22.4: *Invited Paper:* Augmented Vision Head-Mounted Systems for Vision Impairments

Eli Peli[1], Gang Luo[1], Alex Bowers[1], and Noa Rensing[2]
[1] The Schepens Eye Research Institute, Dept. of Ophthalmology, Harvard Medical School, Boston, MA
[2] MicroOptical Eng. Westwood, MA

Abstract

We have developed, implemented and tested a novel concept of vision-multiplexing using augmented vision systems for people with vision impairments. Minified contour images from a head-mounted, miniature video camera are presented on a see-through display providing visual field expansion while still enabling the full resolution of the residual central vision to be maintained.

1. Background

With normal vision we enjoy the benefits of a wide field of view, primarily used for navigation and orientation, together with high-resolution capabilities that enable discrimination of fine details. Visual impairments due to disease or injury typically affect only one of these aspects, either restricting the wide peripheral visual field (VF) in conditions such as retinitis pigmentosa (RP) and glaucoma, or damaging the high-resolution fovea in conditions such as age-related macular degeneration (AMD). When peripheral VF loss is severe (leaving useful VFs less than 20° in diameter – tunnel vision), a patient's mobility can be affected due to reduced ability to spot obstacles and difficulties in navigation. Social interactions of patients may be affected by failing to note or respond to people appropriately. In addition, RP and related diseases often cause night blindness due to early loss of rods.

Traditional low-vision devices recover, at least partially, the lost visual ability, but at a high cost for the remaining functionality. For example, magnification increases resolution but inherently limits the field of view. Similarly, minifying devices increase the field of view, but cause a loss of resolution in addition to spatial distortions, and may restrict scanning eye movements.

A design approach for low-vision devices called "vision multiplexing" attempts to avoid or reduce these limitations by 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 [5]. Augmented vision systems lend themselves to vision multiplexing.

For patients with tunnel vision, we have suggested the use of a head-mounted display (HMD) augmented vision system that implements spatial multiplexing via superposition [5] (See Fig. 1). A miniature video camera with a wider field of view than that of the see-through HMD is mounted on the device. The camera's images are processed at video rate to provide cartoon-like edge images of the scene, and are shown in the HMD minified. The minified edge images enable the patients to see and detect potential obstacles and locate other objects that, without the minification, would fall outside of their residual VF. Once an object is detected in the HMD, it can be examined through the transparent display and be seen in full resolution and color. Since the edges occupy only a small portion of the display, the user can see clearly through the display. We have developed and started testing such a system for patients with tunnel vision for use in daytime and nighttime.

Figure 1 – Simulation of the appearance of a street-crossing scene as it might appear to a patient with tunnel vision using the augmented vision system. The lady's head is seen in full resolution through the display and slightly to the left in the minified cartoon. The cartoon (edge-image) provides a wide field of view enabling detection of the pedestrian (on the left) crossing in the other direction (representing a potential collision that would not be visible without the display).

2. Hardware

2.1 The HMDs

Initial evaluation compared 4 off-the-shelf HMD systems and 2 different cameras [6]. The HMDs were Glasstron PLM-50 (Sony Corp., Tokyo, Japan), Virtual Stereo I-O i-glasses HMD (I-O Display Systems, Sacramento, CA), PC Eye-Trek (Olympus Optical Co. Ltd. Shinjuku-ku, Tokyo, Japan), Integrated EyeGlass (MicroOptical Corp., Westwood, MA), and two of MicroOptical's ClipOn systems: the QVGA CO-1 and VGA CO-3. Following the initial evaluation, we contracted with MicroOptical to modify their integrated EyeGlasses design for further assessments. Early prototypes [6] were used to demonstrate the VF expansion and vision multiplexing potential of the system, and to assess usability with 2 RP patients. The patients, who had severely restricted VFs, thought that the augmented-vision concept could be useful for navigation, obstacle avoidance, and hazard prevention. They did not find a small-field display to be restrictive, provided the design was open [8], and preferred a relatively high level of minification and minimal user control (automated system). A number of designs and experimental iterations served to refine the carrier lens size and the shape of the frame, including facilities for adjustments to ensure the frame fits securely and comfortably on people with varying facial dimensions. The current generation of HMD (Fig. 2) represents a substantial improvement in cosmetics and ergonomics (reduced weight and better fit). In addition it provides a vertically expanded exit pupil that serves to compensate for the movement of the display during walking. The current field of view of the display is 16°(H) by 12°(V).

