ORIGINAL ARTICLE

Vision Multiplexing: an Engineering Approach to Vision Rehabilitation Device Development

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ABSTRACT: Multiplexing is the transmission of two or more messages simultaneously over the same communication channel in a way that enables them to be separated and used at the receiving end. The normal visual system provides us with a very wide field of view at an apparent high resolution. The wide field of view is continuously monitored at a low resolution, providing information for navigation and detection of objects of interest. These objects of interest are sampled over time using the high-resolution fovea. Most disabling visual conditions impact only one of the components, the peripheral low-resolution wide field or the central high-resolution fovea. The loss of one of these components prevents the interplay of central and peripheral vision needed for normal function and causes disability. Traditionally low-vision aids replace or supplement the missing function, but usually at a cost of a significant loss in the surviving function. For example, magnifying devices increase resolution but reduce the field of view, whereas minifying devices increase the field of view but reduce resolution. A proposal to resolve many of the problems of current visual aids by exploring a general engineering approach—vision multiplexing—that takes advantage of the dynamic nature of human vision is presented. Vision multiplexing seeks to provide both the wide field of view and the high-resolution information in ways that could be accessed and interpreted by the visual system. This paper describes the use of optical methods and computer technologies in the development of a number of new visual aids, all of which apply vision multiplexing to restore the interplay of central and peripheral vision using eye movements in a natural way. (Optom Vis Sci 2001; 78:304–315)

Key Words: hemianopia, tunnel vision, central field loss, ARMD, prism, visual aids, peripheral vision

The population of the U.S. and other industrialized nations is aging. Low vision or vision impairment affects mostly the elderly. Consequently, both the absolute number of people with visual impairment and the proportion of the population that is visually impaired are expected to increase rapidly in the next two decades. Prevent Blindness America[1] reported that about 2.5 million Americans over the age of 40 years have moderate visual impairment and an additional 1 million have severe impairment including blindness (about 300,000). About half of those with low vision have age-related macular degeneration (ARMD). ARMD is the most common cause of vision impairment. It affects the fovea, the central retinal area used for high-resolution vision. Loss of central vision reduces the patient's ability to read, recognize faces, watch TV, and drive. Peripheral field loss (PFL), which affects patients suffering from glaucoma and retinitis pigmentosa (RP), limits patient mobility because of the inability to spot obstacles and difficulties in navigation.[2, 3] About 2% of adults <40 years suffer from glaucoma (as many as 4% of nonwhite adults).[1, 4] An estimated 20 to 33.3 per 100,000 individuals suffer from RP.[4, 5]

Although the problem of reading can be solved in most cases for patients with ARMD by using various types of magnifiers, and large screens or telescopes may be effective for TV viewing, limited help is available for face recognition. The current aids for patients with peripheral field loss are largely ineffective. Minifying devices are frequently rejected because of their negative impact on resolution,[6] and most prism devices fail to expand the field,[7] as discussed further below. I propose to resolve many of these problems by exploring a general engineering approach that takes advantage of the dynamic nature of normal vision and the need for its restoration. That engineering approach is vision multiplexing. Vision multiplexing aims to provide the patient with access to both the wide field of view and high-resolution view in ways that are accessible by the visual system.

VISION MULTIPLEXING WITH LOW-VISION DEVICES

Multiplexing refers to the transmission of two or more signals on the same channel so that all information can be used at the receiving end. To enable the discrimination of the signals at the receiving

end, they should be separated in some domain. In communications (radio, TV, telephone, and fiber optics) temporal and frequency multiplexing are common. Temporal multiplexing refers to alternating the signals being sent at every instant. Frequency multiplexing is implemented by placing separate signals on a different frequency carrier similar to the transmission of radio or TV channel signals at different radio frequencies. In fiber optics, spectral multiplexing refers to sending separate signals at different light wavelengths (colors). It is important to note that without the ability to separate the signals received, multiplexing does not occur.

The visual system has evolved to provide us with a very wide field of view (as much as 180°) at an apparent very high resolution (about 1 min arc). Achieving high resolution over that wide field instantaneously would require information transmission from the eye to the brain that far exceeds the capacity of the optic nerves. The visual system performs the task using temporal multiplexing and variable spatial resolution. Although the wide field of view is continuously monitored at a low resolution, it provides sufficient information for navigation and the detection of targets of interest. The central high-resolution fovea (about 1° in diameter) is scanning or sampling targets only at about 5 samples per second using mainly saccadic eye movements. Thus the high-resolution information from a number of targets of interest is temporally multiplexed and provided for the brain. This approach, combined with effective reconstruction algorithms, provides us with an apparently high detail view over a wide field, even though at any instant only a fraction of the field is seen in high resolution. The vision multiplexing devices described here take advantage of this reconstruction ability and other capabilities of the visual system by providing multiplexing of the wide field of view and the high-resolution view in various domains.

Most disabling visual conditions that cause low vision impact only one of the components, the peripheral low-resolution wide field or the central high-resolution fovea. The loss of central vision is the hallmark of ARMD, the leading cause of visual impairment in the elderly.[8] Diabetic retinopathy, optic neuropathy, central retinal vein occlusions, and other conditions also cause central field loss (CFL).

PFL takes on two distinct forms. The first, tunnel vision, is a severe constriction of the peripheral field leaving only the central 5° to 10° of field functional (and frequently intact). This condition is the result of RP, a leading cause of visual impairment in the younger population, and glaucoma, which affects mostly the elderly. Although patients with peripheral vision in the better eye limited to 20° of visual angle are considered legally blind, such patients frequently function quite effectively. The impact of visual field restriction on mobility is most significant when the loss is severe in both eyes, to the level of ≤10° residual field.[9] At this point they face grave difficulties in mobility and frequently need to use a cane or even a guide dog. (In advanced stages, RP and glaucoma may affect the central field as well, and advanced diabetic retinopathy may affect peripheral vision.)

