Vision multiplexing:
An optical engineering concept for low-vision aids

Eli Peli[*]
Schepens Eye Research Institute, Department of Ophthalmology, Harvard Medical School
Boston, MA

ABSTRACT

The normal visual system provides a wide field of view apparently at high resolution. The wide field is continuously monitored at low resolution for navigation and detection of objects of interest. These objects are sampled using the high-resolution fovea, applying a temporal multiplexing scheme. Most vision impairments that cause low vision impact upon 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. Traditional low-vision aids improve the impacted component, but usually at a cost of a significant loss in the surviving component. For example, magnifying devices increase resolution but reduce the field of view, while minifying devices increase the field of view but reduce resolution. A general optical engineering approach — vision multiplexing — 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. The use of various optical and electro-optical methods in the development of a number of new visual aids, all of which apply vision multiplexing to restore the interplay of high-resolution and wide-angle vision using eye movements in a natural way, will be described. Vision-multiplexing devices at various stages of development and testing illustrate the successes and difficulties in applying this approach for patients with tunnel vision, hemianopia (half blindness), and visual acuity loss (usually due to central retinal disease).

Keywords: bioptic telescope, in-the-lens telescope, IOL, macular degeneration, peripheral prisms, retinitis pigmentosa

1. INTRODUCTION

Low vision or vision impairment affects mostly the elderly. As the population of most developed nations is aging, both the absolute number of people with visual impairment and the proportion of the population that is visually impaired are expected to increase rapidly. Of Americans aged over 40, 3.7 million (2.9%) have low vision (visual acuity < 20/60), 937,000 (0.8%) are blind (visual acuity < 20/200) [1], and 1.75 million (1.5%) have age-related macular degeneration (AMD) [2]. The most common cause of blindness, AMD, affects the central retinal section used for high-resolution vision (the fovea and its surrounding macula), sparing peripheral vision. Central vision loss (CVL) affects the ability to read, recognize faces, watch TV, and drive. Peripheral field loss (PFL), which affects patients suffering from glaucoma, Retinitis Pigmentosa (RP), and hemianopia, limits patient mobility due to difficulties in orientation, navigation, and spotting obstacles [3]. About 2% of adults over the age of 40 years suffer from glaucoma [4, 5] and an estimated 0.020% to 0.035% of individuals have RP [4, 6]. Patients with residual peripheral vision in the better eye limited to 20º of visual angle are considered legally blind. The impact of visual field restriction on mobility is severe when the residual field in both eyes is limited to 10º [7]. Homonymous hemianopia is a frequent consequence of brain damage from stroke, injury or surgery to remove tumors. In the USA there were almost 5 million stroke survivors in 2002 [8], and at least one third of stroke survivors in rehabilitation have either homonymous hemianopia or spatial neglect [9]. Hemianopia is a loss of vision in half of the visual field (on the right or the left) in both eyes. Hemianopic patients complain of bumping into obstacles on the side of the visual field loss and getting bruised. The rate of such incidents may decrease with time, presumably because patients become more cautious to avoid the pain. However, many patients continue to suffer from the effects of hemianopia [10].

The visual system has evolved to provide us with a wide field of view (about 180 deg. horizontally) at an apparent high resolution (about 1 min. of arc). There are no displays or imaging devices that even approach these capabilities.

---

[*] eli.peli@schepens.harvard.edu; phone 1 617 912-2597, fax 1 617 912-0112, http://www.schepens.harvard.edu/faculty/peli

Achieving high resolution over that wide field instantaneously also far exceeds the capacity of the optic nerves. The visual system achieves this performance using temporal sampling and variable spatial resolution. While the wide field of view is continuously monitored at a low resolution, it provides sufficient information for navigation and detection of targets of interest. The central high-resolution fovea (about 1º in diameter) samples targets of interest at only about 3-5 samples per second, using eye movements. Thus, the high-resolution information from a few areas of interest are temporally multiplexed and provided to the brain. Combined with effective reconstruction algorithms, this 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.

Most disabling visual conditions that impair vision impact upon only one of the components, the peripheral low-resolution wide field or the central high-resolution fovea.

The loss of one of the visual system's components prevents the interplay of central and peripheral vision essential for the high performance discussed above, leading to loss of function, impairment and disability. Devices designed to aid people with low vision traditionally addressed these problems by attempting to replace or supplement the missing function, usually at cost of impacting the residual function. Devices that increase resolution through magnification rob the patient of the functional peripheral vision necessary for navigation and safe mobility [11], and therefore have limited usefulness when used in these situations. Minifying devices such as spectacle-mounted reversed telescopes have been used to increase the span of the field seen instantaneously by a patient with tunnel vision [12]. However, these devices reduce the resolution of the central field and require head movements for scanning over a wider field of view [13]. Most prism devices used to treat hemianopia fail to expand the visual field [14], as discussed further below.

I proposed an optical engineering approach that may resolve many of the limitations of previous devices [15, 16]. That approach, called *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 to the visual system. In implementing vision multiplexing we developed a number of novel devices, and tested them in variety of laboratory and real world environments. The emphasis in this work is not on the traditional image quality measures (although optical quality is as crucial here as in any other optical device) but rather on the human factors engineering. Considerations are particularly given to the way the devices are to be used, with the aim of making them more effective, intuitive, and comfortable to apply. A secondary but highly important consideration is the visual appeal of the devices. As these devices are worn on the face the way they look may be almost as important as the way things look through them. Thus in all our projects much attention is paid to designs that will be cosmetically acceptable to the potential users.

A vision multiplexing visual aid should combine the missing visual component (high resolution or wide field) with the residual one (wide field or high resolution, respectively) in a way that is accessible to and usable by the visual system. Thus, for the patient with visual acuity loss (CVL), 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 (rather then replace) 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. The approaches we implemented include *spatial multiplexing*, in which the two views are superimposed on each other or are shifted relative to each other; *temporal multiplexing*, in which they alternate in time; *biocular multiplexing*, where two different views are presented to the two eyes; and *spectral multiplexing*, in which the views are separated by color. More than one of these multiplexing approaches may be implemented in the design of a single device, providing more flexible and robust multiplexing capabilities.

2. TEMPORAL MULTIPLEXING

2.1 Bioptic Telescopes for low visual acuity

Spectacle-mounted and head-mounted telescopes have been used to compensate for loss of visual acuity. The magnification provided by the telescope effectively improves the resolution capability of these patients. Objects seen through the telescopes may be recognized from distances at which they will 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 12º for 8.0× to 3.0× telescopes, respectively) [17]. With such a narrow field, navigation in the visual environment is difficult (and may be dangerous) and requires scanning head movements. Spectacle-mounted telescopes may be mounted centrally in the spectacle lens for constant use (as is common in Europe), or near the edge of the lens for intermittent use (bioptic), as they are commonly fitted in the USA. The magnified visual motion of the environment as seen through the telescope conflicts with the vestibular head movement signal from the inner ear. This may limit adaptation to telescopes worn centrally and used continuously [18]. A bioptic telescope is usually 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), benefiting from the intact peripheral vision. When a distant object is detected which cannot be recognized due to the reduced acuity, the patient tips his head slightly down, bringing the object of interest into the field of view of the telescope. A short examination (1 to 2 sec.) 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 telescopes are now permitted as visual aids to driving in 36 states in the USA [19]. While driving, the bioptic telescope is used mostly for reading road signs and street names, and examining traffic lights, and is in use only about 5 percent of the time [20]. In non-driving situations the telescope is used even less frequently, yet it provides convenient, easy, comfortable and safe access to detailed vision at distance. Temporal multiplexing with a bioptic telescope is probably very efficient and easy to learn and use, since it functions very much like the natural sampling of the environment with normal foveal vision.