ISSN/007-0966X/07/3802-1074-$1.00 © 2007 SID

2.2 Cameras

The 2 cameras used in the early study [6] were the Mitsubishi M64283FP CMOS Artificial Retina (Mitsubishi Electric Research Laboratories, Cambridge) with 128×128 in-chip image processing, including edge enhancement that provided horizontal angular fields of 58° and 78° with 2 lenses, and a color 640×480 adaptation of the ViCam® USB PC Digital Camera by Vista Imaging Inc. (San Carlos, CA) that provided 59°, 72°, and 97° horizontal fields with 3 lenses provided. In a further evaluation we used a Marshall V3214 lipstick CCD camera that provided horizontal fields of 52° and 90° with 2 lenses. This was replaced with a Supercircuits PC206 CMOS camera that provided a field of view of 60°. Because the sensitivity of that camera was insufficient for the night vision application, it was replaced with a Supercircuits PC182XS camera equipped with Sony's Ex-View CCD chipset, which provides a field of view of 80°. This camera is currently used for both the day and night time application of the system and provides 5× field expansion.

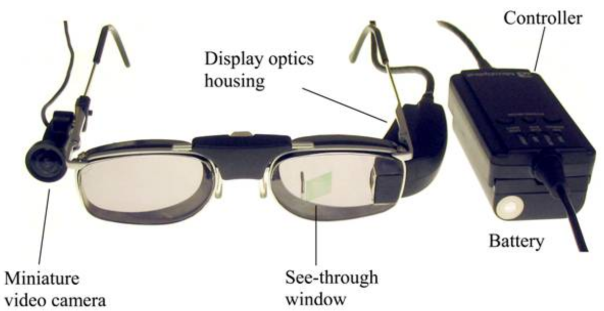


Figure 2 – The current generation of augmented vision system for patients with tunnel vision. The wide-angle image captured by the video camera is processed by the controller to provide edge contour images of the scene. The edge images are displayed on the see-through display providing an expanded view. Once an object is detected via the minified cartoon, it can be examined with full resolution and color through the transparent display.

2.3 Edge detection

The early evaluation [6] applied edge detection using software provided with the cameras. Convolution with a simple 4-pixel neighbor gradient filter performed the enhancement which was followed by thresholding to obtain a binary edge image (bright lines over a black background). The update rate of the systems was compromised in these early designs. These were replaced first with a dedicated edge detection system developed for us by DigiVision (San Diego, CA) and more recently by an edge-detection algorithm implemented by MicroOptical. The DigiVision FPGA-based system provided edge video images at a rate of 30 frames/sec with only a 73µs delay (a little more than one scan line of NTSC signal). Such a small delay was not a problem for our augmented vision system, as there is no registration requirement. The DigiVision edge detector, powered by a 3Lb SLA battery, was used in the visual search study described in section 3.1.

In the latest system (Fig. 2), a deck of cards sized controller box includes the edge detection functionality, and also drives the camera and display. This controller weighs only 175g (6.5Oz) including a 2-hour battery. The weight of the headborn components is approximately 110g. The edge detection was implemented on the FPGA (100K gates) of the control box of the display system. The algorithm used a 3 line and 3 pixel difference filter with adjustable threshold.

3. Laboratory and outdoor evaluations

A series of studies were conducted to test the value of the augmented vision system for a variety of tasks and conditions. Laboratory studies allowed us to assess device prototypes, identify limitations, acquire early users' feedback, and thereafter improve design and configuration. These studies were interleaved with successive prototype development. For example, pilot trials with the device indicated that patients with severe tunnel vision might have difficulty locating a real target, even though they could see a contour image of the target in the HMD. We realized that with residual VFs much smaller than the display, patients could not determine where within the display they were looking, and therefore they had difficulty in registering the minified view to the real-world view. A center mark was added to the display as a registration aid to help users locate targets in the real world. The camera and display are spatially aligned using a simple calibration procedure so that when a target contour is noted in the display, moving the head to align the center mark with the target contour image will bring the real target into the see-through view. We also noted in mobility studies that the up-and-down movement created when walking caused occasional disappearance of the display view. The prototype was redesigned with a vertically elongated exit pupil that improved image visibility.

