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ORIGINAL ARTICLE

Augmented-View for Restricted Visual Field: Multiple Device Implementations

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ABSTRACT: *Purpose.* An augmented-view device for patients with severely restricted peripheral visual fields (tunnel vision) was proposed, combining a see-through head-mounted display and a simultaneous minified view of a wide field presented as contour information. Here we create and evaluate multiple implementations of the augmented-view concept and report responses from potential users. *Methods.* Several prototypes using commercial off-the-shelf devices were implemented. Then they were evaluated in real environments in daylight and at night by two retinitis pigmentosa patients. *Results.* Effective expansion of the visual field of patients was achieved. Patients indicated their preferences for different properties, devices, and combinations. *Conclusions.* Patients found the augmented-view concept of help for their impairment, but wanted much more ergonomic design than the prototypes provided. Benefits, limitations, and possible improvements for the evaluated devices are discussed (Optom Vis Sci 2002;79:715–723)

Key Words: head-mounted display, field expanders, wearable displays, augmented reality, retinitis pigmentosa, glaucoma, night blindness, low vision

Several eye diseases such as retinitis pigmentosa (RP) and glaucoma cause a severe restriction of the peripheral visual field (tunnel vision), although the patients may maintain their central vision with high resolution.[1–4] When peripheral vision loss is severe (leaving useful fields $<20°$ across), a patient's mobility can be reduced because of a reduced ability to spot obstacles, resulting in difficulties in navigation. Social interactions may be affected as well. For example, patients with severe peripheral visual loss may have difficulty localizing speakers or other members of a group or difficulty noticing relatives and friends on the street.

In addition to this restricted visual field, RP and other related diseases (congenital stationary night blindness, Usher syndrome, and vitamin-A deficiency) often cause night blindness, also called nyctalopia, typically before visual field loss.[1, 2] Individuals suffering from night blindness not only see poorly at night, but also require more time to adapt to changes in lighting conditions during both day and night.

Current visual aids for tunnel vision increase the field of view by minification (i.e., reducing the image size of the objects) thus compromising the resolution of the remaining central vision. These aids range from handheld divergent lenses[5, 6] to amorphic spectacle-mounted reversed telescopic devices.[7, 8] Partial rejection of these devices by tunnel vision patients has been reported, especially in normal dynamic environments.[7, 9–12] The dissatisfaction arises from several causes, including loss of resolution, distortion of the image, and restriction of the dynamic field achieved by free scanning eye movements.

Visual aids for night blindness are more common because of their development for purposes such as military use, night hunting, and surveillance. Several generations of night visors using light amplification have been proposed as visual aids for patients with night blindness.[13–16] A portable video device, composed of an infrared video camera in combination with a head-mounted display (HMD) has been evaluated as well.[17] These aids provide a gray-scale image with sufficient illumination to be perceived at photopic levels (defined as luminance levels >0.3 cd/m^2). These aids cover a limited field (up to 40°), and they prevent scanning eye movements over a wider visual field.

Another possible strategy for night blindness is to illuminate the environment and objects. Portable wide-field high-intensity lamps have been developed and compared for effectiveness with the night visor technology.[18–21] The lamps were judged to provide true stereoscopic vision and a more realistic or natural perception. These studies showed little advantage of either technology in mobility performance.

Review of the literature suggests the following requirements for mobility visual aids for tunnel vision:

1. Provide information about objects in the peripheral field.
2. Be compatible with the remaining visual capabilities.
3. Be compatible with natural scanning eye movements.

4. Able to function in light and dark (important when the disease causes night blindness).
5. Permit use of spectacle correction.
6. Be portable, low weight, long lasting in operation, and cosmetically acceptable.
7. Use commercial off-the-shelf (COTS) design, preferably, due to the small size of the market.

In response to theses requirements, we proposed an augmented-view device and implemented a new approach to visual aid design for severe loss of peripheral visual field.[11, 22] This augmented-view principle compresses information from a wide visual field into the remaining narrow visual field of the patients. This can be achieved by visual multiplexing (merging) of the high-resolution residual vision and the wide field of view.[23] The approach consists of a combination of a see-through HMD, a wide-angle video camera, and an image-processing unit. The head-mounted video camera provides an image of a wide field (up to 75°). The image-processing unit creates an outline "cartoon" of the scene by using a contour (edge) detection algorithm. Contours are presented as monochrome bright lines and shown on the see-through HMD with a scene reduction (minification) of 3 to 7 times. The "minified" scene outline displayed is superimposed onto the normal view seen through the display, which retains full high resolution.