The second type of PFL, hemianopia, is caused by brain injury due to stroke, surgery, or trauma. Hemianopia is a loss of vision in half of the visual field (on the right or the left) in both eyes. Hemianopic field loss causes problems in mobility and navigation. Patients frequently complain of bumping into obstacles on the side of the visual field loss and getting bruised on their arms and legs.[10]

In all cases, the loss of one of the system's components prevents the interplay of central and peripheral vision that is essential for the high performance discussed above, leading to loss of function, impairment, and disability. Low-vision rehabilitation has traditionally addressed these problems by attempting to replace or supplement the missing function, without sufficient attention to the need to reconstruct the interplay of central and peripheral vision and the use of eye movements. Thus, devices that increase resolution in CFL through magnification, e.g., electronic head-mounted magnification devices such as the low-vision enhancement system[11] and the V-MAX (Enhanced Vision Systems, Huntington Beach CA), completely rob the patient of the functional peripheral vision necessary for navigation and safe mobility[12] and therefore have limited usefulness. Minifying devices such as the Amorphic lens (a spectacle-mounted cylindrical reversed telescope) have been used to increase the horizontal span of the field seen instantaneously by a patient with tunnel vision.[13] However, these devices reduce the resolution of the central field and require head movements for scanning over a wider field of view.[6] It is arguable that intuitive integration of central and peripheral vision is necessary for successful rehabilitation and the effective use of visual aids.

To provide vision multiplexing, the visual aid should multiplex the missing component with the residual one in a way that is accessible by the visual system. Thus, for the patient with CFL, the high-resolution image (usually obtained with magnification) should be multiplexed with the available wide field of view in a way that will permit the visual system to separate the two and use them in a natural way. Similarly, for a patient with PFL, a view of the missing peripheral field should be multiplexed with the available high-resolution central view. Here, too, the multiplexing should be of such a nature that the visual system might use its natural capabilities to separate the two views and use them effectively. This article describes spatial multiplexing, in which the two views are superimposed on each other; temporal multiplexing, in which they alternate in time; bi-ocular multiplexing, where two different views are presented to the two eyes; and spectral multiplexing, in which the views are separated by color.

Discussed below are a number of new and potential multiplexing visual aids, in various stages of development, that aim to restore the natural interplay of central and peripheral vision. The presentation is organized by device. Whenever appropriate, other devices that have been used for the same condition are reviewed, and their limitations are discussed. The new (and old) devices are classified based on the type or types of multiplexing used. The discussion starts with an example of the vision multiplexing principles embodied in a successful existing low-vision device, the bioptic telescope.

TELESCOPES: TEMPORAL, BI-OCULAR, AND SPATIAL MULTIPLEXING

Bioptic Telescopes: Temporal and Bi-Ocular Multiplexing.

Spectacle-mounted telescopes have been used as low-vision aids for about 50 years. The results of most studies on the use and effectiveness of telescopes was summarized in the introduction of a recent paper by Lowe and Rubinstein.[14] The magnification pro-

vided by the telescope effectively compensates for the loss of resolution suffered by patients with CFL and other causes of low vision. Thus, objects seen through the telescopes may be recognized from distances at which they would not be recognized by visually impaired patients with unaided vision. However, the field of view through the typical low-vision telescope is narrow (6° to 12° for 8× to 3× telescopes, respectively).[15] With such a narrow field, navigation in the visual environment is difficult (and may be dangerous) and requires scanning head movements rather than natural eye movements. In addition, the magnified visual motion of the environment seen through the telescope conflicts with the vestibular head movement signal from the inner ear. This causes difficulties in adaptation to devices when worn centrally in the spectacle lens and used continuously.[16] Although in the U.S. low-vision telescopes are occasionally used in the central position for specific tasks, the most successful application of this technology is in the bioptic position. In Europe, bioptic telescope use is far more limited, to the point that a recent survey of distance telescopes user success from England did not even mention bioptics,[14] and a new system for fitting telescopes onto spectacle frames from the Netherlands was designed only for centrally mounted telescopes.[17] The bioptic telescope is mounted at the top of the spectacle lens, above the pupil of the better eye, with a slight inclination upwards (Fig. 1). The patient views the environment, most of the time, through the regular spectacle lens (the carrier lens) enjoying the benefits of intact peripheral vision. When a distant object is detected that cannot be recognized with the reduced resolution, the patient tips his head slightly down, bringing the telescope in front of the eye and the object of interest into the field of view of the telescope. A short examination (1 to 2 s) of the target through the telescope provides the patient with the level of detail required for target recognition. This use of *temporal multiplexing* makes the bioptic telescope an effective, comfortable, and safe device. Low-vision

FIGURE 1.

Bioptic telescope, an example of a visual aid that is successful due to implementing a vision multiplexing principle (temporal multiplexing in this case). The user views the world most of the time through the carrier lenses. The telescope is used intermittently to inspect high-resolution targets that are detected but not resolved through the carrier lenses. The user is shown looking through the telescopes with the head tilted slightly down. A binocular device is shown, although it is usually prescribed monocularly. When used only over one eye, it also implements the bi-ocular multiplexing principle. Photo courtesy of Designs for Vision.

telescopes are permitted as visual aids to driving in 34 states in the U.S.[17a] While driving, the bioptic telescope is used mostly for reading road signs, examining traffic lights, and scanning far ahead for possible obstacles[18] and is in use only about 10% of the time. In other situations, the telescope is used even less frequently, yet it provides convenient, easy, comfortable, and safe access to detailed vision at distance. It is quite possible that the ability to use bioptics for driving in the U.S. is the cause for the different pattern of prescription and use across the Atlantic.

The spectacle-mounted telescope can be fitted to one or both eyes. A recent survey of users in England found that more than half of the patients were fitted with binocular telescopes.[14] The use of a single bioptic telescope in a patient with two functional eyes is *bi-ocular multiplexing* when the patient views through the telescope. The magnification of the telescope results in an inherent ring scotoma. If a 10° field of view is visible through a 4.0× telescope, it occupies a retinal area of 40°. The difference between 10° and 40° represents retinal area that cannot be used to image other parts of the scene. Thus, a 4.0× telescope with a 10° field will have a ring of 15° of the surrounding environment being obscured. (This ring scotoma is a direct result of the magnification and has nothing to do with the structure of the telescope case.) However, if only a single telescope is used, the fellow eye continues to see the part of the environment that is lost to the eye with the telescope. This is an important safety feature because any threat or obstacle appearing at that field location during the telescopic glimpse might be detectable by a patient with a single telescope, but not by a patient with binocular bioptic telescopes.

Micro Telescopes: Spatial Multiplexing.

