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Treating with Spectacle Lenses: A Novel Idea!?

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ABSTRACT: A design approach to low-vision device development—vision multiplexing—was introduced recently. This approach has been applied successfully to the design of novel electronic and optical low-vision aids. This paper discusses the application of the vision-multiplexing concept to spectacle lens design to address issues of low vision and to resolve problems of color discrimination and glare in driving. Because spectacles are considered a fashion accessory as much as they are a vision aid, cosmetic considerations are critical to the design of such aids. Spectacle-borne devices that are not concealed or attractive are unlikely to be used widely. Efforts to combine the functionality of vision multiplexing with improved appearance are illustrated. (Optom Vis Sci 2002;79:569–580)

Key Words: vision multiplexing, low vision, driving, color deficiencies, traffic lights, hemianopia, rehabilitation

With unimpaired vision, we enjoy the benefits of a wide field of view, which is most effective for navigation and orientation, together with high-resolution capabilities that enable discrimination of fine details. Fig. 1a and Fig. 1b illustrate the view of an airport terminal scene for a single fixation[1, 2] (where resolution varies as a function of eccentricity), whereas Fig. 1c shows the perceived view resulting from integration across multiple fixations. When the observer is fixating the woman's head (Fig. 1a) it is seen in high detail, but the sharpness decreases rapidly with increasing eccentricity from the fixation point. If the observer shifts their view to the man's head (Fig. 1b), the resolution map is shifted and is centered on this new fixation point. The integration of the wide peripheral view and the high-resolution central view across multiple fixations to various points of interest in the scene results in a perceived image with both wide field of view and high resolution across the whole scene, as illustrated in Fig. 1c. Visual impairments typically affect only one of these aspects, restricting the wide field in conditions such as retinitis pigmentosa, glaucoma, and hemianopia, or damaging the functionality of the high-resolution fovea in conditions such as age-related macular degeneration, diabetic retinopathy, and optic atrophy.

Most low-vision devices help recover, at least partially, the lost functionality, but usually at a high cost for the remaining functionality. For example, magnification that is effective at increasing resolution inherently limits the field of view. Similarly, minifying devices increase the instantaneously available field of view but cause a corresponding loss of resolution. I have proposed a design approach for low-vision devices called "vision multiplexing" that attempts to avoid or reduce such limitations.[3] Vision multiplexing refers to combining the wide field-of-view and the high-resolution capabilities in devices in ways that permit these functionalities to be both separable and useful for the user. A number of different modes of multiplexing have been proposed and implemented[3, 4] in a range of devices. Spatial multiplexing refers to superposition of the wide field and sharp central vision (e.g., augmented vision device for patients with tunnel vision).[5, 6] Temporal multiplexing is the alternate presentation of wide peripheral field and the high-resolution view (e.g., the use of bioptic telescopes). Biocular multiplexing is the presentation of a wide peripheral field view in one eye while the central high-resolution view is presented to the other eye (e.g., monocular use of intraocular telescope[7]). Spectral multiplexing is the presentation of the wide field view in one color and the central view in another (e.g., dichroic mirror for hemianopic patients[8]). A secondary consideration of the multiplexing paradigm is to enable free and comfortable use of head and eye movements. The control of view with eye and head movements is natural and, therefore, it is effective, accurate, and intuitive. Devices that restrict either eye or head movements are of limited use.

Although multiplexing lends itself to use with a number of electronic devices, it is also quite natural to apply these principles to special-purpose spectacle lenses. The advantages of spectacle lenses over electronic appliances include lower cost, generally lower weight (no need for a power source), no need for maintenance, and an important potential for better cosmetic appearance. The need for attractive—if not invisible—design for low-vision devices cannot be overestimated. Although some patients are willing to wear any device that will improve their performance, the vast majority of patients of both genders are clearly reluctant to wear any device that will mark them as handicapped or that is esthetically unattractive. The need for less-obvious or more-attractive designs can be more easily met with spectacle lenses than with electronic devices, although this may change in the future.

FIGURE 1.
An illustration of the effects of the reduction of contrast sensitivity and spatial resolution with retinal eccentricity and the integration of perception across fixation on the appearance of an image. a: The view of an airport scene for an observer fixating the back of the head of the woman. Note that resolution gradually declines with distance from the point of fixation. b: The same effect occurs when fixation is shifted to the head of the man. c: This image illustrates the scene, perceived by an observer. This image has high resolution across the whole scene as a result of integration of multiple views obtained across a number of fixations. The images were generated using software provided by Geisler.[2]

The following sections describe various implementations of the multiplexing concepts using spectacle lenses in low-vision as well as other applications. The devices presented span a spectrum of development stages and range from devices already in clinical use to those in early design and prototyping stages. In all cases, we paid attention to the principles of maintaining free head and eye movements. I describe efforts to attend to and improve the cosmetic appearance of the devices.

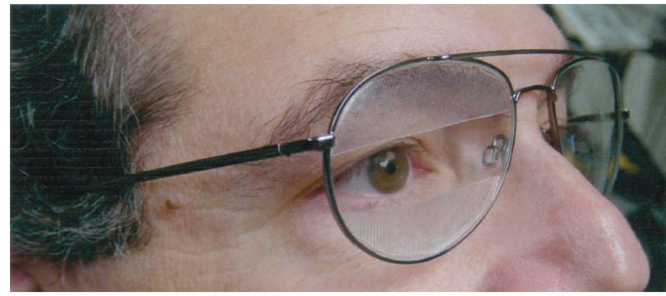


FIGURE 2.
Peripheral prisms for hemianopia. Fresnel prisms (40 Δ base-out) are placed in the upper and lower peripheral segments across the whole lens. For a patient with right hemianopia, the prisms are placed on the right lens only. The effect of the prisms is to expand the field by about 20° in the lower and upper fields. The effect is maintained at all horizontal positions of gaze.