Fig. 1 shows an illustration of the wearer's view with such a device. The image represents the instantaneous view as might be perceived by a patient with severe peripheral vision loss facing another person across a room. Bright lines displayed by the HMD are perceived separately from the background (see-through view) and they provide information about a wider field. For instance, the patient may see only the face of the person with his remaining vision. The augmented-view lines show that the person is seated in a group of empty chairs. Yet the user can enjoy the high resolution of the central vision with the see-through view. The head-mounted camera records the field facing the wearer's head, therefore the user can select the scene—displayed as minified outline image—using head movements. The same head movement can be used to shift the contours away from details to be inspected with full resolution in the see-through view.

FIGURE 1.

Augmented-view simulation showing the instantaneous patient view with the device. The image represents the patient visual field (8° across) when looking at a face across the table. The see-through head-mounted display shows a minified (about eight times) outline image from a wide angular field (bright lines). This outline provides additional visual information about the rest of the body of the observed person and the relative position of objects around him. At the same time, the patient can still benefit from a full-resolution image through the head-mounted display.

Because of the minification factor in image size between direct view (see-through) and the augmented view, speed of motion in the images is also modified (in parallel with image size). This difference in image motion provides another useful clue for separating the see-through HMD view from the augmented-view image. For instance, assuming a minification factor of five, if the gaze is horizontally displaced by rotating the head, the image of the augmented-view scene seems to move (referenced to the head) five times slower than the see-through scene. Video simulations of the augmented-view concept are available on our website: http://www.eri.harvard.edu/faculty/peli/index.html

With few modifications, this concept could be implemented as an aid for night blindness. These modifications are a high-sensitivity camera that can achieve good images in low-illumination environments, allowing infrared imaging, an additional infrared illumination source (e.g., LED), an automatic control of the display brightness, and using another color scheme (e.g., displaying red lines).

The purpose of this project was to assess the feasibility of the spatial-multiplexing augmented-view concept as a field-expansion device as well as a night blindness aid. In addition to the need to develop preliminary prototypes that could be assessed by patients for the potential usability and acceptability, we were also interested in comparing variety of parameters of the systems to guide further development.

Due to the limited target population that can suitably use these aids, the use of COTS devices is a desirable approach. To reduce the cost of the aids, we took advantage of technologies that are already developed and being produced for other purposes with a large consumer base. The aim of the current work was to demonstrate a real implementation of the augmented-view concept as a visual aid for tunnel vision and to obtain responses from potential users. In this study, the preferences for several implemented combinations of COTS devices under typical environmental conditions were obtained as the basis for further device development.

METHODS

Several combinations of COTS components (cameras and HMD's) were used to create the proposed augmented-view systems that were then evaluated by normally sighted observers (the authors) and two RP patients with severely reduced visual field (5° and 10°) and good visual acuity (20/30 and 20/20, respectively). Initial evaluation was carried out in the laboratory to measure the objective performance of several elements.

When the devices were modified to be portable, further evaluations were performed while walking indoors, climbing stairs, in light and dark environments, and finally on the sidewalk under daylight and night conditions. Patients indicated preferences between configurations and commented on the augmented-view

concept. An additional evaluation performed by the authors was only used to interpret and describe appropriately the patients' responses. Subjects signed informed consent forms approved by the institutional review board in compliance with the Declaration of Helsinki.

COTS Components

Two cameras were tested in the study (Fig. 2): the Mitsubishi M64283FP CMOS Artificial Retina and the MicroOptical USB ClipOn Camera.

The Mitsubishi M64283FP CMOS Artificial Retina (Mitsubishi Electric Research Laboratories, Cambridge, MA; http://merl.com) is a CMOS sensor chip with 128 × 128 black/white pixels. This camera provided in-chip image processing including edge enhancement (Fig. 2b). The horizontal angular fields achieved were 58° and 78° with the lenses V-4302 and V-4301 by Marshall Electronics (El Segundo, CA; www.mars-cam.com). This camera was used together with its evaluation board IEB-283 (Fig. 2a). Although it could provide a video signal, we were only able to use its digital interface with the software provided by the manufacturer for the evaluation board. Using this configuration we obtained only 5 frames per second (fps) in the edge detection mode. The rate of acquisition (expressed in frames per second) for both cameras depended mainly on the time of integration. At low light levels, more time per frame was needed to collect enough photons to obtain a suitable electrical signal, so the frame rate was reduced. The frame rate was also affected by the image processing time and the transfer of images between the computer and the HMD.