Very small bioptic telescopes may be used in ways that provide for *spatial multiplexing*. The BITA telescope[19] is a very small Galilean telescope that is used in bioptic configuration. When the BITA telescope is positioned on the carrier lens at a slight inclination just above the position where the line of sight intersects the lens in primary position of gaze, it provides what the manufacturer (Edwards Optical, Virginia Beach, VA) called Simulvision.[19] With the telescope in this position, the user can see a magnified view of a part of the scene that appears just above the nonmagnified view of the same area seen through the carrier lens. The two views are available simultaneously, requiring no eye or head movement, and as such are distinct from the temporal multiplexing that typifies the regular use of the bioptic telescope. Because the magnified view is seen above the unmagnified view, this use of the device permits the user to obtain the magnified view without disrupting the full horizontal field of view. Other than its small size and mounting position, there is nothing special about the design of the BITA telescope that provides for this property. Other small Galilean telescopes used in the same way will provide the same advantage, as seen in Fig. 2, obtained using the Microspiral Galilean telescope (Designs For Vision, New York, NY).[20] The Microspiral in its standard mount did not provide the simulvision view provided by the BITA because it was mounted in an adjustable ball-in-socket structure that blocked the view through the carrier just below the telescope.

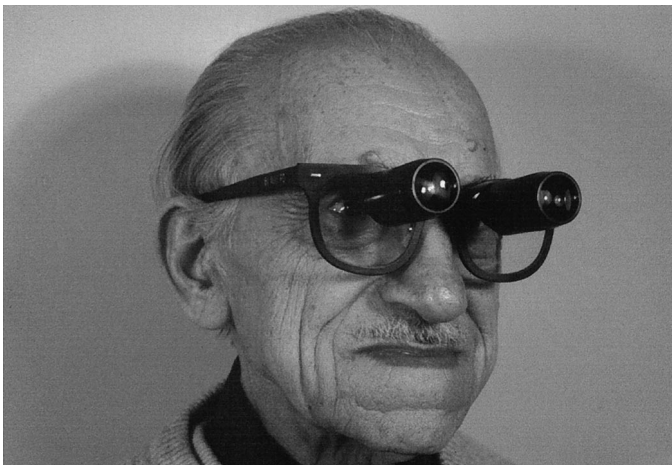The use of bioptic telescopes represents the successful imple-

FIGURE 2.

The simulvision effect simulated with a camera. The effect is achieved with a small Galilean telescope positioned at a slight angle just above the line of sight. The magnified view appears above the unmagnified view permitting continuous view of the horizontal field of view together with high magnification view of a small segment. The photo was taken with a Microspiral telescope by Designs for Vision, placed in front of the camera lens. Note that it is easier to obtain the effect with a camera because the aperture of the camera is larger than a pupil.

mentation of a number of multiplexing approaches. The shifting of view with head movement is based on the temporal multiplexing principle, the use of a single telescope by patients with two functional eyes is an implementation of the bi-ocular multiplexing principle, and the Simulvision that is possible with the BITA telescope is an example of spatial multiplexing. Note that a single device can implement and benefit from more than one form of multiplexing. Increasing the levels of multiplexing available increases the flexibility of the device and its utility. The lessons from the successful use of bioptic telescopes have been applied to the design of a number of novel devices and approaches. Described below, these devices are now being developed and tested.

Implantable Miniaturized Telescope: Bi-Ocular Multiplexing.

A combined spectacle-intraocular lens (IOL) telescope called the catadioptric lens was proposed and implemented.[21–24] In this design, a high-negative-power IOL is implanted in place of the crystalline lens and, in combination with a high-positive-power spectacle lens, it provides magnification. A bifocal IOL system developed by Allergan underwent preliminary testing in the U.S. Despite the positive results reported for such a system in a clinical trial,[24] it has not been brought to market yet. Bailey[25] analyzed the performance of such a system using a ray-tracing program and has argued that this kind of system limits the effective field of view because it prevents scanning with eye movements and requires scanning with head movements. The binocular use of the catadioptric lens also prevented it from providing bi-ocular multiplexing.

A completely implantable miniaturized telescope (IMT) was developed and tested recently by VisionCare.[26, 27] A small optical device, configured as a Galilean telescope, is implanted inside the eye in place of the crystalline lens. The IMT is inserted and held in position using a surgical procedure similar to that used when inserting a standard intraocular lens. Together with the cornea, the IMT acts as a telephoto lens that is in focus at a nominal distance of 50 cm. For closer and further distance views, spectacle lenses are used. The main advantage of the IMT over a spectacle or head-mounted low-vision telescope and the catadioptric lens is the flexibility to scan reading materials and other images using natural eye movements. Magnification within the eye eliminates the increased speed of motion and vestibular conflict that impede the use of other head-mounted low-vision telescopes.[28]

The IMT is designed for monocular use in patients with bilateral acuity loss due to macular diseases and other retinal pathologies. It provides 3.0× magnification and a 6.6° visual field (20° on retina). The fellow eye is used to monitor the peripheral field and enable mobility (bi-ocular multiplexing). Results of clinical trials with >50 patients are encouraging, particularly because they demonstrate that the bi-ocular multiplexing condition is acceptable to most patients and seem to represent little difficulty in use.[27] Further evaluation of patients' vision is needed, and better ways to train patients in its use are currently being developed.

MINIFIED CONTOURS AUGMENTED VIEW FOR TUNNEL VISION: SPATIAL, TEMPORAL, AND SPECTRAL MULTIPLEXING

Minified Contours Augmented View: Spatial Multiplexing.

Current devices for tunnel vision include minifying systems. Minifying systems are usually reversed telescopes, either simple devices[29] or more complex devices such as the cylindrical telescopes (e.g., the amorphic lens[13]) or the "fish eye" nonuniform minifier that was implemented both as an optical device (door security peephole) and as the electronic image remapper.[30] These devices do increase the instantaneous field of view, but in all cases result in loss of spatial resolution and require scanning by head movements instead of eye movements. Most patients reject their minifiers because the benefits (modest increase in field of view, e.g., double) do not compensate for the reduced resolution and the need to scan using head movements rather than eye movements.[6] A recent study implemented the Amorphic minifying lens in a bioptic (lower) position to be used to view the car dashboard instrumentation during driving by patients with restricted field.[13] This study found an improvement in performance with the Amorphic used this way, providing additional support to the concept of temporal multiplexing. Unfortunately, the Amorphic was discontinued by the manufacturer at about the same time, and it is not available for further experimentation.