PERIPHERAL PRISMS FOR HEMIANOPIA

Hemianopia causes problems for patients who are trying to avoid obstacles when walking, especially in a crowded environment, and may cause distortion of their space perception.[9] Many devices have been considered and used for the management of hemianopic visual field defects. Binocular sector prisms[10, 11] are the most commonly used device for hemianopia, but they provide only for field relocation or shifting.[4] Monocularly fitted sector prisms[12, 13] expand the field once the patient directs their fixation within the field of the prism. As long as the patient's eyes are fixed at a primary position of gaze or are directed away from the hemianopic field, the monocular sector prism has no effect on the field of view. The central diplopia induced with a full-field monocular sector prism is unpleasant and confusing to the patient and may account for the limited success reported.[11, 14]

A new method of field expansion[4, 15, 16] involves monocular sector prisms that are restricted to the peripheral field (superior, inferior, or both) (Fig. 2). The peripheral prism is placed across the vertical midline 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 diplopia. Peripheral diplopia is much more comfortable than central diplopia because peripheral physiologic diplopia is common in normal vision.[17] The peripheral prisms for hemianopia have been in use for over 3 years. The author has fitted more than 30 patients with these devices, and a number of colleagues have reported successful application of these prisms with their hemianopic patients.

The peripheral prisms represent biocular 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 might facilitate adaptation to the prism by reducing the ambiguity associated with the peripheral diplopia, clearly marking

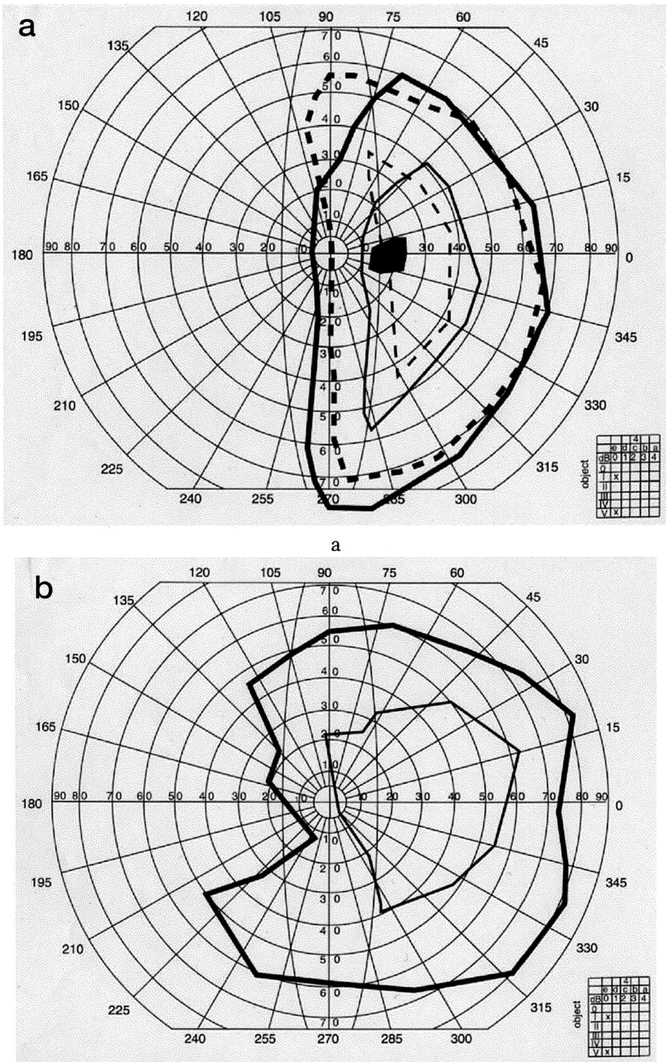


FIGURE 3.
Goldmann visual fields illustrate the field expansion effects of peripheral prisms for hemianopia. a: A left hemianopic field of the right eye (dashed lines) and the left eye (solid lines) without macular sparing. b: The binocular field of the same patient with 40 Δ prisms base-out on the left lens. Note that the asymmetry in the field expansion is consistent with the small asymmetries of the monocular fields. The two isopters corresponds to the targets marked by ×'s in the table.

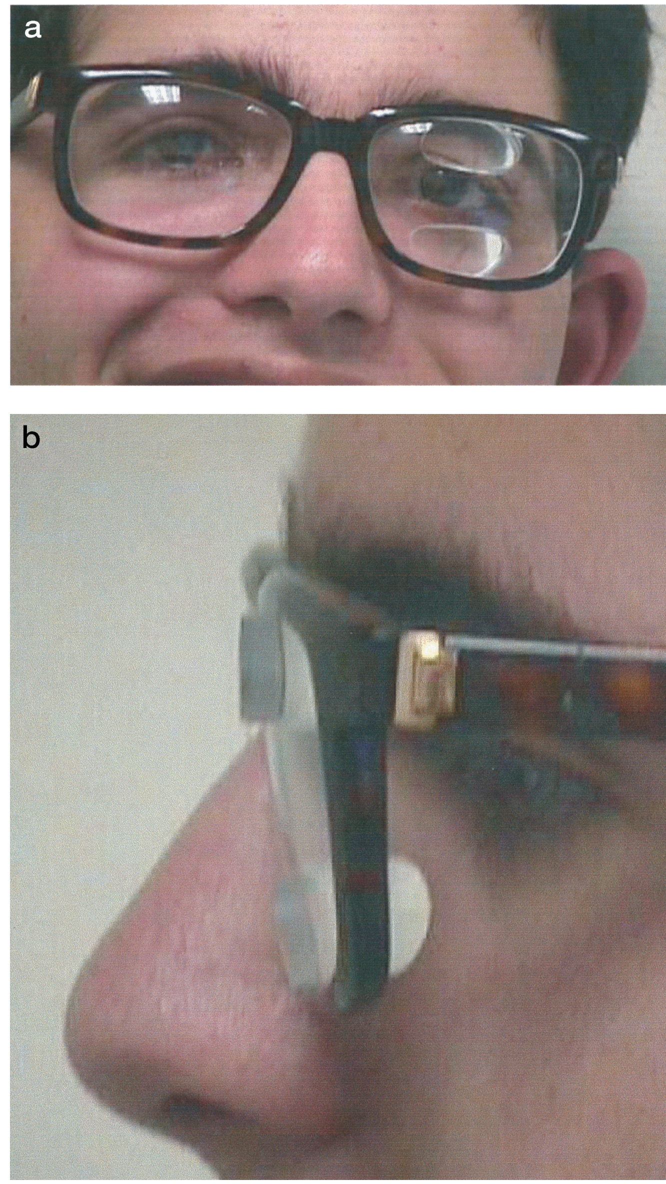
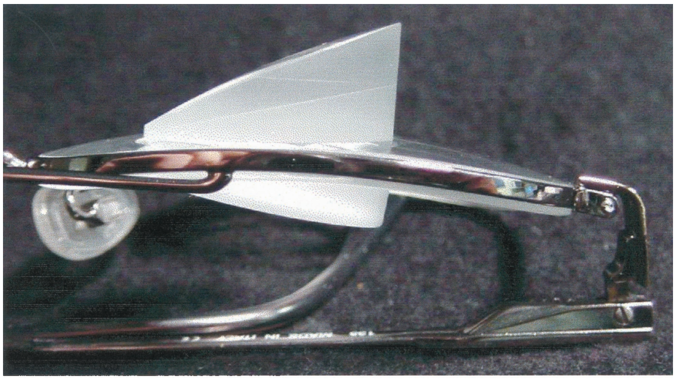