The MicroOptical USB ClipOn Camera (MicroOptical Corp., Westwood, MA, http://www.microopticalcorp.com) is a color web-cam with 640 × 480 pixels that attaches to ordinary eyeglasses temples (Fig. 2c). This camera is a wearable adaptation of the ViCam USB PC Digital Camera by Vista Imaging (San Carlos, CA; http://www.vistaimaging.com). It had high sensitivity at low illumination levels, and auto-gain control. We obtained 59°, 72°, and 97° horizontal fields with the lens provided with the camera, the V4302 lens, and the V4302 lens, respectively. Edge detection (explained below) was performed using software-based processing (Fig. 2d). In this mode, the frame rate was 5 to 22 fps depending on the light level.

We evaluated the system with six commercially available and prototype HMD's shown in Fig. 3: (see Tables 1 through 4 for more technical details).

1. The Sony Glasstron PLM-50 (Sony, Shinagawa-ku, Tokyo, Japan; www.sony.com) is a binocular device that displays a color National Television System Committee signal (TV video standard in use in the U.S.). It has continually selectable see-through density achieved with liquid crystal shutters.[24]
2. The Virtual Stereo I-O i-glasses HMD (I-O Display Systems, Sacramento, CA; www.i-glasses.com) displays a color National Television System Committee signal in see-through mode with an open peripheral design.[25] This HMD has stereo presentation capabilities, although we have not used them in this study.
3. The Olympus Monocular PC Eye-Trek (Olympus Optical,

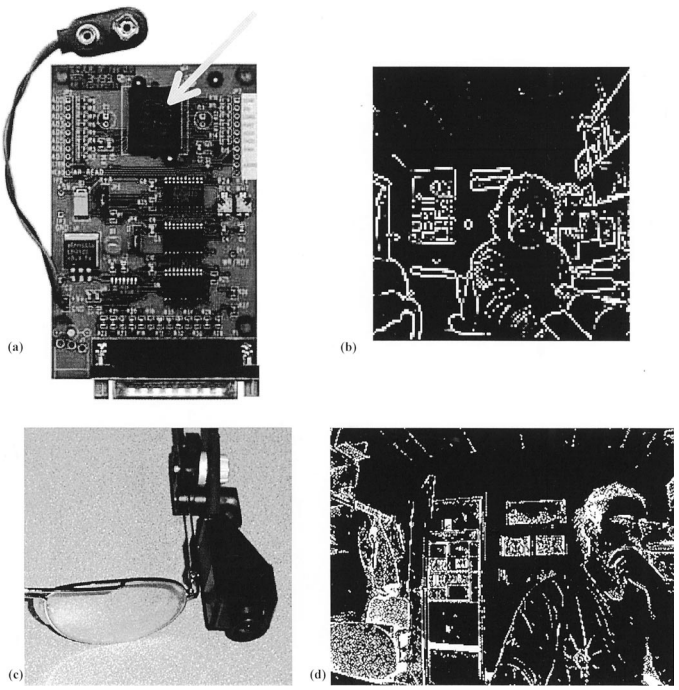

FIGURE 2.

Cameras and sample contour images obtained. (a) Mitsubishi artificial retina on the IEB-283 evaluation board (the arrow points to the actual camera mounted in the board) and (b) an example of the contour image obtained with its in-chip processing. (c) MicroOptical USB camera mounted on a spectacle frame temple and (d) an example contour image obtained with software processing on a portable computer (see also Fig. 4).

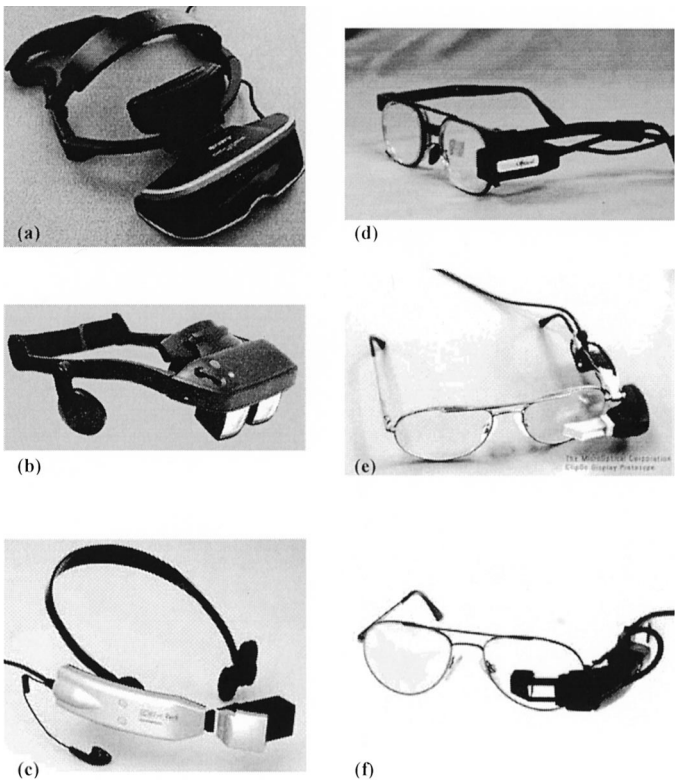

FIGURE 3.