Recently, Peli[31, 32] proposed a novel method that increases the instantaneous field of view without loss of central resolution and without restricting scanning eye movements, which would allow as much as 4× minification. This method is based on the principle of spatial multiplexing using augmented-reality techniques with a head-mounted display (HMD) (Fig. 3). The system includes a see-through HMD that may have a typical horizontal field of view of about 25°. The patient can see the real world through the display without any reduction in resolution or limitations on scanning eye
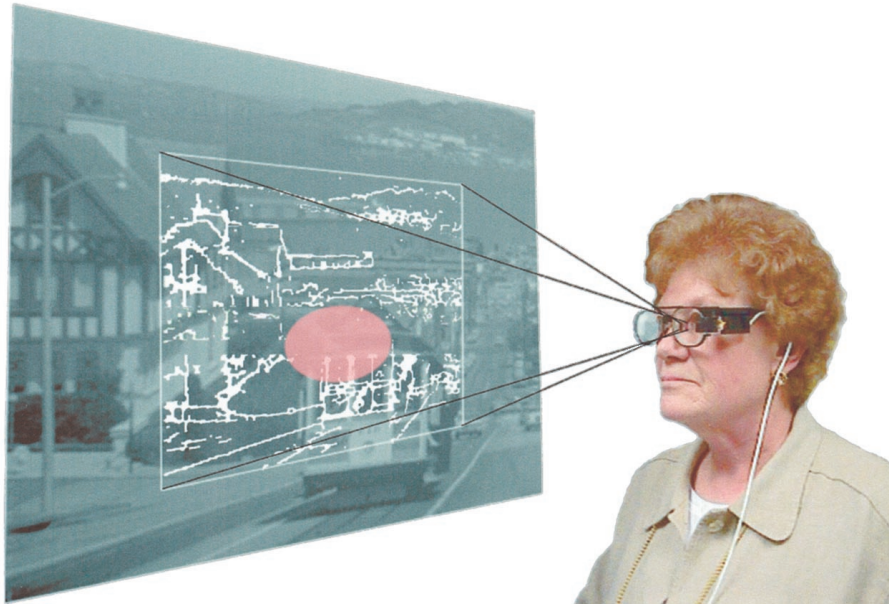
FIGURE 3.

An illustration of the concept of minified augmented view for patients with severely restricted field of view (illustrated as the small shaded elliptical area in the middle of the scene). The natural scene (gray scale image) is seen through the display. A wide-angle camera mounted on the same device obtains a wide-angle view, which is turned into contours and presented as white lines on the display. Thus, the patient can see a wider part of the environment depicted in contours at each glimpse together with normal resolution image through the display. The MicroOptical Eyeglasses display is illustrated.

movements. (Note that scanning larger angles than available within the field of the display involves head movements even in natural situations.) A miniature monochrome video camera mounted on the HMD has a field of view substantially wider than that of the display (factor of 3 to 4 wider). A portable processor provides real-time (i.e., video rate) edge detection from the images captured by the camera. The detected edges are displayed on the see-through display as bright contours. The edges, which represent a very wide field of view (75° to 100°) on a smaller field of view HMD, are minified. Thus, the patient with the severely restricted field of view (illustrated by the elliptical shaded area in Fig. 3) can simultaneously see a full-resolution view of the real world and the superimposed minified view represented by the edge contour map. The contour map, which is of reduced resolution, provides the patient with navigational information, which would otherwise be outside his view. Because the contours are minified, their movements (due to head movements) are slower, and they are easily separated perceptually from the natural view of the world behind them. Because the contours occupy only a small fraction of the display area and are in constant motion, they rarely obscure any detail of the real-world view for any length of time. This system uses *spatial multiplexing* to provide the expanded scannable field of view while maintaining the all-important high resolution of central vision.

The patient's ability to control the camera position with head movements separately from eye movements provides an additional level of flexibility. The patient can maintain the natural view (fixation) through the display on one object or person pend at the same time scan or select other objects in the environment for simultaneous viewing by changing head

position. The same head movement control can be exercised to reduce or eliminate interference from the contour image with the fixated object. A video simulation of the effect may be viewed on the web at: http://www.eri.harvard.edu/faculty/peli/papers/index.htm

A real-time (albeit slow at 5 to 6 frames per second) hardware demonstration system was presented recently at the head-mounted display special interest group (HMD-SIG) at the ARVO 2000 meeting. The system implemented a Mitsubishi prototype image processing camera (M64283FP, Mitsubishi) mounted on a bicycle helmet and a prototype unit of a see-through monocular head mounted display (PC-Trek, Olympus, Japan). The system demonstrated the ease in perceptually separating the two superimposed views and the natural feel of the control of the minified view with head movements.

Minified Contours Augmented View: Temporal Multiplexing.

The same augmented vision system can also utilize *temporal multiplexing*. By using an edge-detection algorithm that detects only edges of objects in motion,[33] the patient can control edge detection in a static environment by controlling the camera movements with slight head movements. While the head is stable, only objects that move in the environment relative to the patient will be detected and displayed as contours. If the patient moves his head slightly, all edges in the environment will be detected and displayed. The patient thus can use slight head motion to temporally control the level of contour display available at any instant.

Minified Contours Augmented View: Spectral Multiplexing.

An infrared camera or high sensitivity camera rather than a standard video camera may be used in such a system to provide visibility at night for patients suffering from night blindness. The display may present the detected edges in red light, reducing the light adaptation that would destroy the patient's ability to view the outside dark environment if white light were used. This use of infrared detector and red display represent a different level of multiplexing (*spectral multiplexing*) that can be used to provide better function with these devices, when properly engineered. Such a system is currently being developed[34] in our laboratory in collaboration with MicroOptical, using their unique miniaturized display technology.[35, 36]

It is apparent that various multiplexing principles can interact and be integrated to provide more flexible and better functional aids. Unlike the bioptic telescope, which is already in use as a low-vision aid, the minified augmented vision system described above still needs to be designed in detail, implemented, and tested within the appropriate patient population.