FIGURE 4.
A permanent prism made by Multilens Optical (Sweden) by mounting elliptical prism segments through the carrier lens. a: The lens shown has 30 Δ of prism power in a form that is fairly acceptable cosmetically. b: A side view of the same lens showing the extent of the protrusion of the lower prism edge behind the carrier lens and toward the eye (the upper prism protrudes similarly, but it is hidden by the temple). The proximity of a sharp prism edge to the eye might pose a risk of injury in case of an accident.

the objects as to the eye of origin. The peripheral prisms provide a field expansion that is measurable by standard perimetry (Fig. 3).

Because these prisms affect only peripheral vision, higher prism power than previously applied for hemianopic corrections can be used despite the inferior optical quality. Fresnel press-on prisms of 40 Δ were fitted originally and are still being used for the initial fitting and trial period. However, after a few months of use, the optical quality of the Fresnel press-on prisms deteriorates to the point that they are no longer useable. In addition, the old prisms appear dirty and discolored, making them much less attractive than the new prisms. As a replacement for the Fresnel prisms, we have developed a number of designs of permanent CR-39 segments with which we fit well-adapted patients.

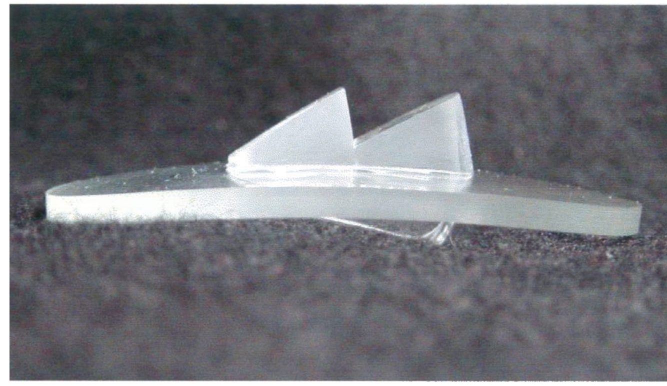
The first such design (Fig. 4a) was an elliptical prism segment inserted into a matching hole cut into the carrier lens (Multilens Optical, Sweden). These lenses were reasonably attractive because the prism was positioned to protrude mostly behind the carrier lens, making the lens appearance similar to that of a vocational double-segment bifocal lens.[18] However, with this design, the sharp edge of the prism protruded significantly behind the carrier lens and close to the eye (Fig. 4b). The risk of eye injury from that edge required us to limit the prism power to 30 Δ to reduce the protrusion of the prism edge. Alternately, the width of the prism could be reduced, but this would limit its effect to only central positions of gaze. A 22 mm, 30 Δ prism had an edge of about 13 mm of which 7 mm protruded behind the carrier lens. A second



a

b

FIGURE 5.
An improved safety design of the Multilens Optical (Sweden) peripheral prism lens showing 40 Δ prism segments constructed by laminating 30 Δ segments to the front of the carrier lens and 10 Δ segments to the back. a: A view from above illustrating the reduction in the extent of the protrusion behind the lens. b: The front view shows that this design is safer but is less attractive than the one shown in Fig. 4.



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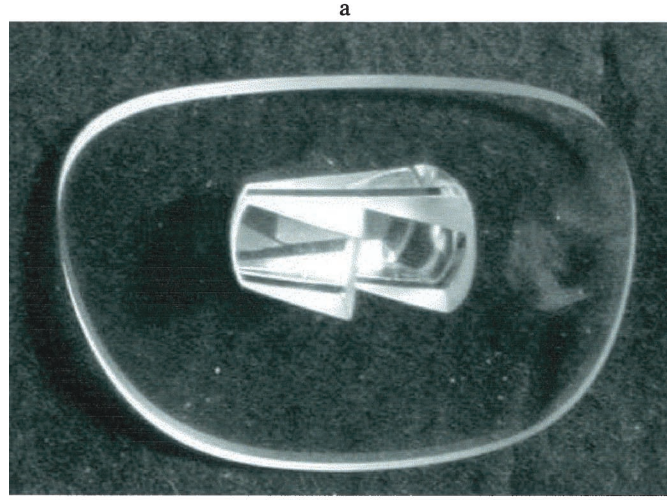

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FIGURE 6.
A further improvement of the prism segments implemented by Chadwick Optical is constructed from two 30 Δ segments in a minimal Fresnel-like configuration laminated to the front of the carrier lens with a single 10 Δ segment laminated to the back of the lens. a: Top view. Note that in this case, the sharp edge of the prism was cut back and was smoothed to further reduce risk of injury. b: Front view. Note that for each prescription, this design requires six prism segments that are cut and filed to the required shape by hand.