Head-mounted displays used: (a) Sony Glasstron, (b) Virtual I-glasses, (c) Olympus PC Eye-Trek, (d) MicroOptical EyeGlass, (e) MicroOptical ClipOn CO-1, and (f) MicroOptical ClipOn CO-3

TABLE 1.
Specifications and patient preferences for cameras

Camera	Field (Horizontal)		Auto Gain Control			Light Sensitivity					Frame Rate			Color/BW[a]			Resolution		
							High/Dim Illumination		Dark										
				Gray Scale	Edge		Gray Scale	Edge	Gray Scale	Edge		High/Dim Illumination	Dark		Gray Scale	Edge		Gray Scale	Edge
Mitsubishi Artificial Retina	58° 78°	x[b] xx	Y/N	x	NA	1lux @ 1fps		x			5 fps			B/W		xx	128 × 128		x
MicroOptical ClipOn Camera	59° 72° 97°	x xx x	Y	xx	xx	1lux @ 6fps	xx	xx	x		6–20 fps	xx		Color	xx	xx	640 × 480	xx	xx

The values are from standard empirical measurements.
[a] BW, black and white; Edge, augmented vision presentation; fps, frames per second; Y, yes; N, no.
[b] The number of patients who preferred or liked an option or parameter setting is indicated by the number of "x" in the entry. A preference for each presented option was indicated without exclusion, so that each patient could indicate a preference to all, some, or none of the options of a given device or parameter.

TABLE 2.
Specifications and patient preferences for displays

Display	Bi-Monocular		Visual Field (Horizontal)		Clearance		See-Through Transmittance		Contrast		Brightness		Brightness Control		Resolution	Gray Scale	Edge[a]	Image Position		Ergonomics/Comfort	
Sony Glasstron	Bi	xx[b]	22°		39° Binocular		Variable		N/M	xx	N/M		Full	xx	262 × 230		x	4 m	xx	Helmet	
Virtual IO	Bi	xx	22°		~Full	xx	5%		87%	xx	N/M		None		262 × 230		x	4 m	xx	Head Band	
Olympus Eye Trek	Mo		21°		26° Monocular	x	15%	xx	63%	xx	N/M	xx	3 levels	xx	800 × 600		xx	0.5 m		Head Band	
MicroOptical EyeGlass	Mo		17°	xx	~Full	xx	47%	xx	30%		N/M		None		320 × 240		x	1 m	x	Build-in-spectacle	xx
MicroOptical ClipOn CO-1	Mo		7.5°	x	~Full	xx	Opaque	NA[a]	N/M	xx	N/M	x	None		320 × 240		x	1 m	x	ClipOn	x
MicroOptical VGA ClipOn CO-3	Mo		16°	xx	~Full	xx	Opaque	NA	N/M	xx	N/M	x	None		640 × 480	xx	xx	1 m	x	ClipOn	x

The values are from standard empirical measurements.
[a] Edge, augmented–vision presentation; N/A, not applicable; N/M, not measured.
[b] Patients selected with "x" the preferred items without exclusion.

TABLE 3.
Specifications and patient preferences for minification factor

Minification	
1:2	
1:3	x[a]
1:4	xx
1:5	xx
1:10	x

The values are from standard empirical measurements.
[a] x represents patient selection as in Table 1.

TABLE 4.
Patient preferences for focusing method

Potential Focusing	
Fixed	
Manual	x[a]
Auto	x
Large depth of field	x

[a] x represents patient selection as in Table 1.

Shinjuku-ku, Tokyo, Japan; www.olympus.com) is a Super Video Graphics Array (SVGA 800 × 600 pixels) color display with see-through optics. The appearance of the display is fairly bright (including three selectable brightness levels). A monocular see-through display provides a higher apparent transparency (compared with a binocular display) because of the fusion of the two see-through images from both eyes (one without the attenuation of the HMD). The unit we used had only a digital gigabit video interface for 24-bit red, green, and blue; therefore an additional converter (provided by Olympus) was needed. Gigabit video interface is a transmission and connectivity standard developed by Sony that is used for digital video connections.