PERIPHERAL MONOCULAR PRISMS FOR HEMIANOPIA: BI-OCULAR, SPATIAL, AND SPECTRAL MULTIPLEXING

Many devices have been considered and applied for the management of hemianopic visual field defects. The effects of these devices may be classified as providing field relocation (shifting) or field expansion. Field expansion is the desired effect because it means that the simultaneously seen visual field is larger with the device than without it. Field relocation only exchanges the position of the visual field loss relative to the environment or relative to the body's midline. Binocular sector prisms,[37, 38] the most commonly used technique for hemianopia (Fig. 4), provide only for field relocation.[39]

Monocularly fitted sector prisms[9, 40] expand the field once the patient changes his fixation to within the field of the prism. As long as the patient's eyes are at primary position of gaze or are directed away from the hemianopic field, the monocular sector prism has no effect on the field of view. Diplopia (double vision) and confusion accompany the field expansion achieved when directing the gaze into the fie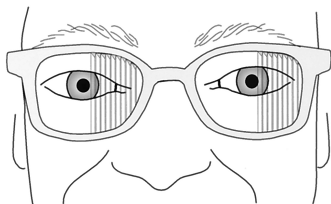ld of the prism. Confusion refers to the appearance of two different objects at the same perceived direction. Confusion in this case represents the intended beneficial effect because it represents the appearance of an object that would be invisible without the prism. However, the central diplopia induced with it is very unpleasant to the patient and may account for the lack of success.[38, 41] A successful hemianopic visual aid will expand the field rather than relocate it, function in all positions of gaze, and avoid the disturbing central diplopia.

These considerations led to the development of a new method of field expansion.[39, 42, 43] This new method involves a monocular sector prism that is limited to the peripheral field (superior, inferior, or both) (Fig. 5). The peripheral prism is placed across the whole width of the spectacle lens, spanning both sides of the pupil, so that it is effective at all lateral positions of gaze. The prism expands the field via peripheral confusion and diplopia. Peripheral diplopia, however, is much more comfortable for the user than central diplopia because peripheral physiologic diplopia is a common feature of normal vision.[44] The field expansion effect of the prism is unaltered by eye and head movements over a wide range of such movements to either side. The prisms used by this method render the patient "exotropic" in peripheral vision while leaving foveal vision unaffected. The constant peripheral exotropia provides a field expansion similar to that enjoyed by exotropic congenital hemianopes.[45–47] Adaptation of peripheral vision that changes the perceived direction has been reported by Kohler[48] for adult subjects wearing partial prisms. If such adaptation is found for the hemianopic patients using the peripheral prism, it would enable the field expansion to be useful and functional.

Thus, this design of hemianopia aids represents bi-ocular as well as spatial multiplexing. Furthermore, the chromatic aberrations of the prisms provide a spectral cue that may distinguish objects viewed through the prism from those seen with the other eye. This spectral multiplexing should facilitate adaptation to the prism by reducing the ambiguity associated with the peripheral confusion, clearly marking the objects as to the eye of origin. Tinting the prism may provide an additional spectral cue to facilitate such distinction.

The peripheral prism design described here provides for a field expansion that is measurable by standard perimetry (Fig. 6). In addition, because the prism affects only peripheral vision, a prism
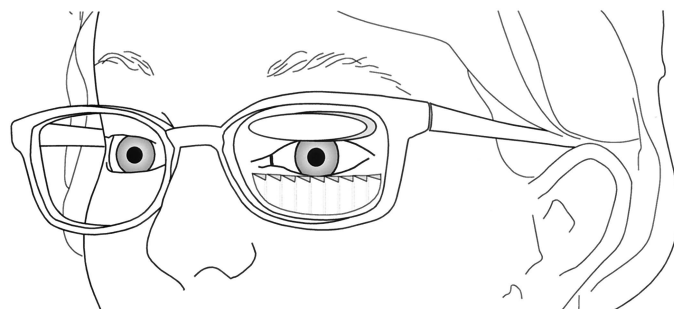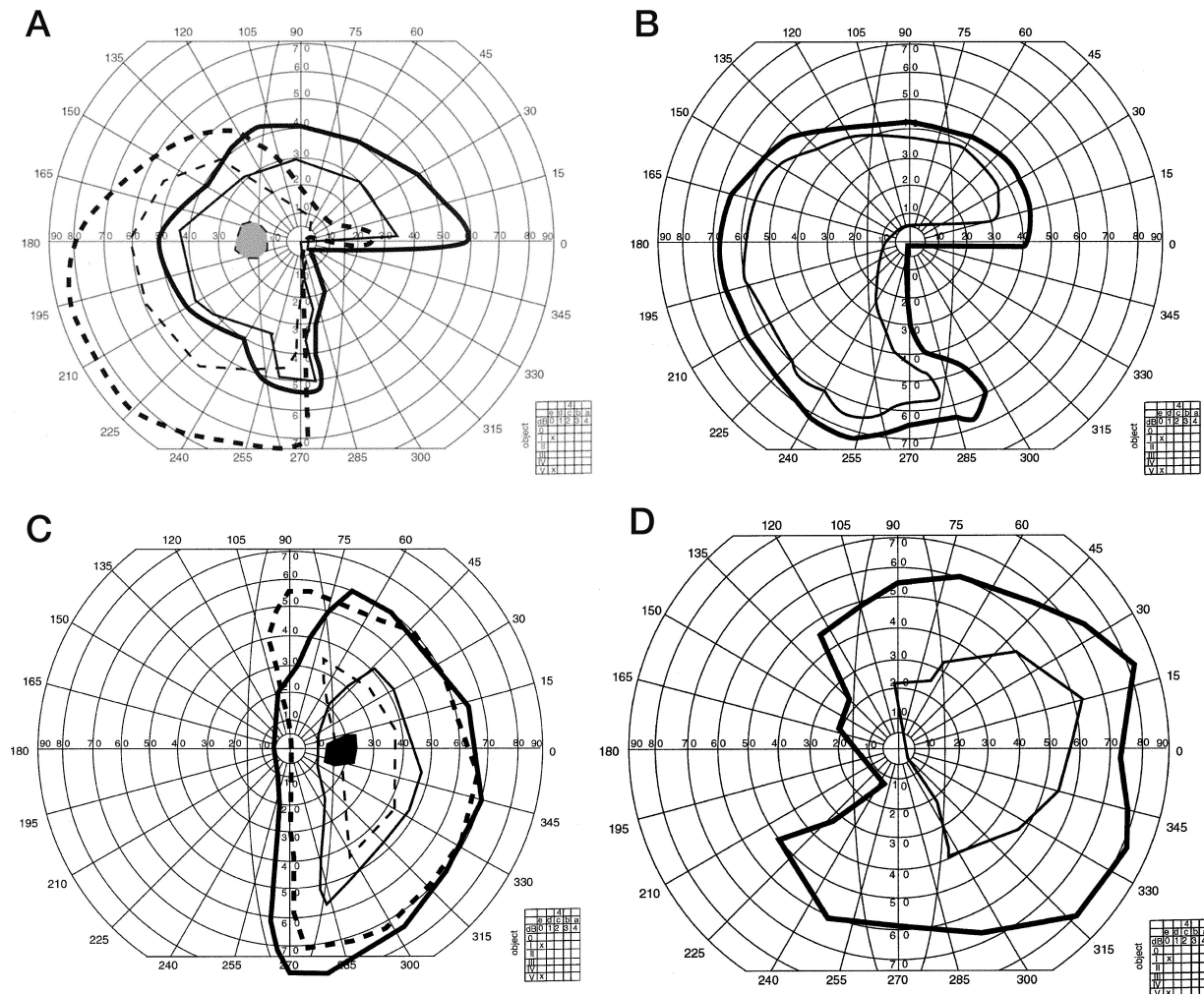

FIGURE 4.