3.1 Visual search

Within a controlled environment, visual search tasks resemble some of the visual demands of daily life (e.g., navigation, scanning the environment, and finding objects of interest). Kuyk *et al.* [2, 3] found that scanning ability in a visual search task was one of the main predictors of mobility of visually impaired adults. We conducted a search study similar to Kuyk's. Subjects with severe tunnel vision searched for targets with and without the augmented vision system, and with an auditory cue indicating target direction [4]. The search targets were displayed on a gray blank background in random positions outside of subjects' residual VFs. Therefore, the targets could not be detected with natural vision when looking straight ahead at a fixation point at the center of the screen (Fig 3).

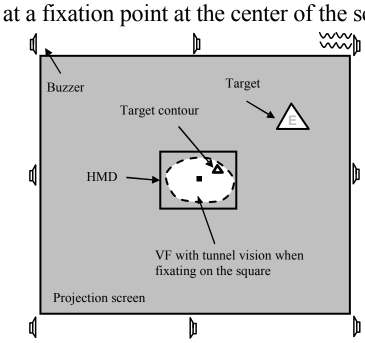
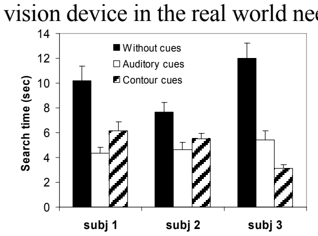


Figure 3 –The visual search task. Targets were presented outside subjects' visual fields. The minified target contour (edge) images seen in the HMD provided cues for both the direction and eccentricity of targets. Auditory direction cues were provided by buzzers around the screen.

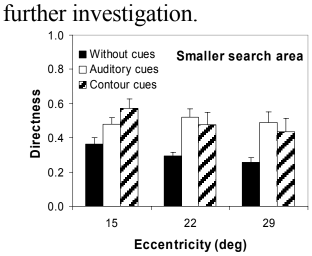
Targets were composed of a random low-contrast letter surrounded by a black frame (triangle, square, or circle selected randomly), 3º or 5º in size. Only the target frame could be detected and recognized in the minified contour view. Subjects had to look through the display to view the targets foveally in order to identify the letter. Two studies were conducted using different search area widths (90º(H) and 66º(H), respectively). Subjects were allowed to move their eyes and heads freely during the search. Head and eye positions were recorded and used to compute the gaze positions, directness of search path, the angular speed of gaze, and to determine the search time to find the target. The directness score for a whole search path was the average cos(θ), where θ was the angle between the current sample gaze shift and the target direction, weighted by the length of the current gaze shift. A perfect path would have a directness of 1, regardless of gaze speed. Normally-sighted subjects performing the same task had directness scores of about 0.95.

For the larger search area used in the first study, all three subjects found the targets significantly faster using either auditory cues or contour (edge-image) cues than without a cue (Fig. 4a). For the smaller search area used in the second study, the contour cues significantly improved the directness score (Fig.4b), but the search time performances with the HMD were mixed. Six out of the 9 subjects, those with VFs >10° found targets more quickly with the device, but the 3 with smaller VFs (<10°) were slower. Gaze speed was quite slow when using the augmented vision device (about half the speed without the device), which we believe was associated with lack of device familiarity (subjects had only about an hour of training before the study). Regression analyses suggest that, if the gaze speed increases, the minimum VF required to gain a benefit from the device would be less than the 10° we found [4]. Since the directness of the search improved for all subjects, any increase in gaze speed would then result in reduced search times, even for patients with smaller VFs. In fact the analyses suggest that, in relative terms, patients with smaller VFs would benefit more, but of course their absolute performances would remain lower than those of patients with wider residual VFs.

In this study, targets were presented on a simple blank gray background, which was not representative of the real world. When the contours of targets were within the subjects' VFs, they could be easily detected. However, this might not be the case if targets were embedded among many distracters. The usefulness of the augmented vision device in the real world needs further investigation.



a



b

Figure 4 –a) Visual search time of the three subjects in the larger area search. Auditory cues and contour (edge-image) cues significantly reduced search time for all subjects. b) Mean (SEM) directness of the 9 subjects in the smaller area search. In both studies, directness with either auditory or contour cues was better than without cues.