design substantially reduced the prism sharp edge protrusion toward the eye by shifting the prism forward. This was achieved by gluing the 30 Δ prism segments to the front of the carrier lens and additional 10 Δ segments to the back (Fig 5). In this design, a 30 Δ prism of 22 mm had an edge thickness of 13 mm protruding in front of the carrier and a 10 Δ protruding 5 mm behind the carrier. This was a much less attractive but a safer design. However, patients who were shown these lenses expressed concerns about the appearance of these lenses. This was true even for patients who had never seen the earlier more-attractive design. Although the 10 Δ prism at the back of the carrier lens had a thinner edge (5 mm) and therefore terminated much farther from the eye, it was still perceived as a possible risk due to the sharp edge. Chadwick Optical (White River Junction, VT) subsequently developed for us a modified design to overcome both limitations; this latest design included a smoothing and rounding of the edge of the 10 Δ prisms at the back of the carrier lens. The prism segments in the front were split into two segments each, creating a minimal Fresnel prism-like design protruding only 8 mm in front of the carrier and only 4 mm behind it (Fig. 6). This prism split reduces the forward edge thickness significantly, resulting in a much-less-obvious lens. The split does not affect the optical quality of these lenses, and their care and maintenance is as simple as that of any CR-39 lens. This last design is currently being offered to patients, although further improvements in functional design and appearance are being considered.

DRIVING GLARE

Control of Solar Glare

Drivers frequently complain of the disabling effect of glare. In early morning and late afternoon, especially in the winter months, the glaring light of the low sun causes major traffic slowdowns on the highways and is blamed for numerous accidents. A news report on the ABC affiliate WCVB-TV in Boston on February 11, 2002 cited solar glare as one of the worst hazards of winter driving and described a number of severe car crashes caused by drivers who were blinded by the low sun. An article in the April 2000 issue of *Lens Talk*[19] cited numerous newspaper accident reports from around the country, which blamed solar glare for disabling drivers. Although solar glare affects all drivers, it is particularly difficult for elderly low-vision patients.[20] The glare-disabling effects are more severe in patients with conditions such as cataracts, corneal opacities, vitreous floaters, macular edema, and other disturbances of the optics.[21] Furthermore, the recovery from glare-impaired vision takes longer for patients with retinal diseases such as age-related macular degeneration.[22]

In the past, solar glare used to affect drivers heading east or west in the morning or afternoon, respectively, for longer periods of time. Recent improvements in car visor designs have improved the situation: modern car sun visors have variable or fixed extensions that cover the area near the rearview mirror. That opening used to be a significant source of solar glare even when the sun was fairly high in the sky. With the new visors, the solar glare remains a serious problem when the sun is low on the horizon, essentially right over the tops of other cars on the road. Various devices have been proposed to reduce solar glare. The basic car visor is effective when the sun is not too low. However, for the very low sun positions, the visor cannot be used because it will block the view of the road at the same time that it blocks the sun glare. The visor may not extend far enough for some drivers, thus visor extensions—both opaque and tinted—have been marketed. Visors are of limited effectiveness for two reasons: (1) their distance from the eyes creates a soft shadow at the pupil requiring a deeper insertion of the visor into the visual field and (2) their fixed position means that any vertical movement of the vehicle or changes in the road grade require readjustment of the visor position relative to the eye. Although some of this adjustment can be achieved by head position, the range for such adjustment is minimal. Adjusting the visor by hand is possible but is slow, difficult, and may distract the driver.

Sunglasses are frequently recommended for solar glare.[19] However, the tint reduces the brightness of the scene by the same factor that it reduces the brightness of the sun. Thus, regular sunglasses reduce the discomfort caused by glare, but do little to reduce disability glare. Polarized sunglasses may provide some relief from solar glare, but they differentially affect only that portion of the solar glare that is reflected from the car's hood or from smooth or wet road surfaces.[23] Polarized lenses, however, have no advantage over regular sunglasses with regards to the direct glare of the sun.

It should be noted that the desirable effect in solar glare control is to block the near peripheral field (where the sun is) while maintaining central vision (where other cars on the road should be viewed). This requirement is similar to that of multiplexing except that the peripheral field has to be blocked rather than preserved. This can be achieved with a spectacle lens that is tinted with a very dark strip at the top of the lens (a strip just a few millimeters wide) (Fig. 7). To effectively block the direct sun, the tint has to be very dark, no more than 1% transmission. The tinted strip is at the very top of the lenses so that in normal use, it does not block any part of the visual field that is important for driving. When low sun glare is encountered, the user only has to tilt his/her head slightly to place the sun at the top of the lens behind the dark tint. With slight head tilt adjustments, the sun can easily be maintained at the proper blocked position during vehicle movement and road grade changes. The close proximity of the dark strip to the eyes' pupils makes the shadow cast by the strip sharp and crisp, permitting a clean transition from the visible road and vehicles to the blocked sun. Users can adjust the shadow position with a head tilt—a simple, accurate, and intuitive approach that requires little or no training.

Control of Headlight Glare

Night drivers are faced with bright light from oncoming headlights that scatters inside the eye and causes a veiling glare that reduces contrast and thus impedes visibility.[21, 24] As with solar glare, headlight glare becomes a more acute problem for the elderly[25, 26] and for people with cataracts (even after cataract surgery), corneal problems, and diabetic retinopathy because of the increased scatter of light in the affected eyes. As a result, patients with cataracts are more likely to report difficulty driving at night.[27] In recent years, a new type of brighter car headlight called high-intensity discharge has been introduced. These headlights provide three to four times more illumination for the driver and are therefore advantageous for older drivers who need more light to see at night. However, the high-intensity discharge lights cause more glare problems for oncoming drivers.

Rearview (tailing) headlight glare is caused by tailing cars with main or high beams reflected in the rearview mirrors. Most rearview mirrors are equipped with an antiglare device that tilts the silvered part of the rearview mirror at an angle that deflects the glare, yet leaving a weak reflection in a glass surface (≈4% reflectance) to maintain a view of tailing cars' headlights. Some recent model cars are equipped with a light sensor that causes the rearview mirror and the outside mirrors to darken (using electrochromic technology) when impacted with high-intensity light.[28]

The effect of headlight glare extends for some time after the glare-causing car has passed. The recovery time is longer for patients with retinal diseases such as age-related macular degeneration and diabetic retinopathy.[22] However, there are no devices on the market to control headlight glare from oncoming cars, even though oncoming headlight glare is a much more common complaint than rearview headlight glare (possibly due to the effectiveness of the existing glare control in rearview mirrors).