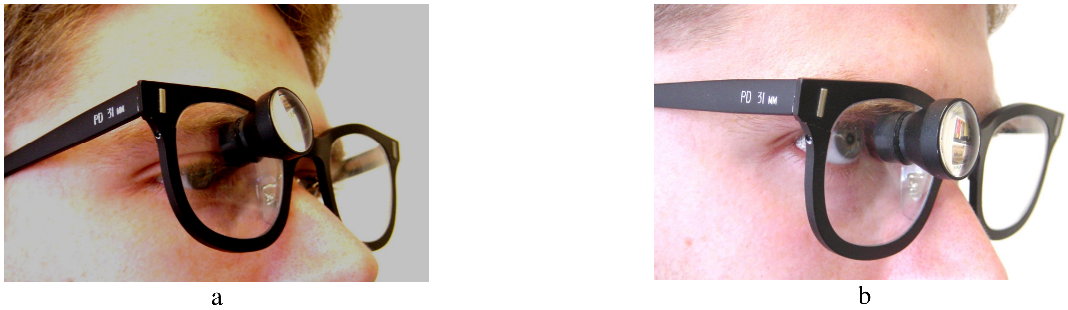


Fig. 1. Temporal multiplexing with a bioptic telescope. a) most of the time the patient is viewing through the carrier lens (under the telescope). b) When an object of interest is spotted through the carrier lens, a slight head tilt forward brings the telescope in front of the pupil and the object of interest into view through the telescope. A 3.0× Galilean telescope by Designs for Vision Inc. (Ronkonkoma, NY) is shown.

2.2 Bioptic minifiers for tunnel vision

Spectacle-mounted reversed telescopes providing minification have been used as aids for patients with tunnel vision [12, 21-24]. The use of minification seems to be logical, but frequent rejection of these devices has been reported [23, 25, 26]. Those studies' findings suggest that the rejection or failure could be attributed mainly to two factors: the resolution loss and change in perceived visual direction resulting from minification. The minifiers were originally fitted centrally in the carrier lens, and were designed to be used constantly. To deal with the objectionable loss of resolution, a field expander telescope worn in a bioptic position, above or below the center of the lens, has been suggested [12, 27]. This *temporal multiplexing* may appear at first to be equivalent to the use of a bioptic telescope for loss of acuity, but the two situations are not symmetric. When using a bioptic magnifier, the patient can see an object through the carrier lens that can not be resolved and requires the use of the telescope, while a tunnel-vision patient wearing a bioptic minifier is not aware of objects to be detected (e.g. obstacles) that were missed through the carrier. The wearer thus has no external cue telling him when to use the minifier. Patients using a bioptic minifier, therefore, need to glance frequently into the expander to notice objects that they would not otherwise be aware of. It is not known if random or regular glancing into a bioptic minifier would be a sufficient or effective strategy. Thus, the use of bioptic minifiers has had minimal acceptance. Temporally-multiplexed use of bioptic minifiers might be useful for orientation, as when the user wants to look for street signs or other indications of current location. However, no research has evaluated such use.

2.3 Combined spectacle-intraocular lens telescope

A combined spectacle-intraocular lens (IOL) telescope for patients with macular degeneration was proposed and implemented. In the basic design, a high-negative-power IOL is implanted in place of the eye's crystalline lens, and, in combination with a high-positive-power spectacle lens, it provides telescopic magnification [28, 29]. A bifocal-IOL improvement for this system was developed by Allergan Inc. [30, 31]. In this system the high negative lens occupies only a small section in the center of the IOL. The patient can benefit from the magnification when wearing the appropriate high-power spectacle lens, or use the periphery of the IOL as a standard IOL without the magnification, but with an unrestricted peripheral field. The system underwent preliminary FDA testing. Despite the positive optical results reported from the clinical trial [31], it has not been brought to market (though for a few years essentially an identical system was marketed in Europe by Morcher, Germany). The high-power spectacle lens (about 30 diopters) was constructed as a doublet in an unsightly large and heavy frame. In all reported studies [31, 32], patients either did not benefit from the telescope or they refused to use the spectacle component at all. As far as I could determine, the spectacle portion of the Morcher system was only applied on a temporary basis in one small study in Holland [33]. Thus, most patients implanted with this "AMD – IOL" never received the spectacle correction that activated the potential magnification. Bailey [34] analyzed the performance of the system, using ray-tracing, and has argued that although the spectacle-IOL system had a slightly wider instantaneous field of view than bioptic telescopes, it severely limited the effective field of view, because it prevents scanning with eye movements and requires scanning with head movements [35]. This severe limitation of field together with the inconvenience associated with the need to wear and remove the unsightly spectacle system may account for the rejection of this system.

I have patented an improvement for this system that implements *temporal multiplexing* by using a double bifocal spectacle-IOL system [36], where both the IOL and the spectacle lenses are bifocals (Fig. 2). In this design, most of the time the user looks through the carrier lens using the periphery of the IOL in combination with a standard pseudophakic correction for a full field of view. When noting an object of interest that can not be resolved, a small head tilt down brings the high-power bifocal spectacle lens segment in front of the pupil, providing the magnification in combination with the high negative center of the IOL. This magnification-on-demand is convenient, and the small size of the high-power lens makes it possible to obtain reasonable optical quality in a format that is acceptable cosmetically. This temporal multiplexing system was never tested, as Morcher discontinued the distribution of the IOL. This is an example where attention to the optical quality of the system, to the detriment of attention to the cosmetic effect and the mode of use, may have resulted in a lost opportunity for a useful device to succeed in the marketplace.

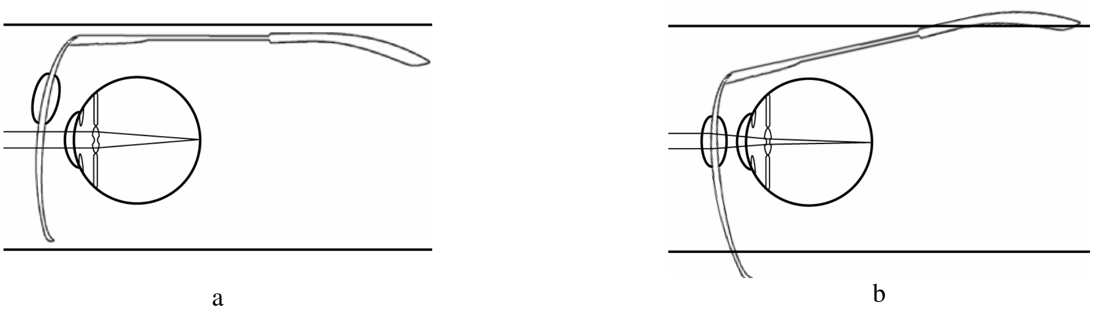


Fig. 2. Temporal multiplexing with a double bifocal spectacle-IOL telescopic system. a) When viewing through the carrier lens the periphery of the IOL provides standard pseudopahkic correction with a wide field of view. b) A slight head tilt forward brings the high-power bifocal segment on the carrier in line with the pupil and, combined with the high-power negative lens at the center of the IOL, a magnified view with a restricted field of view is achieved.

3. SPATIAL MULTIPLEXING BY SHIFTING

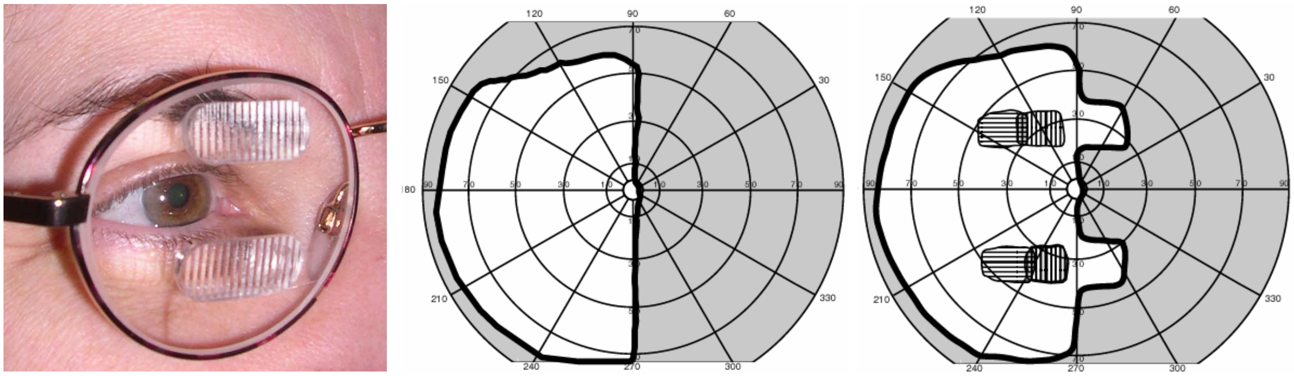
3.1 Binocular Peripheral Prisms for hemianopia

Hemianopia causes problems with obstacle avoidance when walking, especially in crowded environments like shopping malls, airports, and train terminals, and can cause distortion of space perception [37]. In 22 states, driving is prohibited for people with hemianopia, while in many other states they are discouraged from driving [38]. As 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 accident record is not known, as very few hemianopes were included in the one large study of driving records of people with field loss [39].