4. The MicroOptical Integrated EyeGlass (The MicroOptical, Westwood, MA; www.microopticalcorp.com) is a monocular, built-in-spectacle, Quarter Video Graphics Array (QVGA 320 × 240 pixels), see-through display.[26] This HMD represents a significant improvement in esthetic appearance because only a prism beamsplitter is placed in front of the user's eye, embedded inside the spectacle lens. Its appearance is similar to bifocal spectacle optics for presbyopia.
5. The MicroOptical QVGA ClipOn CO-1 is an opaque, color, monocular display that attaches to the eyeglasses temple. Its small size and the open optics around the display make it an attractive candidate for visual aids. It has the advantage of supporting both NTSC VGA video formats
6. The monocular MicroOptical VGA ClipOn CO-3 is a similar device to the previous one, with improved resolution (640 × 480 pixels) and wider visual field, although it supports only VGA format.

Edge Detection Algorithms

For edge detection, we followed the same COTS strategy of using only the software provided by the manufacturer for each camera. Edge enhancement of the camera signal was controlled by software for both cameras, although in the case of the Mitsubishi Artificial Retina, it was performed at the sensor chip level. This is a desirable feature, in general, to improve the display speed of the final device. However, particularly in this Artificial Retina device, the implementation of the in-chip image processing compromised the update rate of the camera signal.

The software applications provided a display window in a Windows98 SE environment, that we displayed in the HMD's. These programs, provided by the manufacturers, were SCAR, for the Mitsubishi Artificial Retina and IEB-283 evaluation board, and ViViewer Application, for the MicroOptical USB ClipOn camera.

The strategy for edge detection was similar in both applications and is illustrated in Fig. 4 with a sample image. Both software applications provided an enhancement of edges in the video image, called *image sharp* control in both programs. Convolution with a simple four-pixel neighbor gradient filter was applied to perform the enhancement, and the result was added to a mean background level. We selected the highest value allowed for that enhancement (Fig. 4b). After this, a binary image was obtained (only bright lines over a black background) by selecting the highest *contrast* control value in the software and the display, obtaining a rather saturated image (Fig. 4c), and adjusting the *brightness* (also called *gain*) in the software until we obtained an outline version of the original image (Fig. 4d). Internally, the brightness adjustment was actually performed before the contrast saturation that finally binarized the image. The contrast saturation and gain adjustment performed the same function as a high–threshold function (inexistent in both software programs) on the edge-enhanced image.

A laptop computer was necessary for the camera control (and is not expected in a final product). Selecting the lenses for the cameras and modifying the image window size of the application in the computer screen desktop enabled us to achieve the different minification values used in the study.

The users also tried an additional configuration, in which the HMD displayed the direct image from the camera, without any edge enhancement. Images, similar to the ones viewed in this configuration, will be termed "gray scale" images. Images with outlines will be referred to as "edge" images.

Optical Measurements

Camera horizontal fields of view were measured with available lenses by focusing them at a distance of 0.5 m and acquiring the image of a horizontal ruler. This procedure provides the tangent field of the camera at the distance from the ruler to the entrance pupil of the camera. We were more interested in the horizontal field because of its importance in navigating. The vertical field can be derived from the format of the camera that was either 4:3 or 1:1 for the MicroOptical and Mitsubishi cameras, respectively.

HMD angular visual fields and clearance (horizontal) were measured using perimetry with a normally sighted observer. We make a distinction between *angular visual field* as the angle subtended by the active image area (screen) of the HMD, and *clearance*, defined as the angular span of visual field within the HDM frame that is not blocked by it. In see-through HMDs, the inner edge of the frame frequently subtends more than the active area of the screen,

therefore the clearance is larger than the angular visual field. In some HMDs, such as the Glasstron, the frame totally blocks peripheral vision, and in other more open designs, such as the I-glasses, a minimal peripheral ring is blocked (<1° width). Low clearance values imply a limitation to the scanning of the peripheral visual field through the display. In the case of opaque models, perimetry was achieved by displacing the HMD exit pupil slightly off-axis with respect to the eye pupil, therefore both the display and the perimeter target were visible at the same time. The measured visual fields and clearances (Table 2) depended on the user's anatomy (distance between the eye and the display); hence, they did not always match the nominal values provided by the manufacturers.