3.2 Collision detection

Once a person with tunnel vision detects an obstacle, s/he can judge potential collisions, so that timely maneuvers to avoid a collision can be taken. When a patient is wearing the augmented vision device, it might be preferable if the risk of collision could be judged directly from the minified edge images, as that would speed up the response. However, the minified edge images may impede the user's ability to make such judgments accurately and confidently. One concern is that with minification patients might feel that they are going to collide with everything seen in the display. This could cause too many unnecessary collision-avoidance maneuvers. To evaluate the ability to make collision judgments with the minified edge images, we conducted a study in a virtual environment (a walking simulator). Ten normally sighted subjects stood 77cm from a wide (94º ×79º) rear-projection screen that displayed a photo-realistic video representation of a shopping-mall corridor. The movie scene was updated as if a subject was walking at 1.5m/s down a preset path. Each trial consisted of moving down one straight segment of the path while a stationary human-sized obstacle appeared at 5m and stayed on for one second. The obstacles were placed at varying distances from the trajectory of the path segment (path offset). For each subject 44 tested path offsets were distributed from -20cm to 120cm on each side of the path. Subjects reported verbally whether they would make any contact with the obstacle if they continued on the same trajectory without an avoidance maneuver. The subjects were instructed to make a forced choice. Response values at different path offsets were fit to a Gaussian cumulative density function. The mean of the Gaussian represents the perceived safe passing distance (PSPD), calculated for left and right sides separately, and the standard deviation represents the decision certainty. Each subject performed the task with and without the augmented vision device. The see-through views of both eyes were blocked so that subjects could only see the images in the display with one eye. In the without-device condition, the eye that would not be fit with the display in the with-device condition was patched. On the camera side, the minification from the augmented vision device caused a small, but significant increase in the PSPD (p=0.004), but the effect was not significant for the display side (p=0.890). The small increase in PSPD (18%) was much smaller than the anticipated effect of the 5× minification factor of the device tested. The difference between the two sides is likely to be a result of the parallax due to the position difference between the display and the camera. There appeared to be a trend for the augmented device to reduce judgment certainty, but that effect was not statistically significant (repeated measures ANOVA, $F_{1,9}$=3.6; p=0.089). It is encouraging that despite the very small and low resolution images seen in the HMD, subjects' judgments of potential collisions did not change much compared to the natural viewing condition. This suggests that with training users should be able to use the minified images directly for obstacle avoidance in addition to obstacle detection.

3.3 Night vision system evaluation

Two generations of the prototype augmented-vision night vision device have been evaluated by patients with RP and night blindness. The first study [1] evaluated an early prototype (LV-3), in which the edge-image mode had not been implemented, and therefore the device displayed only gray-scale images. Visual function measurements (acuity, letter contrast sensitivity and VFs) and indoor mobility assessments (high-density obstacle course) were conducted without a device, with the LV-3, and with a commercially-available comparison device (Multi-Vision), which is an opaque HMD showing gray-scale images in 1:1 scale. The measurements were conducted at light levels representative of well-lit (~16 lux) and poorly-lit (~2 lux) streets. As expected from the minification, the LV-3 substantially expanded patients' VFs by 18.4° (or 287%) at 2 lux. Patients preferred its better comfort, fit and lighter weight in comparison to the Multi-Vision device (Fig. 5). However, walking speed was slower and mobility errors were greater with the LV-3 than without a device. Insufficient light sensitivity of the prototype camera limited LV-3 performance, subjects had only brief training in how to use the device, the prototype did not include a center mark on the device display, and the subjects found it difficult to make use of the gray-scale images superimposed over the see-through view.

In response to the feedback received and device limitations noted in the first study, the prototype underwent further development and an improved version (NV-3) was evaluated in a small-scale, extended wear pilot study. The improved prototype incorporated a full implementation of the minified edge-image mode, a software-adjustable center (registration) mark, and the Supercircuits PC182XS camera with better sensitivity at low light levels. Four RP patients participated in the second study, each taking the device home for a minimum of 2 weeks. All patients demonstrated VF expansion with the device when tested at low light levels in the clinic environment. Questionnaire responses and informal observations of mobility during training walks with the device on a specially designed outdoor course [9] confirmed that patients were able to see the minified edge images superimposed over their natural view, and that with practice they could identify objects from the image and to a limited extent could use the image for orientation and to guide mobility. These preliminary findings provide evidence that patients with night blindness can use the augmented vision HMD within a real world environment, and derive benefit from the VF expansion provided by the minified edge-images. However, the patients had very poor night vision and the see-through feature of the HMD did not help much in badly-lit (very dark) areas. We also noted that, even with the better camera, the edge images were degraded at low light levels while the gray-scale images were still useable. In conducting these experiments we also realized that the combination of harsh winter weather and the long daylight hours in summer makes night time mobility studies very difficult in Boston. The same conditions resulted also in many patients with night blindness modifying their lifestyle to severely limit outdoor night mobility.