Many devices have been considered and applied for the management of hemianopic visual field defects, mostly using prisms (though mirrors were also proposed in variety of designs, but with little success or acceptance). The effects of the prism devices may be classified as providing field relocation (shifting) or field expansion. Field expansion is the most desired effect, as it means that the instantaneously-seen visual field is larger with the device than without it. Field relocation, as implemented by previous designs, only exchanges the position of the visual field loss relative to the environment or relative to the head's midline. Binocular full prisms or binocular sector prisms [9, 40] provide only for field relocation [41]. Binocular full prisms add a prism with base to the side of the field loss (base left for left hemianopia) over the full area of both spectacle lenses. Sector prisms, the most commonly used technique, applies the same prisms only to part of both lenses (e.g., left of the pupil position on both lenses in the left hemianopia case). Once the patients adapt to these prisms and adjust their eye movements to compensate for the prismatic effect (which takes only seconds), these prisms provide no measurable effect or demonstrable value. Further, because high-power prisms degrade visual acuity [42] and cause objectionable spatial distortions [43], only very modest powers (up to 20 prism diopters (Δ)) are typically used, providing shifts of no more than 10º.

Visual field shifting may provide a benefit if the gained field is located more centrally while the loss is in the far periphery and if the peripheral field is shifted relative to the central foveal vision, which avoids the prism adaptation change in principal direction. This is attainable with a new method of visual field expansion, a binocular peripheral prism, a variant of the monocular peripheral prism approach [41, 44] discussed later. This new approach implements binocular prisms segments that are limited to the peripheral field (superior, inferior, or both) (Fig. 3a). High-power peripheral prisms are placed across both spectacle lenses, spanning both sides of the pupil, so that they are effective at most lateral positions of gaze. The base of the prisms is directed to the side of the visual loss (base right for right hemianopes). The binocular peripheral prisms improve the visual field via *spatial multiplexing by shifting*. An identical effect would be achieved for a patient who is hemianopic and has only one functional eye (the other eye is blind).

The binocular peripheral prism design described here, unlike the previous binocular prism devices, provides for field expansion that is measurable by standard perimetry (Fig 3c). The prisms shift the upper and lower field across the midline into the previously blind area. Of course, the same amount of monocular visual field loss occurs at the apex of the prisms due to the optical blind spot (scotoma) that always exists at the apex of a prism. The apex scotomas occur farther in the periphery and can be pushed even farther into the periphery by extending the prism in the apex direction. The peripheral binocular scotomas may be reduced or eliminated if the positions of the apices of the prisms in front of both eyes do not overlap (Fig 3c). This peripheral scotoma is not as debilitating as the loss of field right next to the vertical meridian, which is gained due to the shift. Thus this trade-off provides a significant benefit. Because the prisms are mounted in front of the upper and lower peripheral retina, where visual acuity is reduced, high prism powers may be used. We have used routinely 40Δ and have recently implemented 57Δ peripheral prisms, providing about 23º and 30º of expansion, respectively, in the upper and lower central fields.



a b c

Fig. 3. A binocular peripheral prism for right hemianopia. a) Permanent 40Δ prism sectors (Chadwick Optical (White River Junction, VT)) embedded in the carrier lens base right for both eyes. b) The binocular visual field of a patient with right hemianopia (Shaded areas represent blind areas). c) The visual field of the same patient wearing binocular peripheral prisms. Two areas of about 20º of field expansion to the right of the vertical meridian are gained while similar monocular blind areas due to the prism apex scotomas appear in the left peripheral field, one from the right lens (vertical striations) and one more peripheral from the left lens (horizontal striations). The monocular optical scotomas overlap only slightly, and a binocular scotoma exists only where they overlap. The size of that binocular scotoma may be decreased by extending the prism segments on the left lens farther to the left.

4. SPATIAL MULTIPLEXING BY SUPERPOSITION

4.1 Minified contours augmented view for tunnel vision

To provide field expansion without losing resolution in the central field, we proposed an augmented-vision head-mounted display (HMD) system implementing *spatial multiplexing by superposition* (Fig. 4) [16, 45-47]. The novel system employs an optical see-through HMD that superimposes minified (0.2 - 0.3×) contour (edge) images of the ambient scene over the wearer's see-through natural vision. Because the contour pixels in the display only occupy a very small portion of field of view, they do not substantially occlude the wearer's natural see-through view, preserving the full resolution while simultaneously providing a low-resolution wide-field view.

The patient's ability to control the camera's position with head movements separate from eye movements provides an additional level of flexibility. The patient can maintain fixation through the display on one object and 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. Simulation videos of the appearance of an augmented view can be accessed on our web page:

http://www.eri.harvard.edu/faculty/peli/lab/videos/augmented/augmented.htm.

Following a preliminary evaluation of a number of systems constructed using off-the-shelf components [46], a monocular see-through HMD system was developed for us by MicroOptical (Westwood, MA), providing a 16º×12º field of view. A miniature camera, mounted on the opposite temple from the display (Figure 4a), captured video images of ambient scenes. Contour video images shown in the HMD were generated first by an edge detection processor developed by DigiVision (San Diego, CA). Later-generation systems incorporated the edge detection capability (Figure 4b & c) into the MicroOptical system drivers packaged into a cigarette-box-size pocket system.

Early pilot trials with the device found that patients with tunnel vision had difficulties perceiving the direction of the real targets, despite seeing the target contours in the HMD. It was determined that the patients could not tell where within the display they were looking, and therefore they had difficulty initiating the head movements required to register the minified view to the real world view. A pair of crosshairs was implemented in software to serve as a center mark as well as a registration mark. When a target contour is noted in the display, moving the head to align the crosshairs with the target contour image brings the real target into the see-through view.

a b c

Fig. 4. An augmented-vision head mounted display system for the left eye. a) A miniature camera beside the right eye captures video images of the ambient scenes, and the cartoon-like minified wide-angle contour view is overlaid in a small area at the center of the normal see-through view, using the beam splitter. b) A see-through view photographed through the lens is shaded here to illustrate the 15˚ visual field of a possible patient. c) An enlarged view of the minified display in b. The woman and trash container can be detected in the minified view, but would be missed without it. The user can see the minified contour images and the ambient scene through the display simultaneously.

A number of studies were carried out with this system to examine the utility of both the daylight [47-49] and the night vision [50, 51] versions of the device. (Many potential users with RP suffer from night blindness.) We have found that even with minimal training, the superposition of minified contours enabled a faster search and a more direct search pattern for the gaze [48]. Using the minified contours only, subjects are able to properly judge impeding collision in a walking simulator [49], suggesting that the contour image is sufficient for response, not only for detection of obstacles.

5. BIOCULAR MULTIPLEXING

5.1 Implantable miniaturized telescope

A completely implantable miniaturized telescope (IMT) was developed and tested recently by VisionCare Inc. (Saratoga, CA) [52-55]. A small optical device, configured as a Galilean telescope, is implanted inside the eye in place of the cataractous crystalline lens. The IMT is inserted and held in position using a surgical procedure similar to that employed when inserting a standard IOL in cataract surgery. Only standard spectacle correction is required for distance vision or for reading. The main advantage of the IMT over a spectacle- or head-mounted low-vision telescope and the spectacle-IOL system is the flexibility to scan 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 [35].