See-through transmittance and on-off contrast were measured with a luminance meter (LS-100, Minolta Camera, Japan). The transmittance was measured as the ratio of the measured luminance of a calibrated extended light source to the same source measured through the HMDs while actively displaying a black background (OFF state). Contrast was measured as the ratio of the luminance of HMDs in their maximal brightness when displaying a white background (ON state) to the luminance of black background (OFF state). We were unable to objectively measure effective retinal illumination (brightness) because of the interaction between the display exit pupil and the luminance meter aperture, which is not identical to the interactions with the human eye.[27]

Visual Field Measurement

The unaided and expanded visual fields were measured using the Auto-Plot Perimeter (Bausch & Lomb, Rochester, NY) in dim room illumination, with white light targets of 3 mm and 6 mm diameter at a distance of 1 m. Fig. 5 shows an example of the measurement results. A similar kinetic perimetry technique was used for Fig. 6. For this measurement, custom software simulated the Auto-Plot Perimeter by using a Davis Powerbeam-VI DLP projector and a Stewart Lumiflex130 rear projection film screen. After proper calibration, the software had features similar to the Auto-Plot Perimeter and permitted automatic recording of subjects' responses.

RESULTS

Expanded Field of View

The main purpose of the augmented-view device—the effective expansion of the visual field—depended strongly on device parameters such as contrast and brightness and ergonomic variables such as stability and adjustment features. Hence, a direct measurement of the expanded visual field was needed in the evaluation of the device. As an example, we measured the expanded visual field of a tunnel vision patient using two different HMDs and compared the results with that of his unaided visual field.

The systems evaluated were the Sony Glasstron HMD and MicroOptical EyeGlass HMD, both in conjunction with the Mitsubishi Artificial Retina camera. The Glasstron combination had a minification factor of 2.6, whereas the EyeGlass combination had a minification factor of 5.0.

Fig. 5 shows the perimetry results in the subject for unaided vision (seeing through the HMD) and augmented-view using the two systems. The expanded field using the Glasstron PLM-50 fulfilled expectations. However, the field was only tripled using the EyeGlass, despite the actual minification factor of five. This was

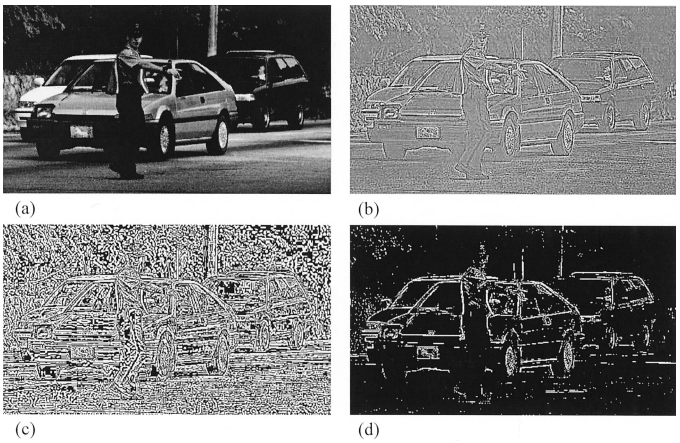

FIGURE 4.

Augmented-view algorithm: the process used to obtain the contour images using the available software in both systems. Images shown are for the MicroOptical USB camera software. (a) Original image; (b) after edge enhancement; (c) after high–contrast gain (the displayed image appears saturated but the digital image is only partially saturated); and (d) after brightness adjustment (reduction of brightness) and contrast saturation. The original image is a free on-line picture from *The News & Observer* at: http://cgi-bin.nando.net/nao/hurricane/photos/tours/090996/FRAN5.MW.090996.TSS.html.

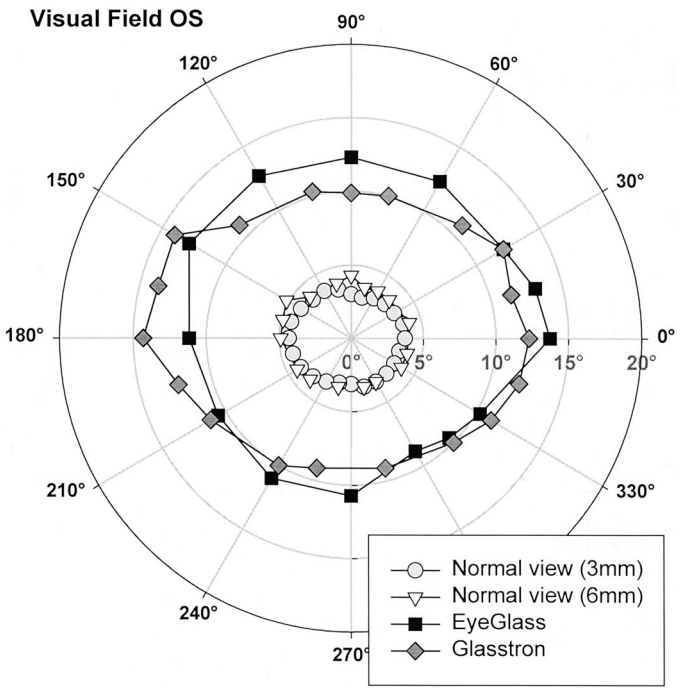

FIGURE 5.

