Use of an Augmented-Vision Device for Visual Search by Patients with Tunnel Vision

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Purpose. To study the effect of an augmented-vision device that superimposes minified contour images over natural vision on visual search performance of patients with tunnel vision.

Methods. Twelve subjects with tunnel vision searched for targets presented outside their visual fields (VFs) on a blank background under three cue conditions (with contour cues provided by the device, with auditory cues, and without cues). Three subjects (VF, 8°–11° wide) carried out the search over a 90° × 74° area, and nine subjects (VF, 7°–16° wide) carried out the search over a 66° × 52° area. Eye and head movements were recorded for performance analyses that included directness of search path, search time, and gaze speed.

Results. Directness of the search path was greatly and significantly improved when the contour or auditory cues were provided in the larger and the smaller area searches. When using the device, a significant reduction in search time (28%~74%) was demonstrated by all three subjects in the larger area search and by subjects with VFs wider than 10° in the smaller area search (average, 22%). Directness and gaze speed accounted for 90% of the variability of search time.

Conclusions. Although performance improvement with the device for the larger search area was obvious, whether it was helpful for the smaller search area depended on VF and gaze speed. Because improvement in directness was demonstrated, increased gaze speed, which could result from further training and adaptation to the device, might enable patients with small VFs to benefit from the device for visual search tasks. (*Invest Ophthalmol Vis Sci.* 2006;47:4152–4159) DOI:10.1167/iovs.05-1672

Visual field (VF) is an important aspect of visual function. It is strongly associated with the ability of visually impaired patients to perform activities of daily living.[1–12] Severely restricted peripheral field (known as tunnel vision), which is often caused by retinitis pigmentosa (RP), glaucoma, and choroideremia (CHM), makes some daily tasks extremely difficult. Among the problems, patients with tunnel vision frequently have collisions, stumbles, and failures to find objects.

To solve the problem of restricted VF, various field expanders based on the principle of minification have been proposed, such as a handheld divergent lens,[13] a reversed telescope,[14,15] an amorphic lens,[16,17] and a video remapper.[18] The use of minification seems to be logical, but partial rejection and failure of these devices has been reported.[15,16,19,20] For instance, Lowe and Drasdo[19] found that a reversed telescope with 3 × minification did not help subjects with peripheral field loss to perform a simple visual search task. Kennedy et al.[15] reported that subjects found it difficult to walk while looking through reversed telescopes and that good visual acuity (VA) was needed to succeed with the use of field expanders. These findings suggest that rejection or failure could be attributed primarily to two factors: resolution loss and change in perceived visual direction resulting from minification.

Resolution loss is usually a tradeoff for wide field in conventional minification devices. However, few patients with tunnel vision have such excellent VA that they can afford to lose resolution. Szlyk et al.[6,7] concluded that VA is a critical visual function related to the performance of daily activities for patients with RP. Conventional field expanders with the inherent problem of resolution loss might actually impair patients' abilities. To deal with the loss of resolution, a field expander worn in a bioptic position (a small device mounted on a spectacle lens, above or below the center of the lens) has been suggested.[17,21] However, patients using a bioptic minifier must glance frequently into the expander to see objects they would not otherwise notice. It is unclear whether random or regular glancing into a bioptic minifier can be an effective strategy. This is a different situation from the bioptic use of a magnifying telescope by which users first notice objects and then use the bioptic telescope to distinguish the details.

To provide field expansion without loss of resolution in the central field, Peli et al.[22,23] proposed an augmented-vision head-mounted display (HMD) system based on a principle of spatial vision multiplexing (Fig. 1). The novel system uses an optical see-through HMD that superimposes minified (3×–10×) contour (edge) images of the ambient scene over the wearer's see-through natural vision. Because the contour pixels in the display occupy only a very small portion of field of view, they do not substantially occlude the wearer's natural see-through view. We have implemented such a system and are testing its performance.

As a first step toward direct evaluation of its usefulness in aiding patients with tunnel vision with their daily tasks, we assessed the helpfulness of the device in laboratory-based visual search tasks. Within a controlled environment, visual search tasks resemble some visual demands of daily life, such as navigation, scanning the environment, and finding objects of interest. Indeed, Kuyk et al.[3,4] found that scanning ability (quantified in a searching test similar to ours) was one of the dominant predictors of mobility in adults with low vision. Our findings should be useful to better understand the effect of the device in less-controlled environments. Furthermore, laboratory visual search studies allow us to assess the device prototype, identify limitations, acquire user feedback, and thereafter improve its design and configuration.