Special spectacles—with segments of both lenses tinted dark (as in sunglasses)—were invented and patented by a number of individuals to provide control of headlight glare.[29–32] These spectacles generally have a dark area on the left side of both lenses, to cover the position of the outside left mirror, and a strip or section of dark tint at the top of the lenses corresponding to the position of the rearview mirror (similar to Fig. 7). Although tailing headlight glare comes through the mirrors, glare from the headlights of oncoming cars is mainly limited to a triangular segment of the visual field occupied by the traffic lane(s) going in the other direction (Fig. 8). A number of inventors, therefore, patented spectacles that include a triangular section of dark tint to cover the area of the field corresponding to the position of the oncoming traffic lane(s).[30, 31, 33] It is important to note that for any of these devices to work, the user's head has to be at a fixed position in the car relative to the mirrors and the road. Users may certainly be able to position themselves in such a way, as suggested in some patents. If the user takes this fixed position, the dark tint will reduce the visibility of the corresponding portions of the road both in front and behind the vehicle at all times, even when there are no cars with glaring headlights in sight. A few patents[30, 32, 34, 35] therefore suggested that the tinted area

FIGURE 7.
Glare control glasses. The dark tinted strip at the top of the lens is used to block solar glare. A small head tilt is sufficient to bring the glaring sun into the dark strip and maintain it there despite road grade changes and vehicle movements. The dark tinted strip on the left may be used to control glare from oncoming car headlights as well as from trailing car headlights reflected in the left side mirror.

would be brought into place by active head and eye motion only when needed and moved up or to the side once the offending car has passed, clearly implementing temporal multiplexing. One patent[31] suggested blocking oncoming headlights only for one eye (the right eye), providing a type of biocular multiplexing. It is not clear how such monocular glare protection is intended to function. The glare control spectacles shown in Fig. 7 provide flexible multiplexing control of oncoming headlight glare by using dark strips on the left side of the lenses. The position of the dark strips is adjusted so that when the driver's head is at the primary straight-ahead position, the whole road—including the oncoming traffic lane(s)—are in view through the clear segments of the lenses. When an oncoming car with bright headlights is approaching, the driver just has to turn his head slightly to the right while maintaining a straight-ahead eye fixation. This head adjustment is easily made, and the oncoming headlights are seen through the dark strips. This adjustment leaves the travel lane in the clear segment of the lens and reduces or eliminates the glare effect of the oncoming headlights. As the oncoming car approaches, the driver's head turn is continuously reduced until the head is back in its primary position when the car has passed. This adjustment of head position and eye position is easy and natural and requires little training because the feedback is continuously available. The lower portion of the left strip also may be left clear, permitting continuous monitoring of the side of the road through a clear lens at all times (Fig. 9). This

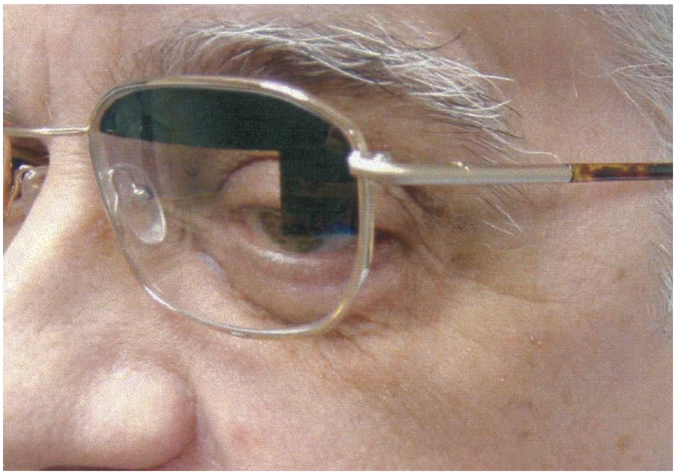

FIGURE 9.
A glare-control spectacles design for both solar glare (dark top strip) and for oncoming headlights glare (dark partial strip on the left side). A slight head tilt to the right and down will block oncoming headlight glare. Head position can be adjusted as the oncoming car approaches and passes. These spectacles can also be used to block glare from the rearview and side mirrors. With this design, compared with the one shown in Fig. 7, with the driver's head in the primary position, the dark strips do not block any part of the field that is relevant to the driving task.

design requires that the aforementioned head turn also incorporates a small vertical component (a downward movement of the head) to assure that the oncoming headlights are included in the dark left strip. It is interesting that this design—which I believe is the most-effective design—was already patented in 1926.[32] Yet, there is no such product available on the market, and I know of no study that examined the effectiveness of any of the many designs. It is possible that the less-than-desirable cosmetics of such glasses resulted in a lack of adoption. One could provide such glare protection for exclusive use while driving by cutting clip-on sunglasses, but a careful fitting for each individual is needed for proper and safe use. In addition, most clip-on sunglasses may not be dark enough to provide sufficient glare relief.

