicroOptical Clip-on when used in the see-through mode. As with monocular HMDs the other eye sees objects unobstructed when viewing binocularly, the see-through targets in Table 1 are reported for the monocular visual field.

An interesting effect was noted with the MicroOptical Clip-On. Depending on the position of the HMD relative to the eye, the scotoma caused by the fully reflective mirror can completely overlap the display [Fig. 6(a)], or the "mirror scotoma" can be displaced relative to the display [Fig. 6(b)-(d)]. The relative displacement of the mirror scotoma can be achieved by a small off-axis misalignment of the CO-1 HMD with respect to the eye pupil. Figure 7 illustrates this effect horizontally in a schematic diagram. Due to the misalignment of the HMD, the display is not imaged through the full pupil, different parts of the display being imaged through more or less pupil area, making the brightness vary across the display. As the HMD mirror is misaligned relative to the visual axis, the shadow of the mirror that causes the scotoma is displaced on the retina of the eye relative to the image of the display.

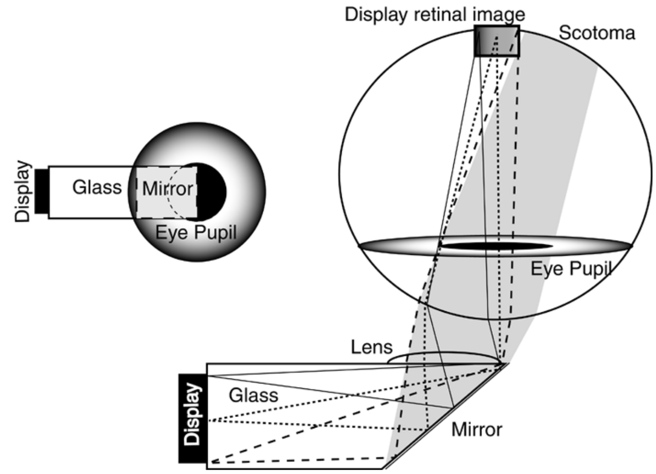

FIGURE 7 — Schematic diagram illustrating the cause of the displacement of the "mirror scotoma" from the display image shown in Figs. 6(b)-6(d). The HMD was slightly misaligned (in this illustration, horizontally) with respect to the eye pupil as is shown in the reduced front view (left). The top view (right) illustrates the ray tracing of the display image for the CO-1 HMD with the off-axis alignment. Note that the image of the display varies in brightness depending on the amount of pupil available to image that part of the display. The gray shadow represents the scotoma created as the projection of the mirror on the retina. The misalignment creates parallax of the mirror and the virtual display image due to their different distances from the eye.

This is because the image of the display provided by the HMD optics and the mirror are at different distances from the eye, hence, there is a parallax effect when the HMD system is misaligned with the pupil. Given this parallax effect, if the HMD is tilted relative to the visual axis (not shown in Fig. 7) the displacement on the retina of the eye relative to the image of the display may be further altered.

A consequence of this effect is that the MicroOptical CO-1 display can be opaque or see-through. As shown in Table 1, the smallest target visible through the display depends on the placement of the MicroOptical Clip-On HMD. This characteristic permits a see-through functionality in a device that was built as an opaque display. This could be an advantage in applications that may benefit from see-through, but could be detrimental to functionality when high contrast is necessary. In the example shown in Fig. 6(c) the scotomata was displaced to overlay the blind spot. Under these conditions the scotoma includes an area of the eye that does not have vision anyway. But more important, usually the other eye covers the scotomata caused by the MicroOptical Clip-On HMD. Thus, position of the display and its consequence to the separation of the screen and the scotoma should be explained and training in their control should be provided to users. For example, displacement of the scotoma to the inferior visual field could be detrimental to safe walking.[1]

4 Impact

When using a non-immersive HMD, the user could and sometimes might be expected to interact with the environment while mobile. Most such devices are distributed with a strong warning against their use while operating motor vehicles or heavy machinery. However, many are clearly designed to be mobile and thus would be expected to be operated by users who are walking or otherwise interact with other equipment and devices. In such situations, the visual field available for the user is important both for safe operation, avoiding obstacles and for fast and efficient navigation through the environment and locating objects needed for task performance. These issues are clearly on the mind of designers of such devices as is evident by the results reported above. While the binocular HMDs caused scotomata in the binocular visual field, the monocular HMDs provided essentially an open environment with minimal field obscurations when used with both eyes open. While such open designs clearly provide the necessary field of view required for detecting large obstacles and threats, the ability to attend to the peripheral field when attending to the display is certainly reduced. Thus, the open designs we measured do not prove in any way that it is safe to operate such displays while walking and moving around. Although vision is not obstructed, attention might not be easily divided between the display and the environment; thus it might not be safe to move around while operating the display. However, it appears that with proper design, a sufficiently open visual field may be available such that a user may safely move from one place to another without a need to remove the display. An option to eliminate display imagery may be of benefit both to visibility and attention when moving.

Arditi[8] introduced the concept of the volume visual field, and noted that conventional visual field measurements, such as we have reported, do not completely describe the functional visual field. In particular, Arditi[8] noted that the overlap of monocular scotomata will vary with the viewing distance at which detectability is measured, and that this varies with gaze direction and convergence (near viewing). The situation with HMDs is even more complicated since the cause of the scotomata is not fixed to the eye (*i.e.,* is a different position relative to the eye as gaze and convergence change) and has a finite distance from the eye. Therefore, the impact of the scotomata reported above on visual function and mobility is not clear, given that the eyes scan the environment as we walk.

We have shown that with small displays such as the MicroOptical Clip-On, care in the positioning of the device might control the location of the scotomata created by the display. Further, the finite size of the eye's pupil permits separation of the display and the scotoma enabling the use of a nominally opaque display as a see-through display. The users of such displays should either be trained or get clear instruction on the issues relating to such operation. With training, it is possible that mobile computing displays could be used safely and efficiently and provide rapid and convenient access to information on the go.

Acknowledgments

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