The IMT is designed for monocular use in patients with bilateral acuity loss due to macular diseases. It provides 2.2× or 2.7× magnification with a field of view of 24º or 20º, respectively (though an earlier model had narrower fields of views). The fellow eye is used to monitor the peripheral field and enable safe mobility. Thus this system applies *biocular multiplexing*. Results of the most recent clinical trial with 217 patients [55] are encouraging, as they demonstrated a mean improvement of 3.5 lines in distance visual acuity for the implanted eyes, compared with only 0.8 lines for the fellow eyes. (56% of patients were implanted with the 2.2× model.) However, binocular improvement in visual acuity was not reported [55], and might not have been as large as it could have been, since most patients were implanted in the poorer eye, as required by the FDA. That protocol limited the ability to evaluate the full potential impact of the device on the patients. Improvement in quality of life, based on questionnaires was reported, but the number of patients that actually used the implanted eye for any activities of daily living was not reported. Anecdotal reports, including my own evaluations of a few patients, demonstrate that some patients could use the implant eye for high acuity tasks such as watching TV, and the fellow eye for mobility. Thus they demonstrated that the biocular multiplexing condition might be acceptable [53]. However, patients that ended with better acuity in the fellow eye generally did not use their implanted eye at all. Evaluation of patients implanted in the better eye is needed. Better ways to facilitate patients' use of this biocular multiplexing device are discussed below.

6. COMBINING MULTIPLE MULTIPLEXING MODES

Various multiplexing modes can interact and be integrated into the same device to provide more flexible and better functional aid. Next, I review a number of low-vision devices that implement more than one multiplexing mode.

6.1 Biocular multiplexing and temporal multiplexing

6.1.1 Monocular Bioptic Telescopes

Spectacle-mounted telescopes can be fitted to one or both eyes. When fitted binocularly, the bioptic use implements *temporal multiplexing* as described in section 2.1. If a 10º field-of-view is visible through 4.0× binocular telescopes, the image occupies retinal areas of 40º in both eyes. The difference between the 10º and 40º diameters represents retinal areas that can not be used to image other parts of the scene (see Fig. 6a below). Thus, a 4.0× binocular telescope with a 10º field-of-view will have a 15º wide ring scotoma that obscures the surrounding environment. This ring scotoma is a direct result of the magnification and has nothing to do with the structure of the telescope case. Professionals who object to the use of the bioptic for driving frequently raise the presence of the ring scotoma as a cause for concern [56]. In most cases, however, the bioptic is fitted over one eye only (monocularly). It has been argued that the other eye, if it is functional, can continue to monitor the area corresponding to the ring scotoma and thus avoid this potential difficulty [57, 58].

A monocular bioptic telescope, as used by a patient with two functional eyes, implements *biocular multiplexing*. When viewing through a single telescope, the fellow eye continues to see that part of the environment that is lost in the ring scotoma of eye with the telescope. This might be an important safety feature, as 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. It should be noted however, that the reports regarding the ability of the fellow eye to monitor the area corresponding to the ring scotoma [57, 58] are based on standard perimetry, where the ability to detect light or a target over a blank background is determined. It is possible that binocular rivalry and suppression may impede such functionality when both eyes are seeing real-life complex images, especially with moving objects and while the telescope user is in motion. Studies to evaluate this are underway in our lab.

6.1.2 IMT with partially occluded spectacle lens

The implantable telescope in one eye requires implementation of biocular multiplexing. Some patients appear to be able to use each eye for different tasks as necessary. Using *dichoptic* perimetry, in which stimulus and fixation targets were presented to separate eyes, we were able to show that some patient are able to detect targets on a blank background with the fellow eye, when fixating with the implant eye. However there is, as yet, no direct evidence reported that any patient is able to use both eyes simultaneously in activities of daily living. Some patients clearly alternate between the eyes, and a few seem to be able to trigger a switch using a blink, while others have difficulties. To facilitate switching between the eyes, I have developed a temporal multiplexing approach using a partial occluder on one of the spectacle lenses. A telescope implanted inside the eye can not collect enough light to compensate for the magnification, due to the small entrance pupil. As a result, an IMT with 3.0× magnification result in retinal images dimming on the order of 1 log unit [35]. Since, in binocular rivalry, the eye with the brighter image usually dominates, one might expect the fellow eye to be dominant for most patients, even if the acuity in that eye is much poorer post implantation. This is actually desirable, as the wide field of view of the fellow eye is necessary for safe mobility and orientation. Thus, with both eyes open, the patient might be expected to suppress the implant eye. Using a partial occluder, made from a frosted tape (as shown in Fig. 5), the patient can block the view from the fellow eye using a slight head tilt, similar to the use of a bioptic. With the fellow eye blocked, the implant eye with its magnification can now be used to examine the fine details of targets of interest. The occluder may be needed all the time, or it might be used just for training the patient to control eye dominance at will. If the patient can learn to control the dominance and switch eyes without the occluder, the tape can be removed. With the tape in place, the system implements a combination of biocular and temporal multiplexing. If, for some reason, the telescope eye dominates when both eyes are open, a similar partial occluder in front of the telescope eye may be used to switch the roles. That narrow strip of tape may be mounted in front of the pupil on the carrier lens of the implant eye, permitting telescope use with the same head tilt down.

Fig. 5. Biocular and temporal multiplexing with the implantable miniature telescope (IMT). a) When looking with both eyes, the fellow (left) eye is dominant and enables safe mobility with a wide field of view. b) When wishing to examine an object of interest in detail, the patient can tilt her head down, blocking the view of the fellow eye with the frosted tape occluder. This renders the telescope eye dominant and enables use of the magnification on demand.

6.2 Spatial multiplexing by shifting and temporal multiplexing

6.2.1 Micro-telescopes

Although bioptic telescopes implementing temporal and biocular multiplexing can be used effectively in a variety of settings, many visually-impaired people reject them [59]. The obvious and unsightly cosmetic aspects of these prosthetic devices have been identified as a major reason for the reluctance of people with visual impairment to use bioptic telescopes. Very small telescopes may reduce this problem, and thus a number of such micro telescopes were introduced [60-62]. Very small telescopes are limited by their very small field of view and dim images. However, it was noted that they may be used in a way that provides for *spatial multiplexing by shifting,* in addition to their *temporal (and biocular) multiplexing* characteristics. For example when the BITA micro telescope is positioned on the carrier lens at a slight inclination just above the position where the line of sight intersects the lens in the primary position of gaze, it was found to provide what was termed Simulvision [60]. With the telescope in this position, the user can see a magnified view of a part of the scene that appears just above the non-magnified view of the same area seen through the carrier lens. (A similar effect is illustrated in Fig. 6b.) 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. We have confirmed that BITA and the Behind the Lens telescope [63] actually enable multiplexing by shifting, by showing that the magnification (“ring”) scotoma of these telescopes is shifted above and below the field of view of the telescope, respectively [64]. This mode permits the user to obtain the magnified view without disrupting the full horizontal field of view. Increasing the number of multiplexing modes available increases the flexibility of the device and its utility.

6.2.2 In-the-lens telescope

To overcome many of the limitations of previous bioptic telescope designs, we designed a telescope built into the spectacle lens [65, 66]. This design allows a relatively wide field of view, high magnification, and a bright image, while being cosmetically appealing and permitting the wearer’s eye to appear natural. The design also lends itself to spatial multiplexing by shifting (Fig. 6), in addition to its customary temporal-multiplexing use, and it could be use monocularly (biocular multiplexing) or binocularly.

The principal concept of the in-the-lens telescope involves periscopic folding of the optical path inside the lens itself. This can be implemented very simply for a Galilean design [65] by simply inserting periscopic mirrors into the lens. The magnifying elements may be lenses or mirrors attached to the lens surface or embedded in it. Keplerian telescopes have many advantages. Following a number of preliminary designs and prototypes using laminated lenses or off-axis parabolic mirrors as the power elements, we chose to implement the design shown in Fig 7a. This approach twice employs magnifying elements of the type used in the MicroOptical in-the-lens electronic display [67].

a

b

Fig. 6. Simulated view of a road sign viewed through a 3.0× telescope. a) The view through a conventional binocular bioptic. The magnified image on the retina blocks the view of much of the intersection, creating a ring scotoma (blind area). b) Spatial multiplexing by shifting. The rectangular field of view through the in-the-lens telescope described here. The magnified image is shifted up, blocking in part the view of the pedestrian bridge overhead but leaving the traffic in the intersection in full view. Note the non-magnified view of the road sign seen under the magnified view. The white line surrounding the magnified images is added only for clarity of these illustrations.