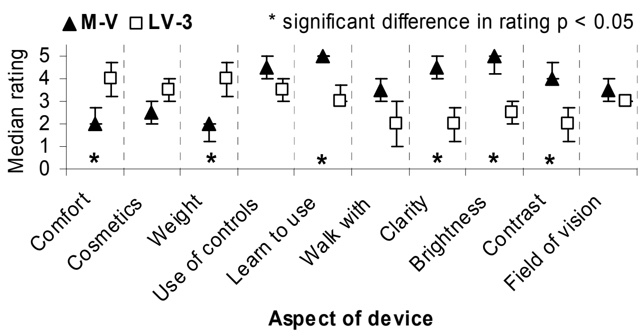


Figure 5. Median ratings for various aspects of device performance based on experiences during the indoor and outdoor assessments (1= Very Poor; 2= Poor; 3= Fair; 4=Good; 5= Very Good). LV-3 was highly rated (score of ≥ 4) for comfort and weight and M-V was highly rated for ease of use and image quality. Error bars represent interquartile range

4. Discussion

The augmented vision system appears in initial laboratory-based evaluations to enable more efficient visual search, which with more training may provide increased speed of search for tunnel vision patients even with very narrow VFs. The ability to properly judge collisions using the minified edge image carries the promise that users will be able to respond directly to that image initiating early avoidance maneuvers. Both functions should increase the safety and comfort of patients' mobility.

Active eye-movement scanning is a very important method by which patients can compensate for their VF loss. It is much more natural, easier, and more effective to move the eyes than to move the head. Despite restricted VFs, eye movements of patients with tunnel vision are not largely confined. In walking, only the horizontal eye position dispersion was found to be smaller than that of normally sighted people [7]. Saccade sizes of patients with tunnel vision are similar to those of normally sighted people, and they make many saccades into areas not seen when the eye movement is initiated.

Therefore, a visual aid for tunnel vision should not restrict eye movements. Optical see-through HMD systems with an open design have advantages over opaque HMD systems for daytime use, as patients can move their eyes freely when wearing them. However, because patients with night blindness can not benefit from the see-through view on badly-lit streets under night conditions [1], an opaque HMD presenting a gray-scale image may have advantages over an optical see-through HMD, provided the opaque HMD system has a sufficiently wide field of view to minimally limit eye movements (30º). The multiplexing concept can be implemented in opaque HMD systems. If VF expansion multiplexing is desired, the minified edge images of the wide field can be superimposed on gray-scale intensified night vision images shown in the display, creating a video-augmented view in place of the optical-augmented view of our basic system.

5. Acknowledgement

Supported in part by NIH grants EY12890 and EY 05957 (to EP) and EY12912 (to NR)

6. References

[1] 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," Ophthalmic Physiological Optics, 24/7, 296-312 (2004).

[2] T. Kuyk, J.L. Elliot and P.W. Fuhr, "Visual correlates of mobility in real world settings in older adults with low vision," Optometry and Vision Science, 75, 538-547 (1998).

[3] T. Kuyk, J.L. Elliott and P.S. Fuhr, "Visual correlates of obstacle avoidance in adults with low vision.," Optometry and Vision Science, 75/3, 174-182. (1998).

[4] G. Luo and E. Peli, "Use of an augmented-vision device for visual search by patients with tunnel vision," Investigative Ophthalmology & Visual Science, 47/9, 4152-4159 (2006).

[5] E. Peli, "Vision multiplexing: an engineering approach to vision rehabilitation device development," Optometry and Vision Science, 78/5, 304-315 (2001).

[6] F. Vargas-Martin and E. Peli, "Augmented-view for restricted visual field: multiple device implementations," Optometry and Vision Science, 79/11, 715-723 (2002).

[7] F. Vargas-Martin and E. Peli, "Eye movements of patients with tunnel vision while walking," Investigative Ophthalmology & Visual Science, 47/12, 5295-5302 (2006).

[8] R.L. Woods, I. Fetchenheuer, F. Vargas-Martin and E. Peli. "The Impact of Non-Immersive HMDs on the Visual Field," SID 2002 San Jose, CA: Digest of Technical Papers Society for Information Display 2002, 998-1001 (2002).

[9] 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," Journal of Visual Impairment & Blindness, 99/10, 663-670 (2005).