Binocular sector prisms have been commonly prescribed for homonymous hemianopia. For left hemianopia, the prisms with base to the left are placed on both lenses, left sides up to the pupil. Note that these prisms have no effect when the patient's eyes are at primary position of gaze or are looking right (where all visual stimuli originate). When the patient looks through the prism, the field is simply shifted, not expanded. These prisms also cause an optical scotoma at the center of the lens.

FIGURE 5.

An illustration of the peripheral prisms correction. For left hemianopia the prisms are worn only over the left eye. They are restricted to the upper and lower peripheral fields but extend across the whole lens so that they are effective at any position of lateral gaze. Illustrated are both options a simple mounted prism for the upper segment and a compound Fresnel press-on prism on the lower segment.

A

B

C

D

FIGURE 6.

Visual field measured without and with the peripheral prism correction (40 PD). A: Goldmann monocular fields of a patient with right lower quadrantanopia secondary to seizures. The right eye field is shown in the solid lines, and the left eye field is the dashed lined. B: The binocular field recorded with a lower prism segment shows about 20° of field expansion in the lower field. In this case, the segment was mounted low on the carrier lens. C: The Goldmann monocular fields of a patient with left hemianopia secondary to a stroke. D: The binocular field recorded with upper and lower segments shows a similar expansion of both the upper and lower fields.

of higher power than previously applied for hemianopic corrections can be used despite its inferior optical quality. Fresnel prisms of 40 prism diopters have been fitted to more than 25 patients by the author. The successful results with the first 12 patients were reported recently.[39] The field expansion of about 20° provided by these prisms, across the vertical meridian, in all positions of gaze, was reported by the patients to be very effective in providing the necessary view needed to avoid obstacles while walking. In addition, patients reported an adaptation leading to veridical perception of the direction of objects detected with the prisms (however, no formal testing of the mobility or adaptation has been conducted to date).

Hemianopia causes problems with obstacle avoidance when walking, especially in a crowded environment, and can cause distortion of space perception.[49] Although the effect of hemianopia on driving performance has been measured using a simulator,[50, 51] its impact on driving in the real world is not known, probably because driving with hemianopia is not permitted in most jurisdictions. Because most patients with hemianopia can easily pass the

vision (visual acuity) screening tests at departments of motor vehicles, many of these patients do drive, but their record is not known.[52, 53]

TRI-FIELD PRISM CORRECTION FOR BINOCULAR TUNNEL VISION: BI-OCULAR, SPATIAL, AND SPECTRAL MULTIPLEXING

The existing prism treatments for patients with tunnel vision are based on the field-shifting principle. The prisms are mounted on the lens around a central clear portion (usually about the size of the central residual field) with the prism bases always directed away from the lens center. Thus, lateral prisms are aimed out from the lens center with the right prism base to the right and the left prism base to the left. If used, vertical prisms are placed with the base down for the lower prism and base up for the upper prism. This approach has been popularized recently with the InWave lens (InWave, Jansesville, WI[54]), which has three prisms embedded in it with a nonprismatic channel between them. The prism lenses are fitted binocularly for patients with two

functional eyes and may be used monocularly if only one eye is functional. The effect of the prism is presumed to shift the field of view inside (more centrally) when scanning eye movements bring the eye into the field of the prism on the spectacle. In fact, the prisms cause an optical "Jack in the Box" scotoma at the apex of the prisms, and, as a result, the user faces an additional optical scotoma in a ring of about 6° around the central field of gaze with the spectacles. The optical scotoma may be overcome with a combination of eye and head movements, but whether this approach represents an appropriate treatment for PFL is questionable. The InWave lens, which provided such correction in an attractive molded lens containing the patient's prescription, is no longer available, and I am not aware of any study reporting its use.

Peli[55] developed a prismatic solution that implements the *binocular multiplexing* concept. Therefore, this approach is useful only for patients with binocular vision. Unlike previous approaches, the tri-field lens does not simply shift the instantaneous field of view but expands it. The prisms are applied to one eye only, usually the eye with worse visual acuity. The prism may be applied either in the same or in the opposite direction than in the InWave design, with the apices or the bases toward the center of the lens, respectively (Fig. 7). In the preliminary clinical trial, thus far, only two lateral prism segments have been used. No space or clear lens is needed between the prisms. The power of the prisms (expressed in degrees) should be equal to or slightly larger than the horizontal extent of the larger field (better eye) to prevent diplopia.

With these prisms in place, the better eye can continue to scan the environment freely and as effectively as it did before the treatment. While the better eye is scanning, the contralateral eye is brought into the field of one prism and then the other. When the eye is in front of the right prism, for example, the functional field of that eye is presented with a segment of the scene (from either the right or left side of the scene depending on the prism configuration used) that does not overlap with the scene segment seen by the better eye. Because the two scene segments that are simultaneously in view do not overlap, the patient does not have diplopia, which would result if such glasses were worn by a person with normal vision. However, because the two nonoverlapping sections of the scene fall on the foveae of both eyes, they are perceived to be in the same direction relative to the observer, leading to "confusion", i.e., two objects seen in the same place (Fig. 8). When the scanning movements bring the worse eye to the field of the second prism (on the left) the segment seen will be transferred, and a segment from the other side will be visible. Thus with these prisms in place, the scanning eye movements provide, in addition to the normally available central field, similarly scanned peripheral scene segments on either the right or left, depending on the position of gaze and the prism configuration used.

When the eye is centered on both prisms, scene segments from both sides will be available as shown in Fig. 9. The availability of three different scene segments in this position is the source for the name "tri-field" assigned to this treatment. When the eyes are out of the primary position of gaze, only one of the prisms provides an additional view (Fig. 8).