Light entering the carrier lens is reflected by the first beam splitter (BS1) towards the concave mirror serving as the objective lens. The reflected light passes down through the beam splitter, traveling through the carrier lens, forming an intermediate image plane, and proceeding through the second beam splitter. On the way, two additional mirrors complete the image erector needed by Keplerian telescopes. The light reflected off the second spherical concave mirror (the ocular) is then reflected by the second beam splitter into the user's eye. This arrangement provides a terrestrial telescope, but may result in large light loss (94% due to 4 passes through the beam splitters. The light loss can be substantially reduced using polarizing beam splitters and quarter wave plates (Fig. 7).

The first polarized beam splitter results in at least 50% loss of light. Following reflection in the objective curve mirror and passing twice through the quarter wave plate, the reflected light will be polarized appropriately to pass largely unaffected (80%) through the polarizing beam splitter. The light will then be polarized appropriately to be reflected at the second beam splitter without further loss. Thus the total light loss can be limited to about 80% (about 3 times better). The light loss can be compensated for in part by increasing the width of the objective lens, providing more light collection. This is easy to achieve in this design by expanding the objective lens/mirror horizontally. The orientation of the beam splitters is such that their height is limited by the carrier lens thickness but not their width. The width of the field is limited only by the size of the ocular lens. Thus the Keplerian-design in-the-lens telescope has an added advantage that the width of the field of view may be large even for a fairly thin carrier lens (Fig. 7b). The same relaxed constraint on the horizontal dimension of the objective lens permits a wider objective, which increases light collection without affecting the field of view.

The Keplerian design lends itself well to spatial multiplexing by shifting. Tilting beam splitter BS2 a few degrees clockwise shifts the magnified image up, as illustrated in Fig. 6b. This provides the user with an open, wide, horizontal field of view, at the same level as the object that is seen through the telescope, thus combining temporal multiplexing with spatial multiplexing by shifting. If only one telescope is used, the system also implements biocular multiplexing. A prototype is now under construction.

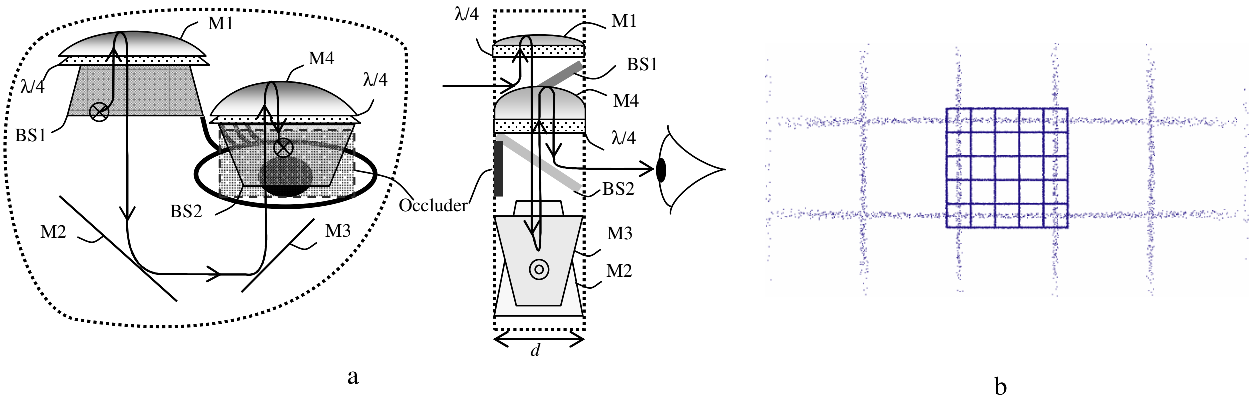


Fig. 7. In-the-lens telescope. a) Front and side views of the Keplerian design in-the-lens telescope using polarizing beam splitters and spherical mirrors. Quarter-wave plates (λ/4) are inserted between the cube beam splitters and the mirrors. Half of the light is lost at the first reflection in the beam splitter, but ideally the quarter-wave plate assures that the light reflected from the mirror is polarized to pass unaffected through the beam splitter. The same effect is maintained twice in the second beam splitter. The occluder in front of the ocular beam splitter is required to block the see-through view and increase the contrast of the magnified image. The ocular beam splitter BS2 may be tilted slightly clockwise, and that will result in the image being shifted upward, creating the spatial multiplexing by shifting illustrated in Fig. 6b. b) Image computed for two square 5×5 grid objects, subtending 5º and 20º respectively. The image illustrates the wide horizontal field of view and minimal distortion associated with this design.

6.2.3 Minified contours augmented view with temporal multiplexing

The minified-contour-based augmented vision system can utilize *temporal multiplexing* in addition to its *spatial multiplexing by superposition*. By using an edge-detection algorithm that only detects edges of objects in motion [68], the patient can control edge detection in a static environment by controlling the camera movement 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 (but supra-threshold) head motion to temporally control the level of contour display available at any instant. This concept has not been implemented or tested yet.

6.3 Biocular multiplexing and spatial multiplexing by shifting

6.3.1 Monocular peripheral prisms for hemianopia

The binocular peripheral prisms described above expand the field via *multiplexing by shifting*. If the prism segments are fitted only monocularly (usually on the lens on the side of the field loss), they also invoke the effect of *biocular multiplexing*. Previous monocular sector-prism designs [7, 69] also expand the field, once the patient changes his fixation to within the field of the prism. The monocular sector prism has no effect on the field of view, as long as the patient's eyes are at the primary position of gaze or are directed away from the hemianopic field. It is interesting that no one has ever documented that expansion in the literature. Diplopia (double vision; seeing the same object in two directions simultaneously) and confusion (seeing two different objects at the same perceived direction) accompany the field expansion achieved with these devices upon directing the gaze into the field of the prism. Confusion, in this case, represents the intended beneficial effect, as it represents the appearance of an object that would be invisible without the prism. However, the central diplopia and confusion that accompany it are very unpleasant and may account for the lack of success of this approach [40, 70]. In contrast, our monocular sector prisms that are limited to the peripheral field (superior, inferior, or both) (Fig. 3) expand the field at all positions of gaze via *peripheral* confusion and diplopia. Peripheral diplopia is much more comfortable and acceptable for the user than central diplopia, since peripheral physiologic diplopia is a common feature of normal vision [71]. The field-expansion effect of the prism is unaltered by eye and head movements over a wide range of such movements to either side leaving binocular foveal vision unaffected. The field expansion provided by this effect is similar to that benefiting some exotropic (outward deviated eye) congenital hemianopes [72-74].

The original design of the peripheral prisms provided a lateral visual field expansion of about 23°, above and below the line of primary gaze, as shown in Figs. 3 and 8b. This expansion is useful for detection of low obstacles and for overhanging obstacles, as well as tall obstacles (e.g. utility poles, doorframes). However, the central part of the hemianopic VF between the two segments remains unaffected. This visual field expansion contributes only minimally to the view through a car’s windshield (Fig. 8a). Using these prisms for driving is of major interest for patients, authorities, and caretakers. We recently patented and developed a new concept of oblique peripheral prisms [75], shown in Fig. 8c. By simply rotating the two peripheral prism segments (without changing their location on the carrier lens) we are able to extend the effect of the peripheral prisms to cover a more-central (vertically) VF area (Fig. 8b). This is achieved without blocking the binocular central vision that is so important for the ease of use of this device. This design utilizes multiplexing by shifting in more than one way.

The peripheral prism design provides for a field expansion that is measurable by standard perimetry. A multi-center community-based study has been completed recently and found that the peripheral prisms provide assistance in detecting obstacles and avoiding collisions in crowded places [76]. We are currently completing an on-the-road driving study comparing the horizontal and oblique designs (in Belgium) and are starting a multi-center study comparing each of these designs to sham (low-power) prisms. The new oblique design of peripheral-prism glasses (Fig. 8c) was evaluated within the controlled environment of a driving simulator [77]. Data from pilot experiments showed that for a group of 3 subjects there was no difference in detection performance with or without the peripheral prism glasses. However for one of these patients, the peripheral prisms significantly improved performance on the blind side. Much more work is needed to understand the effect of these prisms on driving performance.