Headlight Glare in Keplerian Bioptic Telescope

The following case illustrates that not all that is round is symmetrical. A patient with juvenile macular degeneration had been driving with a bioptic telescope (4.0 × EFT from Designs for

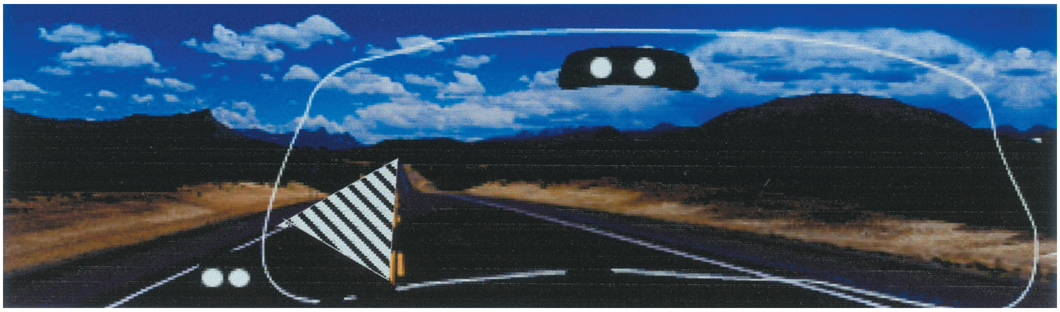

FIGURE 8.
The sources and location of headlight glare. Rearview and sideview mirrors can reflect the glaring headlights of tailing cars. The headlights of oncoming cars mainly occupy (at different times) positions in the triangular segment representing the oncoming traffic lane(s).

Vision, Ronkonkoma, NY) for a few months. He reported that oncoming headlights reflected inside the telescope, and the dim reflections appeared to him as the taillights of a car ahead of him in his lane. The sudden appearance of these phantom cars in his lane was alarming and distracting. I have verified in the lab that such reflections did indeed appear as reported. I asked Mr. Richard Feinbloom of Designs for Vision to see whether the reflections could be eliminated. He reported that the reflection was indeed noted under these conditions but could only be removed by restricting the field of view, which was undesirable. On further discussion, we decided that a possible approach would be to rotate the telescope so the reflection appeared on the other side of the road essentially where the headlights were seen. Note that although a roof prism Keplerian telescope appears externally and when used to be round and symmetrical, the internal structure is not symmetric. The rotation of the telescope shifted the bothersome reflection in the direction of the oncoming car light and completely solved the problem for the patient.

Improving the Recognition of Traffic Lights

About 8% of all men and 0.4% of women have color vision deficiencies that result in difficulty with distinguishing between red and green.[36] This problem is, of course, of some importance for drivers who need to distinguish between red and green traffic lights.

A review of the scientific literature on color vision and driving[37] found that in the majority of studies, no association was reported between color vision deficiencies and crash involvement or driving performance. Such lack of correlation between vision impairment and crash involvement is found in almost all vision parameters considered in driving studies.[38] It is not clear whether this lack of correlation indicates that color-deficient drivers have no difficulties recognizing the traffic lights or that the relations have not been examined correctly. Information obtained from questionnaire-type surveys suggests that a significant number of drivers with color

FIGURE 10.
Spectacles for traffic light color identification using red filter (tinted) strips across the top of the lenses. A slight head tilt can bring the traffic light into and out of the filter, permitting recognition of the light cycle as illustrated in Fig. 11. The front pair is an example in which the red-tinted strips are camouflaged behind a front gradient mirror coating to provide a cosmetically more acceptable solution.

FIGURE 11.
A photographic illustration of the effect of the red filter on the appearance of traffic lights to a color-deficient patient. a: A street scene with red and green traffic lights indicated by white and black arrowheads, respectively. b: The same street scene at the same light cycle is shown with a red filter inserted in front of the camera lens at the top. Note that the red light is highly visible, whereas the red filter extinguishes the green lights. Alternating the two illustrated views is easily achieved with slight head movements (when wearing the red-filter spectacles) and thus provides unambiguous cues to the light cycle status.

vision deficiencies do have difficulty with traffic light signals,[39, 40] especially in an unfamiliar area.[40] Laboratory studies of traffic signal identification indicate that color-defective observers have reduced recognition distances compared with those with normal color vision.[41] Only 19 states require prospective drivers to undergo color vision screening.[42] Ten of them restrict this requirement for commercial drivers. In a few states, low-vision drivers are also tested for color vision. This actually makes some sense because drivers with color deficiency may have difficulties recognizing the color of traffic lights if they also have reduced spatial resolution. Color vision testing is required also for some rail workers who need to distinguish traffic lights, and there are specific color vision requirements for pilots, police, and some marine occupations. In all these occupations, the main need is for the worker to be able to distinguish a red light from a green light. Over the years, a number of colored filters have been offered as remedies for color deficiencies. The filters have been available either as spectacle lenses (ColorMax, Tusin, CA; Coloryte, Norcross, GA) or as contact lenses (ChromaGen, Chester, UK; X-Chrom) for better cosmetic effect. The FDA Ophthalmic Devices Panel Meeting Summary for November 8, 2000 approved the ChromaGen for use in the United States, but specifically concluded that "The lenses do not help wearers to see 'new' colors or to perceive or appreciate colors as people with normal color vision do, but merely add brightness/darkness or hue differences to colors that are otherwise difficult or impossible to distinguish. However, discrimination of at least some other colors is actually impaired." Furthermore, the panel indicated, "The ability to pass diagnostic color vision tests with ChromaGen lenses does not imply the ability to perform other color vision-related tasks. Therefore, ChromaGen lenses should not be used with diagnostic color vision tests to meet occupational performance requirements."[43]

In most states, standardization of traffic lights with the red light at the top reduces the importance of color vision in interpreting traffic signals. Most color-deficient drivers use this spatial position clue and consider the top light in a traffic signal to be the stop signal and the bottom light to be the go signal. A color-deficient or even totally color-blind person can see which of the lights is on, although they may not be able to distinguish or correctly name the colors. The position clue is not always available at night, where it might be difficult to tell the position of the illuminated traffic light. Even during the day, the position of a lighted signal might be difficult to determine for a low-vision driver with moderate vision loss, or when the traffic light is seen against a background of trees or buildings rather than clear skies.

A new type of traffic light using the most efficient and reliable light emitting diodes is now under consideration.[44] Some of these designs have only one fixture for all three colors and may prove problematic for color-deficient and visually impaired drivers. The new single-fixture light-emitting diode lights may have shape clues included such that the red light is a hexagon and the green light is a circle. Although a person with good vision can distinguish these shapes, it may be difficult to differentiate these shapes from a farther distance and more so for drivers with moderate visual acuity loss.