Although it was expected that the patient could discriminate the side being seen by using the direction of the color fringes caused by the prisms, it was found that the fringes and their difference were not sufficiently obvious in most environments (note that lower-power prisms are used in this design compared with the power used in the hemianopia correction). Thus, additional help is needed to indicate to the patient the real-world side of an object seen with the
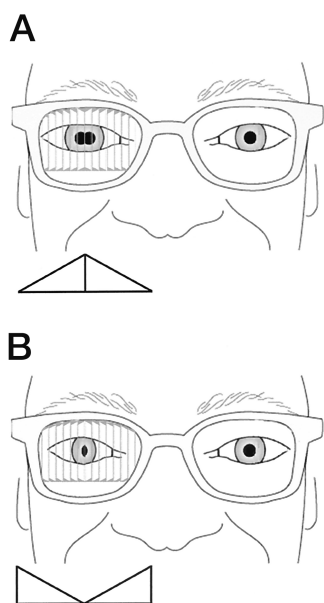

FIGURE 7.

Two possible designs for the tri-field lenses. In both cases, the prisms (Fresnel prisms shown) are mounted in front of one eye only, usually the eye with smaller field or lower acuity. A: Base-center, both prisms mounted with their bases at the center of the lens in front of the pupil. B: Apex-center design. In both cases, the prism power (expressed in degrees) is adjusted to be just larger than the wider visual field extent. The small segment without prism at the bottom of the lens permits binocular reading or other near-point (stereo) activities without the prisms.
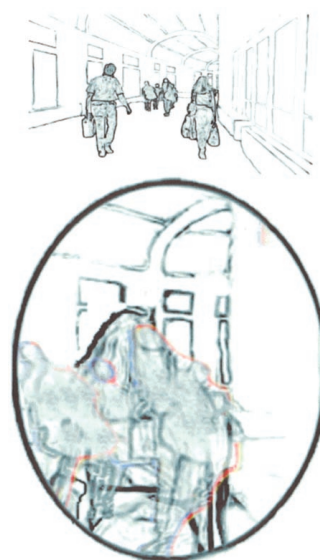

FIGURE 8.

Simulations of the instantaneous appearance of an airport terminal scene (top inset) using the base-center tri-field lens design on a right gaze. Note that the left prism has no effect. The unaided eye is viewing the woman to the right, while the view through the right prism provides for the more centrally located scene segment, which is in the walking path of the patient.
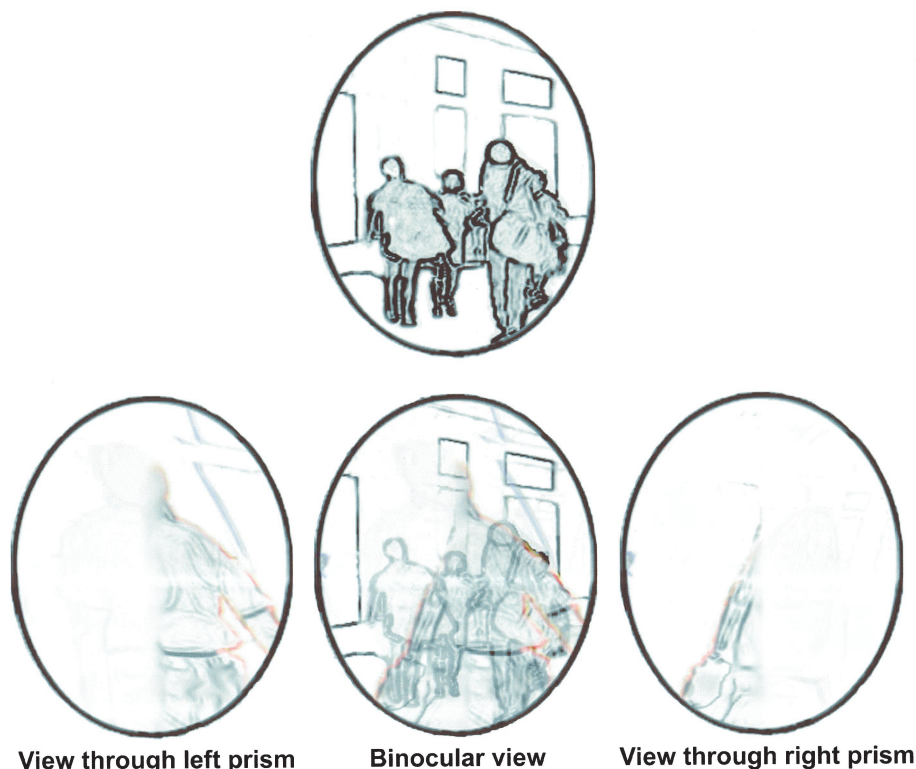
View through left prism   **Binocular view**   **View through right prism**

FIGURE 9.

Simulations of the instantaneous appearance of the same airport terminal scene, in primary position of gaze, with a severely restricted field using the base-center tri-field lens design. Top image: binocular view without correction (this is also the monocular view through the unaided eye). Bottom middle image: binocular view with the base-center tri-field lens. The views through the prisms provide scene segments to the left and right, respectively, which are superimposed on the view from the eye without prism. Note the exchange of position of the right and left views in the binocular view. This exchange makes the base-center confusing and thus less desirable than the apex-center design.

prism. Currently, we are using a red tint on one of the prisms to achieve this effect, again applying *spectral multiplexing* to separate the two overlapping images.

If patients find the constant presence of multiple images caused by this arrangement difficult, it may be possible to use the prisms only on a portion of the lens, leaving either the top or bottom or both segments of the lens clear (Fig. 7). In this arrangement, the patient can move his gaze to the top clear bioptic or the bottom clear position whenever he wishes to avoid the multiple images. This mode of use will combine *temporal multiplexing* with the *bi-ocular multiplexing* that is the basis for this aid design. This is a further example of the possibility of combining various approaches in the design and use of many devices.

## DYNAMIC CONTROL OF MAGNIFIED DISPLAY COMBINED WITH SPATIAL MULTIPLEXING

Patients with a loss of resolution due to CFL could benefit from modification in information displays. The most common modification used today is magnification, which may impede the acquisition of peripheral information attained in normal vision by the use of eye movements. This problem may be addressed in many cases by dynamic control of the display. The control may be automatic, under the user's control, or a combination of both. Dy-

namic display of text for patients with CFL was investigated by a number of laboratories.[56–59] We propose to apply a similar approach to improve access to television.