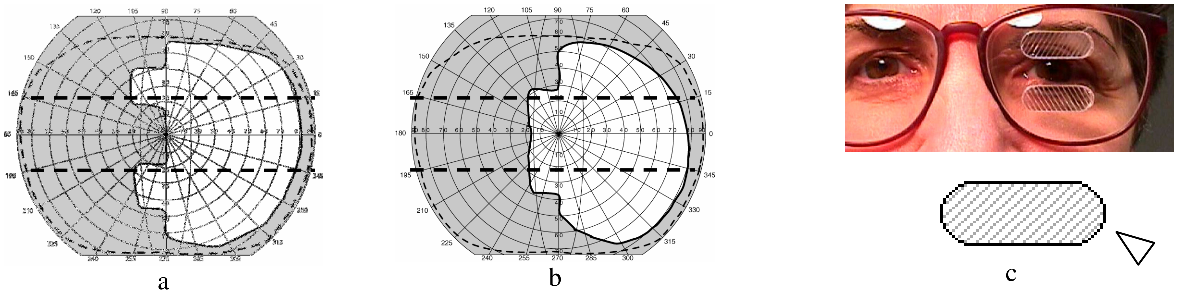

a b c

Fig. 8. Monocular peripheral prisms. a) The binocular visual field of a patient with left hemianopia with monocular horizontal peripheral prisms. Two areas of about 20° x 20° of field expansion are seen. The dashed curve is the binocular field of a normally-sighted person. The area between the two thick dashed horizontal lines delineates the field-of-view through a typical car windshield. b) The binocular visual field of the same patient wearing oblique peripheral prisms at the same peripheral position as shown in (c). The expanded field now covers the central section of the field. c) Top: The oblique prism in the permanent PMMA design. Bottom: The segment shape illustrating the tilt and the direction of prism base for the upper segment.

6.4 Biocular multiplexing, spatial multiplexing by superposition, and spectral multiplexing

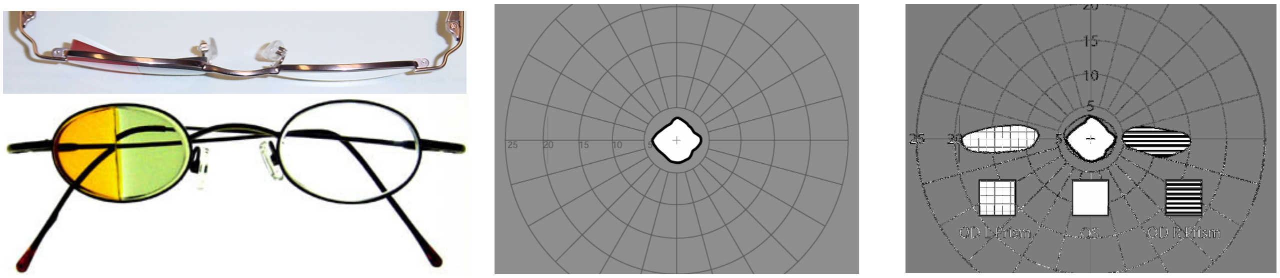
6.4.1 Tri-field prism correction for binocular tunnel vision

Previous prism treatments for patients with tunnel vision have been based on the field shifting (non-multiplexing) principle. These 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, altitudinal prisms are placed with the base down for the lower prism and base up for the upper prism creating a ring around the non prismatic center [78]. 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 prisms is presumed to shift the field of view 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 scotoma at the apex of the prisms, similar to that illustrated in Fig. 3c, and as a result, the user faces an additional optical scotoma in a ring of about 6° (for a 12Δ prism) around the central field of gaze with these spectacles. The InWave lens, that provided such correction in an attractive molded lens containing the patient's prescription, is not available any more, and I am not aware of any study reporting its use.

I developed a prismatic solution that combines the *spatial multiplexing by shifting* with *biocular multiplexing* [79]. This approach is only applicable for patients with two functioning eyes. These *Trifield* glasses consist of two prisms fitted apex to apex, separated by a vertical junction, over one eye (Fig. 9). The other (dominant) eye has a conventional correction. The prism eye receives visual information shifted laterally from the direction of gaze by the prism. The direction of shift depends on the prism, and the prism is selected by the direction of gaze. This creates visual field expansion in the direction of gaze. Unlike previous designs such as the InWave, with our design a visual field expansion can be demonstrated using perimetry (Fig. 9). No space or clear lens is needed between the prisms. The power of the prisms (expressed in degrees) should be equal or slightly larger than the horizontal extent of the larger field (better eye) to prevent diplopia. To help the patient determine the direction of the shifted image, we apply a red tint on one of the prisms and green on the other, adding a *spectral multiplexing* component to help distinguish the two overlapping images.

While the dominant eye is scanning the environment, the other 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 the right) that does not overlap with the scene segment seen by the dominant eye. Since the two scene segments that are simultaneously in view do not overlap, the patient does not have diplopia (which does result when these glasses are tried by a person with normal vision). However, since the two non-overlapping 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.

Later improvements to the original design included consideration of phoria in the prism power, because prism power must be sufficient to avoid diplopia. Thus the prism powers are often asymmetric [80]. In extended testing, two pilot patients evaluated a variety of designs. Implementation with press-on Fresnel prisms caused a reduction in visual acuity and contrast sensitivity that was unacceptable, and was replaced with ground ophthalmic prisms (Fig. 9). Clip-on sunshades (needed by most RP patients) also serve to hide the tinted lenses and improve the cosmetic appearance of the glasses. Selection of small frames reduced the thickness and weight of the prisms and improved cosmesis and comfort without limiting effectiveness.



a B c

Fig. 9. a) Top and front and views of the Trifield glasses showing a conventional spectacle correction over the left eye and a pair of tinted prisms over the right eye. The top view illustrates the placement of the red prism base right and of the green prism base left. b) The binocular visual field of a patient with RP (8.5°). c) The field increased to 34° when wearing the Trifield glasses. Only two of the three field sections shown in (c) are available at any one time, depending on the direction of gaze. Trifield ophthalmic lenses produced by Chadwick Optical.

The Trifield glasses were assessed in an extended wear trial [81]. Nine patients with advanced RP (with residual field range 7º to 22º), wore the Trifield glasses for 6 to 60 weeks. Patients reported detection of obstacles that would otherwise be outside their visual field, but they generally had difficulties determining the location of the obstacle, even with the prism tints. The Trifield glasses provided some benefit to patients, by giving warning of nearby objects and aid in searching for missing objects. However, the benefits were limited, and only experienced by 5 patients. Ten months after completing the study, 3 of 9 patients continued to use Trifield glasses. As discussed above daptation to (central) visual confusion is difficult, even when it provides VF expansion. Low wearing times (range 0.6 to 3.8 hours/day) of Trifield glasses may have reduced success, being insufficient time to adjust to the complex visual scene. An improved design is now being considered in an effort to reduce some of the limitations.

7. CONCLUSION

Developing optical and electronic visual aids is an important component of vision rehabilitation. One is always seeking guiding principles in the development of new devices and techniques. Attending to the way the visual system performs its remarkable tasks in the normally-sighted observer is a very useful place to search for such 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 such a useful guide. The idea of multiplexing led to a number of the new approaches and devices described here, and to a better understanding of the advantages and limitations of existing devices. Designing the various new devices was relatively easy, once the general concept was conceived. Developing these many ideas into a useful or at least testable product, and carrying out such evaluations, is a daunting task. The rewards for development of even one successful low-vision device, however, make the effort worthwhile.

8. ACKNOWLEDGEMENTS

Supported in part by NIH grants: EY12890, EY05957, EY10285, EY14723 and EY12912, and a grant from the Joint Clinical Research Center (of the Schepens Eye Research Institute and the Massachusetts Eye and Ear Infirmary).

Dr. Peli serves as a consultant to a number of companies mentioned. He has patents and patent applications pending regarding some of the technologies, and he has financial interests in several of the devices discussed herein.