A multiplexing solution for the problem faced by color-deficient drivers is the use of spectacle lenses with a strip of *properly* selected red tint at the top of the lenses (Fig. 10).[45] When the driver approaches a traffic light and cannot determine its color, a slight head tilt will bring the traffic light(s) into the field of the red tint. If the light is red, it will pass unaffected through the red tint. If the light is green, it will be completely blocked by the red tint (Fig. 11). Thus, with a couple of quick, nodding head movements, the driver can easily determine the color of the traffic light despite color deficiency, even in the presence of moderate visual acuity loss (in the range of 20/40 to 20/70 that may still be legally driving in many states).

Visually impaired drivers may not consider spectacles with a red tinted strip on the top a cosmetically attractive option. One could use a green tint in a complementary fashion, transmitting the green light and blocking the red light. Some drivers may accept a green tint more favorably. However the green option has a number of limitations. First, it is harder to get a green tint that provides good separation of the red and green traffic lights in both incandescent and light-emitting diode styles. Second, the green filter blocks the red light so that the clue for stopping is a disappearance of the red light. It seems likely that this is not as intuitive for the driver as seeing the red light shining through the red filter. And third, if the driver for some reason lowered his/her head so that the green tint covers the cars on the road ahead it would block the lead car brake lights. The red tint, on the other hand, will transmit those brake lights clearly and even increase their contrast. Thus, a red tint is preferable. We have created such spectacles where the red strip was camouflaged by applying a gradient mirror coating to the front of the lenses (Fig. 10). The denser mirror at the top effectively masks the red strip but does not affect its usefulness for color differentiation. The lighter coating at the bottom of the lenses permits unimpeded driving even in dark conditions. Although these glasses were designed specifically to address drivers' difficulty with recognizing traffic lights, color-deficient patients might use similar glasses with the same or different tints for various other applications. In all cases, a temporal alternation between the filter and the clear lens using head movement can provide the necessary clues for color discrimination. Such glasses can be used to solve the problem of color discrimination of lights in all vocational situations, as well as in driving, particularly at night.

SimulVision with In-the-Lens Bioptic Telescopes

Patients with reduced visual acuity use spectacle-mounted telescopes as low-vision aids. The magnification provided by the telescope helps patients with central field loss and other causes of low acuity to compensate effectively for the loss of resolution. By viewing objects through the telescopes, patients may be able to recognize these objects from distances at which they would not be recognizable with unaided vision. The field of view through the typical low-vision telescope is narrow (6° to 12° for 8.0× to 3.0× telescopes, respectively).[46] With such a narrow field, a user's navigation in the visual environment may be difficult. In addition, the magnified visual motion of the environment through the telescope conflicts with the vestibular head movement signal from the inner ear,[47] causing difficulties in adaptation if worn centrally.[48] The most successful application of telescopes is in the bioptic position, where the bioptic telescope is mounted at the top of the spectacle lens with a slight upward inclination. Bioptic telescopes are typically mounted through a spectacle (carrier) lens by drilling the lens. The positioning of the bioptic allows the wearer to look under the eyepiece most of the time, using their unaided vision through the regular spectacle lens (the carrier lens) to enjoy the benefits of intact peripheral vision. When an unrecognizable distant object is detected, a slight downward head tilt brings the telescope in front of the eye and the object of interest into the telescope's field of view. A short examination of the target through the telescope provides the patient with the level of detail required for recognition. This use of *temporal multiplexing* makes the bioptic telescope an effective, comfortable, and safe device. Bioptic telescopes are available in small, compact Galilean designs that provide narrow fields of view and relatively dim images. Alternative bioptic telescopes are available in larger, heavier Keplerian designs that provide brighter images and wider fields of view.

FIGURE 12.
The ring scotoma caused by the magnification of a telescope. The image of a 10° field magnified by a factor of three is superimposed over the unmagnified view of a scene. The magnified view blocks a large segment of the environment (eight times as large an area as the area of the field of view).

FIGURE 14.
An illustration of the view of the SimulVision effect that is possible with the In-the-Lens Telescope design. The magnified image of the rectangular field of view is projected above, permitting continuous viewing of the entire intersection at the same time that the magnified view is examined.

The magnification of the telescope results in an inherent ring scotoma. As shown in Fig. 12, a 10° field of view visible through a 3.0× telescope will cause a 30° section of the surrounding environment to be obscured. This ring scotoma is a direct result of the magnification and has nothing to do with the structure of the telescope case, which can cause additional scotoma, but would need to be quite large to do so. The use of a single bioptic telescope for a patient with two functional eyes may be an important safety feature, because any threat or obstacle appearing within the ring scotoma during the telescopic glimpse might be detectable with the other eye. However, it is not clear whether the use of *biocular multiplexing* can support navigation in the environment.[49] Such navigational help might be provided by spatial multiplexing, as described below.

Very small bioptic telescopes may be used in ways that provide for *spatial multiplexing*. For example, when the BITA (a very small Galilean 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) calls SimulVision.[50] The user sees 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. Because the magnified view is seen above the unmagnified view, the device permits the user to obtain the magnified view without disrupting the full horizontal field of view. This full-field view may be useful for navigation and orientation. SimulVision configuration is easier to achieve with small-field telescopes because the necessary image shift is small. However, in principle, SimulVision may be achieved with wider field telescopes using the proper optical configuration. We have recently shown that the behind-the-lens[51] Keplerian telescope (with a field of view of 14° for a 3.0× telescope) provides a SimulVision situation,[49] although in this case the magnified view is seen below the unmagnified view, not above it.