In collaboration with DigiVision (San Diego, CA), we are developing a system (Fig. 10) of magnifying television images for the visually impaired using electronic or computational magnification.[60] The user could select the desired level of magnification using a remote control and might vary the magnification used from time to time. Only part of the scene can be presented on the screen at the higher magnification. Consequently, large parts of the scene become invisible. One can effectively select the point in the image on which to center the magnified view, and this information can be broadcast or transmitted with each frame.

The system requires preprocessing of a video program to select a point in each video frame that should be centered on the screen when the image is magnified. This selection should maintain the most relevant details in view, to the degree possible, when magnified. A trained observer using a cursor visible over the playing video could select the point. The selected point of regard could potentially be determined automatically using image processing. We are using eye movement recordings from normally sighted observers watching the video program, which could be averaged to determine the desired center of the magnified view.

As a magnification is selected, the system would magnify the
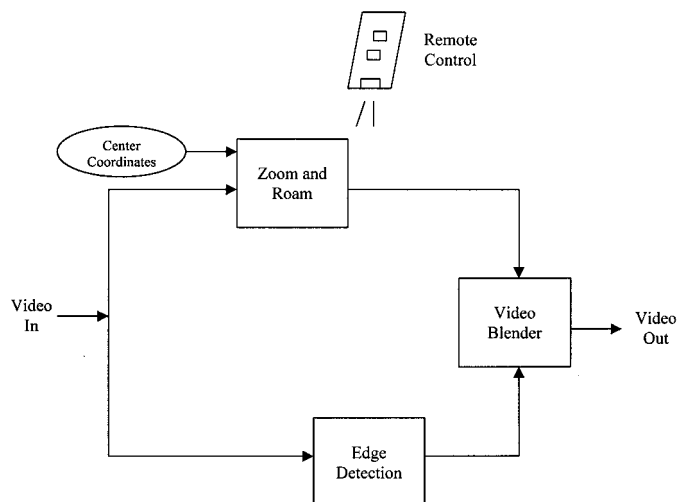
FIGURE 10.
A block diagram of the dynamic position of magnified view in TV system. The zoom system will accept the coordinates of the image point to be centered at each frame and enable control of magnification via a remote control. The edge detection system will generate contour representation of the full video frame. The video blender will combine the images. The output video will include the magnified properly centered image and, superimposed on it, the contour diagram of the whole video frame.

image as required and shift it to center the selected portion on the screen. In addition, it is possible for the user to override this function such that other parts of the magnified image may be scrolled onto the screen and viewed. The override or roaming function is likely to be useful only in static situations and scenes. In fast-moving scenery (as in a typical movie), there is no time to scan the scene before it changes. However, there are many television programs, varying from game shows to talk shows, where such an override may be useful. In addition to its use for television viewing, the same system can be used for any videotape, DVD, or other method of presenting motion videos.

The concepts of dynamic control of magnified display and multiplexing described above can be combined using wide-band enhancement. The full image may be processed to obtain the enhanced display by superimposition of the contour edges over the displayed image. If the image is magnified, the contour edges may remain unmagnified. This hybrid presentation would provide the patient with increased resolution of the important details via magnification. However, at the same time, the contour outline will provide a view of the original video frame compensating for the limited field of view inherent in the magnified view. Using the outline view, the patient may choose when to reduce magnification for a larger field of view or when to override the frame centration and explore by manual control other parts of the video. This returns the situation to the spatial multiplexing discussed above. The only difference is that here the field restriction for which we correct is due to the magnification, not the patient's visual system. Again, this illustrates that the various approaches proposed here can frequently be combined to provide added benefits. Note also that when the magnification is reduced to unity, the overlaid contours provide a wide-band image enhancement.[61] The same wide-band enhancement could be used in a see-through HMD to provide an enhanced view of the real scene seen through the display (Fig. 11).
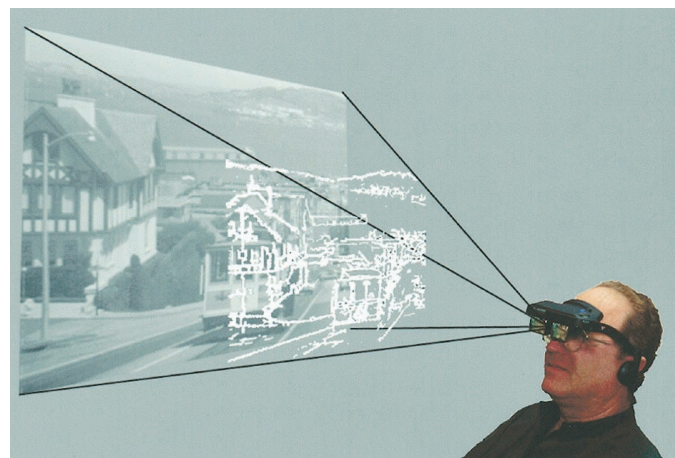
FIGURE 11.
An illustration of the concept of augmented vision using wide-band enhancement for patients with CFL. The edge map computed from a video of the see-through scene is superimposed on the display as bright contours. Here the visual field of the camera is identical to the angular span of the display, and exact registration is required (unlike the system illustrated in Fig. 3). The two views also have to be aligned, which may not be easy to achieve.

In this application, as in the augmented vision for tunnel vision, discussed above, only bright contour lines can be used, whereas contours of both polarities may be used in the enhancement of television. The use of wide-band enhancement is also more challenging because it requires alignment of the contour lines with the see-through image. Such alignment is neither needed nor possible with the tunnel vision application.

CONCLUSION

Developing visual aids is an important aspect of vision rehabilitation. One is always seeking guiding principles in the development of new devices and techniques. Attention to the way the visual system performs its remarkable tasks in the normally sighted observer is a very useful place to start searching for these clues to success. In noting the well-known interplay of central and peripheral vision in integrating vision, the concept of vision multiplexing was developed as a useful guide. The idea of multiplexing has led to a number of the new approaches and devices proposed here. Designing the various devices was relatively easy once the general concept was conceived. Developing these many ideas into a useful or at least testable products and carrying out such evaluations will be the more daunting task. The difficulties we face ahead were discussed in a symposium on the subject at the 1990 meeting of the Academy of Optometry and subsequently in a special issue of this journal.[62] The rewards of development of even one successful low-vision device, however, override any concerns about the journey there.

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