9. REFERENCES

1. N. Congdon, B. O'Colmain, C. C. Klaver, R. Klein, B. Munoz, D. S. Friedman, J. Kempen, H. R. Taylor and P. Mitchell, "Causes and prevalence of visual impairment among adults in the United States," *Arch. Ophthalmol.* 122 (4), 477-485 (2004).
2. D. S. Friedman, B. J. O'Colmain, B. Munoz, S. C. Tomany, C. McCarty, P. T. de Jong, B. Nemesure, P. Mitchell and J. Kempen, "Prevalence of age-related macular degeneration in the United States," *Arch. Ophthalmol.* 122 (4), 564-572 (2004).
3. K. A. Turano, G. S. Rubin and H. A. Quigley, "Mobility performance in glaucoma.," *Invest. Ophthalmol. Visual Sci.* 40 (12), 2803-2809 (1999).
4. B. Robinson, C. J. M. Acorn, C. Craig Millar and W. L. Lyle, "The prevalence of selected ocular diseases and conditions," *Optom. Vis. Sci.* 74 (2), 79-91 (1997).
5. Prevent Blindness America, "Vision Problems in the U.S.," pp. 1-20, Prevent Blindness America, Schaumburg, IL (1994).
6. R. A. Pagon, "Retinitis pigmentosa," *Surv. Ophthalmol.* 33, 137-177 (1988).
7. R. T. Jose and A. J. Smith, "Increasing peripheral field awareness with Fresnel prisms," *Opt. J. Rev. Optom.* (December), 33-37 (1976).
8. M. Lethbridge-Çejku, J. S. Schiller and L. Bernadel, *Summary Health Statistics for U.S. Adults: National Health Interview Survey, 2002*, National Center for Health Statistics (2002).
9. P. W. Rossi, S. Kheyfets and M. J. Reding, "Fresnel prisms improve visual perception in stroke patients with homonymous hemianopia or unilateral visual neglect," *Neurology* 40 (10), 1597-1599 (1990).
10. E. Faye, "Peripheral field defects," in *Clinical Low Vision*, Ch. 19, 233-254, Little Brown & Co., Boston (1976).
11. E. Peli, "Limitations of image enhancement for the visually impaired," *Optom. Vis. Sci.* 69 (1), 15-24 (1992).
12. J. P. Szlyk, W. Seiple, D. J. Laderman, R. Kelsch, K. Ho and T. McMahon, "Use of bioptic amorphic lenses to expand the visual field in patients with peripheral loss," *Optom. Vis. Sci.* 75 (7), 518-524 (1998).
13. F. Fasce, P. Bettin, G. Luca and R. Brancato, "Effects of minification on visual performance in advanced glaucoma.," in *Vision Rehabilitation: Assessment, Intervention and Outcomes*, C. Stuen, Ed., 177-179, Swets & Zeitlinger, Lisse (2000).
14. R. L. Brilliant and L. H. Ginsburg, "Rehabilitation of peripheral field defects," in *Essentials of Low Vision Practice*, R. L. Brilliant, Ed., 251-265, Butterworth-Heinemann, Boston (1999).
15. E. Peli, "Treating with spectacle lenses: a novel idea!?," *Optom. Vis. Sci.* 79 (9), 569-580 (2002).
16. E. Peli, "Vision multiplexing: an engineering approach to vision rehabilitation device development," *Optom. Vis. Sci.* 78 (5), 304-315 (2001).
17. A. Nguyen, A.-T. Nguyen, R. P. Hemenger and D. R. Williams, "Resolution, field of view, and retinal illuminance of miniaturized bioptic telescopes and their clinical significance," *J. Vis. Rehab.* 7, 5-9 (1993).
18. J. L. Demer, F. I. Porter, J. Goldberg, H. A. Jenkins and K. Schmidt, "Adaptation to telescopic spectacles: Vestibulo-ocular reflex plasticity," *Invest. Ophthalmol. Vis. Sci.* 30, 159-170 (1989).
19. E. Peli, "Low vision driving in the USA: who, where, when, and why," *CE Optom.* 5 (2), 54-58 (2002).
20. A. R. Bowers, D. H. Apfelbaum and E. Peli, "Bioptic telescopes meet the needs of drivers with moderate visual acuity loss," *Investigative Ophthalmology & Vision Science* 46 (1), 66-74 (2005).
21. N. Drasdo, "Visual field expanders," *Am. J. Optom. Physiol. Opt.* 53 (9 Pt 1), 464-467. (1976).
22. J. M. Kennedy, "Pictures By And For The Blind," in *A Summary of the Proceedings of an SPSE Technical Section Conference*, 39-41, Society of Photographic Scientists and Engineers (1977).
23. W. W. Hoeft, W. Feinbloom, R. Brilliant, R. Gordon, C. Hollander, J. Newman and E. Novak, "Amorphic lenses: a mobility aid for patients with retinitis pigmentosa," *Am. J. Optom. Physiol. Opt.* 62 (2), 142-148 (1985).

24. R. T. Jose, L. A. Spitzberg and C. L. Kuether, "A behind the lens reversed (BTLR) telescope," *J. Vis. Rehab.* 3, 37-46 (1989).
25. W. L. Kennedy, J. G. Rosten, L. M. Young, K. J. Ciuffreda and M. I. Levin, "A field expander for patients with retinitis pigmentosa: a clinical study," *Am. J. Optom. Physiol. Opt.* 54 (11), 744-755 (1977).
26. J. Lowe and N. Drasdo, "Using a binocular field expander on a wide-field search task," *Optom. Vis. Sci.* 69 (3), 186-189 (1992).
27. F. Vargas Martin, "Survey of a free cost view finder for visual field expansion," *Proceedings of the International Congress* 1282, 1080-1084 (2005).
28. P. Choyce, "Galilean telescope using the anterior chamber implant as an eye-piece: a low visual-acuity aid for macular lesions," in *Intra-Ocular Lenses and Implants*, 156-161, H.K. Lewis & Co., London (1964).
29. A. Donn and C. J. Koester, "An ocular telephoto system designed to improve vision in macular disease," *CLAO J.* 12 (2), 81-85 (1986).
30. T. R. Willis and V. Portney, "Preliminary evaluation of the Koziol-Peyman telediopric system for age-related macular degeneration," *Eur. J. Implant Refract. Surg.* 1, 271-276 (1989).
31. J. E. Koziol, G. A. Peyman, R. Cionni, J. S. Chou, V. Portney, R. Sun and D. Trentacost, "Evaluation and implantation of a teledioptric lens system for cataract and age-related macular degeneration," *Ophthal. Surg.* 25 (10), 675-684 (1994).
32. B. Garnier and X. Colonna De Lega, "Low-vision aid using a high minus intraocular lens," *Appl. Opt.* 31 (19), 3632-3636 (1992).
33. C. Verezen, C. M. Meulendijks and C. Hoyng, "Effectiveness of the teledioptric intraocular lens system for reading (abstract)," in *ARVO 2002*, p. 3801, Association for Research in Vision and Ophthalmology (ARVO CD). Item 3801 (2002).
34. I. L. Bailey, "Critical view of an ocular telephoto system," *CLAO J.* 13 (4), 217-221 (1987).
35. E. Peli, "The optical functional advantages of an intraocular low-vision telescope," *Optom. Vis. Sci.* 79 (4), 225-233. (2002).
36. E. Peli (2001). Double bifocal telescopic IOL-spectacle device for low vision use. United States patent application 60/ 310,664.
37. G. Kerkhoff and C. Zoelch, "Disorders of visuospatial orientation in the frontal plane in patients with visual neglect following right or left parietal lesions," *Exp. Brain Res.* 122, 108-120 (1998).
38. E. Peli and D. Peli, *Driving With Confidence: A Practical Guide to Driving With Low Vision*, World Scientific, Singapore (2002).
39. C. A. Johnson and J. L. Keltner, "Incidence of visual field loss in 20,000 eyes and its relationship to driving performance," *Arch. Ophthalmol.* 101, 371-375 (1983).
40. J. M. Cohen and B. Waiss, "Visual field remediation," in *Remediation and Management of Low Vision*, R. G. Cole and B. P. Rosenthal, Eds., 1-25, Mosby, St. Louis (1996).
41. E. Peli, "Field expansion for homonymous hemianopia by optically-induced peripheral exotropia," *Optom. Vis. Sci.* 77 (9), 453-464 (2000).
42. M. Katz, "Visual acuity through Fresnel, refractive, and hybrid diffractive/refractive prisms," *Optometry* 75 (8), 503-508 (2004).
43. K. Ogle, "Distortion of the image by prisms," *J. Opt. Soc. Am.* 41 (12), 1023-1028 (1951).
44. E. Peli, "Field expansion for homonymous hemianopia using prism and peripheral diplopia," in *Technical Digest on Vision Science and its Applications, Technical Digest Series*, 74-77, Optical Society of America (1998).
45. F. Vargas-Martin and E. Peli, "Augmented view for tunnel vision: device testing by patients in real environments," in *Digest of Technical Papers SID 01* XXXII, 602-605, Society for Information Display (2001).
46. F. Vargas-Martin and E. Peli, "Augmented-view for restricted visual field: multiple device implementations," *Optom. Vis. Sci.* 79 (11), 715-723 (2002).