Visual field of a retinitis pigmentosa patient with the normal view (see-through) and the augmented-view using two different head-mounted displays and the Mitsubishi Artificial Retina. For the augmented-view, only the results of the 6 mm target are plotted; the results with the 3 mm target were not markedly different. The EyeGlass and Glasstron configurations had a nominal minification factor of 5 and 2.6, respectively.

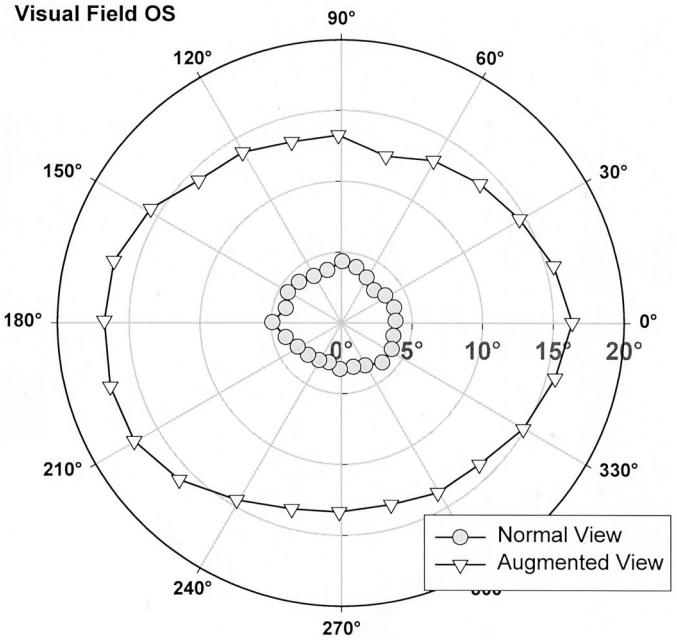

FIGURE 6.
Visual field of the same retinitis pigmentosa patient from Fig. 5 with the normal view and the augmented vision (minification factor four) using an improved EyeGlass head-mounted display and ClipOn Camera.

probably due to the low contrast, primarily as a result of the poor light extinction of the LCD in the prototype unit and a deficient fitting of the device to the subject. The low contrast decreased the patient's detection of the target. In addition, users with tunnel vision may have more difficulties adjusting HMD's with Maxwellian views,[28] such as the EyeGlass. In Maxwellian view configuration, the light source of the HMD is optically conjugated approximately with the user's pupil. A small tilt or misalignment of the device produces a reduction of retinal illumination. See Burns & Webb[28] for more details. To adjust the uniformity of illumination over the display it was necessary to have a complete view of the active screen; for users with tunnel vision, this was difficult. Therefore, such systems need to be better equipped for adjustment and remain more stable on the head.

We monitored the augmented-view video signal displayed on the HMD simultaneously on a desktop display, verifying that the camera was not the limiting factor. To verify the effective expansion of the field with the EyeGlass technology, we measured the same subject using an updated EyeGlass prototype (not included in the study) with higher contrast and brightness. Fig. 6 shows the perimetry result of the same RP subject using the MicroOptical EyeGlass HMD and the ClipMicroOptical USB ClipOn Camera with a visual minification factor of four. With this configuration, the measured field expansion corresponded with the actual minification.

Patients' Evaluation of HMDs and Cameras

Tables 1 through 4 summarize the results obtained in the study, including the objective measurement values for the COTS elements and the preferences of two RP patients. The two subjects were asked to indicate their preferences for different properties, devices, and combinations. Their preferences appear as "×" next to the corresponding item.

In addition to the preferences shown in Tables 1 through 4, patients had the following comments:

1. Binocular displays were preferred, even though monocular HMD's have advantages (field, apparent transparency, weight, cost, and clearance).
2. Patients preferred using their own spectacle correction rather than adjusting a lens on the display.
3. Clip-On concepts were favored for their flexibility (Fig. 7). Patients can use them in either bioptic or central position by choice.
4. Integrated eyeglass design was attractive to subjects due to its esthetic look and the wide-open fixation field around the display (Fig. 8).