Although bioptic telescopes can be used effectively in a variety of settings, many visually impaired people reject them. The obvious and unsightly appearance of these prosthetic devices has been identified as one major reason for the reluctance of the visually impaired to use them.[52] A number of bioptic telescopes have been developed over the last decade in an effort to respond to the need to conceal the telescope. The BITA telescope represents a miniaturization approach applied to the inherently smaller Galilean de-

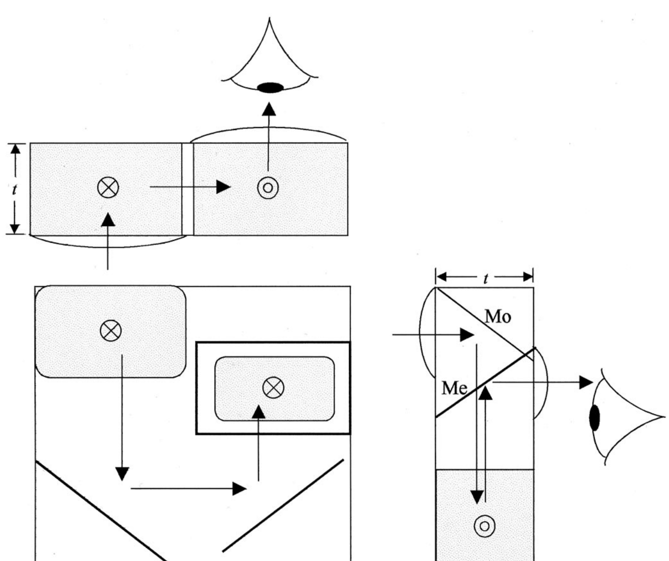

FIGURE 13.
A schematic of the In-the-Lens Telescope in Keplerian design shown in three views (front view-lower left; top view-upper left; side view-lower right). The arrows show the light pass, with crosses in circles illustrating an arrow aimed into the page and two concentric circles and an arrow emerging from the page. The preliminary design shown here includes lenses that serve as the objective and the ocular lenses glued to the surfaces of the spectacle carrier lens (of thickness t). The four plane mirrors are used to erect and reverse the image.

sign.[50] The behind-the-lens telescope is a miniaturized Keplerian telescope that is positioned mostly behind the spectacle lens and is produced in skin color to help in its concealment.[51] The Ocutech VES telescope is based on a folded periscopic design and positioned above the frame, providing a better appearance and a level of concealment.[53]

Low-magnification telescopes can be created by combining a high negative power contact lens[54] or intraocular (i.e., surgically implanted) lens[55] with a high positive power spectacle lens. Although such telescopes are limited in magnification and may severely restrict the field of fixation,[47] they may offer an advantage in cosmetic appearance. However, patients have been reported to reject such devices due to the unsightly appearance of the high-power spectacle lens.[56] A fully implanted intraocular telescopic lens is now available and offers a number of advantages[47] in addition to normal-looking spectacles and eyes, but requires a surgical procedure and may present difficulties with future eye care for the patient.

We have designed a bioptic telescope that is built completely within the spectacle lens.[57, 58] This design provides much better concealment and a suitable cosmetic appearance for the telescope. In addition, it lends itself to SimulVision even with a wide-field Keplerian design. Fig. 13 contains a schematic of the Keplerian design In-the-Lens Telescope. The preliminary design shown includes lenses glued to the surface of the spectacle carrier lens; these glued lenses serve as the objective and the ocular lenses. The four mirrors are used to reverse the image as is necessary in a Keplerian design. As can be appreciated from the diagram, the carrier lens thickness restricts only the height of the objective and ocular mirrors and not their width. Thus, the carrier lens thickness limits only the height of the visual field and not its width. It is generally believed that the width of the field seen through a telescope is more important for mobility and navigation than the height.

If the ocular lens mirror (indicated by Me in Fig. 13) is tilted a few degrees clockwise, the image seen through the telescope will shift up, enabling the user to see the magnified image above simultaneously with the unmagnified view of the same object, as illustrated in Fig. 14. The In-the-Lens telescope in this configuration provides for a spatial (shifted) multiplexing or SimulVision. As is evident from the illustration, such a view is advantageous because it shifts the magnification scotoma to the upper part of the field where important obstacles are less likely to occur. In addition, by leaving the unmagnified horizontal view unobstructed, the view permits easier object navigation and orientation.

The objective and ocular flat mirrors shown in Fig. 13 may be replaced with curved mirrors and thus take on the role of the lenses as well. There are numerous advantages to this design. First, no lenses are needed, and the telescope is wholly built inside the carrier lens, making manufacturing, fitting to individual patient's refraction, dispensing, and care of the telescope easier. The mirrors are free of chromatic aberrations that are a main limitation to the optical quality of the telescope's design. Thus a mirror-based telescope should have higher optical quality. For the same focal length, the curvature of a mirror is one half that of a lens, and thus larger mirrors can be made with the same power, providing a wider field of view. Fig. 15 simulates the appearance of such mirrors only In-the-Lens telescope. This telescope is much less noticeable than current devices and will cause minimal difficulty with eye contact if the patient is looking through the carrier. The In-the-Lens telescope can be produced as a commodity lens blank. It may be surfaced with an individual patient's prescription by any optical lab and edged to fit into a standard frame by any optical shop. These advantages should make it inexpensive and widespread. In addition to its use as a low-vision device, the In-the-Lens telescope may find application for law enforcement, military, and sports applications, as well as for use by the general public. Widescale use may make it also more acceptable for low-vision use.

FIGURE 15.
A simulation of the appearance of In-the-Lens Telescope composed only of mirrors that are wholly embedded in the carrier lens. The objective and ocular lens mirrors are curved and provide the power. The other two mirrors can be curved as well to serve as field lenses.

CONCLUSION

The normal visual system performs as well as it does by integrating the functionality of the wide peripheral field—for detection and navigation—with the high resolution of the fovea. Eye movements are effectively used to accomplish this integration. The vision-multiplexing concept offers the possibility to provide such integration with various visual aids and devices. In particular, multiplexing is an effective mode of operation with novel spectacle lens designs. As effective as visual aids can be, they have to be used by patients to be really effective, and, therefore, the importance of cosmetic considerations in designing devices cannot be overestimated. The wide acceptance of spectacles as fashion accessories is evidence of the importance people, from all walks of life, attach to the way their eyewear looks. Most patients, normally sighted or visually impaired, will not use or even try an appliance that they think will not be attractive on them. We are all vain, and, therefore, cosmetic consideration should be high on the agenda of any product development in this area if it is to succeed in the marketplace.

> ". . . vanity of vanities, all is vanity."
> —Ecclesiastes 1:2

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