47. E. Peli, G. Luo, A. R. Bowers and N. M. Rensing, "Invited Paper: Augmented vision head-mounted systems for vision impairments," in *Digest of Technical Papers SID 07*, 1074-1077, Society for Information Display (2007).
48. G. Luo and E. Peli, "Use of an augmented-vision device for visual search by patients with tunnel vision," *Invest. Ophthalmol. Vis. Sci.* 47 (9), 4152-4159 (2006).
49. G. Luo, L. Lichtenstein and E. Peli, "Collision judgment when viewing minified images through a HMD visual field expander," in *Proceedings of the SPIE. Ophthalmic Technologies XVII* 6426, 64261Z (2007).
50. A. R. Bowers, G. Luo, N. M. Rensing and E. Peli, "Evaluation of a prototype minified augmented-view device for patients with impaired night vision," *Ophthal. Physiol. Opt.* 24 (4), 296-312 (2004).
51. K. Zebehazy, G. Zimmerman, A. Bowers, G. Luo and E. Peli, "Establishing mobility measures to assess the effectiveness of night vision devices: results of a pilot study," *J.Vis. Impairment & Blindness* 99 (10), 663-670 (2005).
52. I. Lipshitz, A. Loewenstein, M. Reingewirtz and M. Lazar, "An intraocular telescopic lens for macular degeneration," *ophthal. Suerg. and Laser* 28 (6), 513-517 (1997).
53. E. Peli, I. Lipshitz and G. Dotan, "Implantable miniaturized telescope (IMT) for low vision.," in *Vision Rehabilitation: Assessment, Intervention and Outcomes*, C. Stuen, A. Arditi, A. Horowitz, M. A. Lang, B. Rosenthal and K. Seidman, Eds., 200-203, Swets & Zeitlinger, Lisse (2000).
54. S. S. Lane, B. D. Kuppermann, I. H. Fine, M. B. Hamill, J. F. Gordon, R. S. Chuck, R. S. Hoffman, M. Packer and D. D. Koch, "A prospective multicenter clinical trial to evaluate the safety and effectiveness of the implantable miniature telescope," *Am. J. Ophthalmol.* 137 (6), 993-1001 (2004).
55. H. L. Hudson, S. S. Lane, J. S. Heier, R. D. Stulting, L. Singerman, P. R. Lichter, P. Sternberg and D. F. Chang, "Implantable miniature telescope for the treatment of visual acuity loss resulting from end-stage age-related macular degeneration: 1-year results," *Ophthalmology* 113 (11), 1987-2001 (2006).
56. G. Fonda, "Approach magnification is safer than bioptic telescopic spectacles for operating a motor vehicle," *Trans. Pa. Acad. Ophthalmol. Otolaryngol.* 35 (2), 137-140 (1982).
57. W. Feinbloom, "Driving with bioptic telescopic spectacles," *Am. J. Optom. Physiol. Opt.* 54(1), 35-42 (1977).
58. O. Lippmann, A. L. Corn and M. C. Lewis, "Bioptic telescopic spectacles and driving performance: A study in Texas," *J.Vis. Impairment & Blindness* 82 (5), 182-187 (1988).
59. H. A. Greene and J. Pekar, "Bioptic telescope utilization survey," *J. Vis. Rehab.* 1 (3), 39-48 (1987).
60. T. Harkins and J. H. Maino, "The BITA telescope: a first impression," *J. Am. Optom. Assoc.* 62 (1), 28-31 (1991).
61. D. R. Williams, "The bi-level telemicroscopic apparatus--(BITA)," *Problems in Optometry* 3 (3), 495-503 (1991).
62. W. F. Hoeft, "The microspiral galilean telescope," *Problems in Optometry* 3, 490-494 (1991).
63. L. Spitzberg, R. T. Jose and C. L. Kuether, "Behind the lens telescope: A new concept in bioptics," *Optom. Vis. Sci.* 66, 616-620 (1989).
64. I. Fetchenheuer, E. Peli and R. L. Woods, "Functional visual fields of monocular bioptic telescopes (abstract)," *The 7th International Conference on Low Vision: Activity and Participation*, 81 (2002).
65. E. Peli and F. Vargas-Martin, "In the spectacle-lens telescope device for low vision," in *Ophthalmic Technologies XII* 4611, 129-135, SPIE - The International Society for Optical Engineering (2002).
66. E. Peli and F. Vargas-Martin (2004). Bioptic telescope system embedded into a spectacle lens. United States patent 6,775,060.
67. M. B. Spitzer, P. M. Zavracky, J. Crawford, P. Aquilino and G. Hunter, "Eyewear platforms for miniature displays," in *Digest of Technical Papers SID 01*, 258-261, Society for Information Display (2001).
68. K. R. Castleman, *Digital Image Processing*, Prentice-Hall, Englewood Cliffs, NJ (1979).
69. D. D. Gottlieb (1988). Method of using a prism in lens for the treatment of visual field loss. United States patent 4,779,972.
70. D. D. Gottlieb, *Living with Vision Loss*, St. Barthelemy Press, Ltd., Atlanta, GA (1996).

71. P. O. Bishop, "Binocular vision," in *Adler's Physiology of the Eye: Clinical Applications*, R. A. Moses, Ed., 575-649, C.V. Mosby, St. Louis (1981).
72. V. Herzau, I. Bleher and E. Joos-Kratsch, "Infantile exotropia with homonymous hemianopia: A rare contraindication for strabismus surgery," *Graefe's Archive for Clinical and Experimental Ophthalmology* 226 (2), 148-149 (1988).
73. C. Buquet, J. Charlier, G. Dhelin, S. Toucas, M. Quere and I. Ingster-Moati, "Assessment of eye movements by image processing: applications in ophthalmology and neurology," *Innov. Tech. Biol. Med.* 14 (3), 253-266 (1993).
74. Y. Levy, J. Turetz, D. Krakowshi, B. Hartmann and P. Nemet, "Development of compensating exotropia with anomalous retinal correspondence after early infancy in congenital homonymous hemianopia," *J. Ped. Ophthalmol. Strabimus* 32, 236-238 (1995).
75. E. Peli (2004). Peripheral field expansion device. United States patent application PCT/US 2004/042390.
76. A. R. Bowers, K. Keeney, D. H. Apfelbaum and E. Peli, "Multi-site extended wear trial of peripheral prisms visual field expansion device for patients with hemianopia (abstract)," *Invest. Ophthalmol. Vis. Sci.* 47 (ARVO suppl.), 3489 (2006).
77. E. Peli, A. Bowers, A. Mandel, K. Higgins, R. Goldstein and L. Bobrow, "Design of driving simulator performance evaluations for driving with vision impairments and visual aids.," *Transportation Research Report: Journal of the Transportation Research Board* 1937, 128-135 (2005).
78. M. Onufryk (1999). Multi-prism image enhancing lens system and method of making same. United States patent 5,969,790.
79. E. Peli, "Tri-field lens correction for binocular tunnel-vision," *Optom. Vis. Sci.* 76 (Suppl.), 102 (1999).
80. R. L. Woods and E. Peli, "Development and testing of Trifield glasses for people with severely restricted visual fields (abstract)," *Optom. Vis. Sci.* 79 (suppl.), 187 (2002).
81. D. W. Stringer, R. L. Woods, R. B. Goldstein, E. Peli, E. L. Berson, R. D. Easton and T. Bond, "Extended wearing trial of Trifield prism visual aid for tunnel vision among patients with retinitis pigmentosa or choroidermia (abstract)," Association for Research in Vision and Ophthalmology (ARVO CD). Item 1400 (2004).