DISCUSSION

Several configurations for an augmented-view visual aid have been successfully implemented in a feasibility study. In preliminary and subjective evaluation, two patients with severely restricted field loss felt that the augmented-view concept could be a useful field expansion aid for navigating, obstacle avoidance, and hazard prevention. They felt that the augmented-view image could potentially allow tunnel vision patients to gain a better appreciation of objects and their spatial localization on a wider field than their residual visual field. A moderate visual acuity is necessary to process the outline image display, although it is also needed to use other visual aids for tunnel vision. Training may be necessary to gain veridical perception of visual direction and correspondence between the real world and the displayed contour image due to the minification factor.

The implementations were based on COTS displays and cameras to reduce the cost of the possible final aid. However, even this limited evaluation suggested that some features of the apparatus should be specific to this kind of application. Preferences, needs, and performance may be different in normally sighted users and tunnel vision patients. For instance, the size and brightness of the display are not necessarily the same for these populations. Another limitation of the COTS approach is that manufacturers can mod-

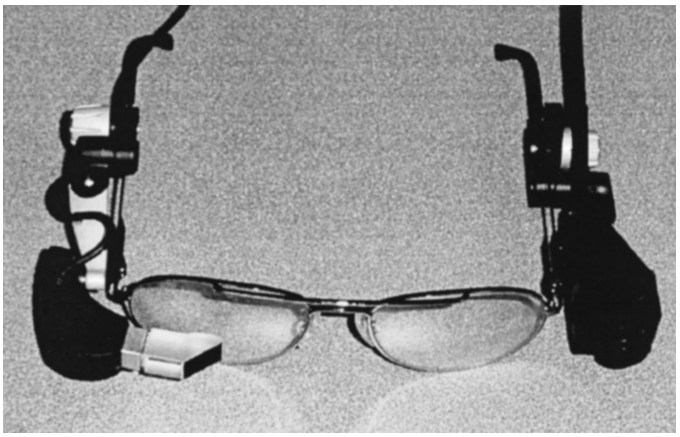

FIGURE 7.
ClipOn CO-1 head-mounted display (right eye) and camera (next to left eye)

FIGURE 8.
Integrated EyeGlass display in front of the left eye. The actual display element is in the temple, and the image is viewed with a small beam splitter embedded in the spectacle lens in front of the user's eye. The frame provides an adjustable PD to permit fitting to various users.

ify features over time or even stop the production and support of the devices.

In view of the responses and comments obtained during this evaluation, we have identified the following aspects of the augmented-view devices that require further development:

1. Small HMD field size is not a limitation. Patients preferred smaller displays. This is further supported by preliminary measurements showing that their fixation field is narrower (50% horizontally) than that of normally sighted people.[29]
2. Minification should be close to five times. This value allows a wide camera field (~75°) in a small display. As a result, patients do not need to scan with eye movements to obtain information from the wide field. However, one of the subjects, who had <10° residual visual field, showed a strong preference for having the display field slightly smaller than his visual field (about 6°) with a minification factor of up to 10 times. This configuration allowed him to notice the whole outlined scene in one glance while still being able to process the information displayed on the display. With higher minification factors, the outline image becomes too small and difficult to interpret.
3. For patients suffering from night blindness, the transparency of the display is an important factor to address. These subjects will not obtain benefit from a dark see-through view, especially under dim illumination. Therefore, the see-through optics should be of as low density as practical.
4. It is necessary to improve camera sensitivity. For the augmented-view, neither color camera nor high resolution are necessary. Therefore, cameras may be infrared-sensitive, and color filters would be unnecessary, thus improving light efficiency. Techniques of pixel binning (pixel clustering) could be used to compromise high resolution in favor of increased sensitivity. To improve edge of detection and supplement image quality in darkness, infrared illumination should be provided.
5. Controlled brightness: the visual display range needs to be variable. High brightness is needed in sunlight, whereas in dim illumination reduced brightness prevents dazzle. On the other hand, patients with night blindness require more display brightness in the dark. In addition, manual control of display brightness in dim illumination is desirable. The use of monochrome HMD's that are generally brighter may be desirable.
6. Video acquisition and display at 30 fps is needed. If the frame rates are slower, patients need to stabilize their head before an image can be viewed.
7. Avoid the need for focusing: patients would prefer an autofocus system or a large depth of field. Furthermore, edge detection requires well-focused images.
8. Avoid the need for a computer for image processing. A specifically designed system should be implemented to perform edge detection, reducing the weight of the aid and the display delay of the augmented-view device.

Another possibility not explored in this study is the implementation of the augmented-view concept in video format without the use of digital processing. In that case, real time analog video processing would be needed.

After the demonstration of the feasibility of such system, we are in the process of implementing many of these recommendations in the next phase of this project. In this next phase, larger clinical trials will be conducted to evaluate the benefits and possible limitations of this new approach.

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