The visual search experiment was conducted in two different setups because we used two different cameras (see "Visual Search Task"). The first camera had a larger field of view (higher minification factor). That camera was discontinued by the manufacturer after three subjects had used it. We decided to use another commercially available camera with a smaller field of view. Accordingly, we changed the experimental setup

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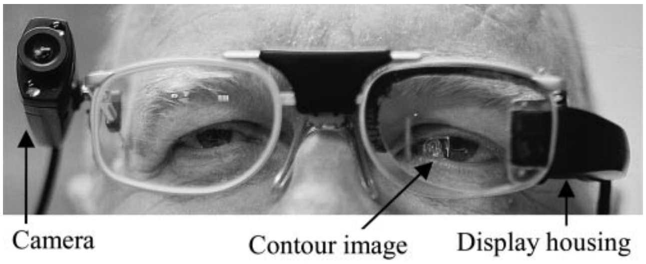

Figure 1. An augmented-vision HMD system for the left eye. A miniature camera captures video images of the ambient scenes, and the contour images of the scenes are shown in an optical see-through display. The user can see the minified contour images and the ambient scene through the display simultaneously. The nose-pad mount provides easy adjustments of monocular pupillary distance, height, and vertex distance.

and tested nine more subjects. The differences between results in the two setups are interesting, so we are reporting all the results in this article.

Methods

Augmented-Vision HMD Device

The see-through HMD device used in this study was developed for us by MicroOptical (Westwood, MA). The display was provided only to one eye, and the field of view was 16°(H) by 12°(V). A miniature camera mounted on the opposite temple of the display captured video images of ambient scenes. Contour video images shown in the HMD were generated by an edge detection processor (DigiVision, San Diego, CA). Simulation videos of the appearance of an augmented view can be accessed on our Web page at http://www.eri.harvard.edu/faculty/peli/laboratory/videos/augmented/augmented.htm.

Early pilot trials with the device found that patients with tunnel vision might have difficulty perceiving the direction of the real targets, even though they could see the target contours in the HMD. The reason was that patients with VFs much smaller than the size of the display had difficulty determining where they were looking within the display and therefore had difficulty registering the minified view to the real-world view. A pair of cross-hairs was implemented to serve as a center mark and as a registration mark to allow users to maintain awareness of the location of the display center and to help users locate the real targets based on the minified contour images. Appropriate adjustments of camera position ensured a real target seen through the display and its contour image in the display to coincide at the center of the cross-hairs. When a target contour was noted in the display, moving the head to align the cross-hairs with the target contour image brought the real target in the see-through view.

Subjects

Twelve patients with tunnel vision (11 with RP, 1 with CHM; ages, 52 ± 9 years) participated in the study. Their horizontal binocular VFs ranged from 7° to 16° wide (average, 11.3°), and the VFs of the eyes that viewed the display ranged from 7° to 16° (average, 10.5°). VF was measured using a tangent screen with an 18-mm white target from 1 m under standard office illumination (400 lux). We also confirmed that 11 subjects had a single patch of central residual VF (Goldmann II4e). Goldmann testing was not performed for one subject. Binocular VAs ranged from 0.0 to 0.40 logMAR (average, 0.22 or 20/33), and the VAs of the eyes viewing the HMD display ranged from 0.02 to 0.50 logMAR (average, 0.24 or 20/35). Three subjects participated in study A, in which the visual search area was larger than that used in study B by the other nine subjects. All subjects were in good general health. The research followed the tenets of the Declaration of Helsinki.

Before the experiment began, the concepts of the augmented-vision device were explained and subjects received a short training session (less than 1 hour). The device was fitted with its display in front of the dominant eye. For subjects who required corrective lenses, a press-on Fresnel lens of the spherical equivalent power was attached on the rear surface of the display carrier lens, and the fellow eye was provided a standard ophthalmic lens with the subject's habitual prescription.

Visual Search Task

In study A, subjects sat 32 inches (0.81 m) away from a rear projection screen, where the screen spanned 90°(H) × 74°(V). In study B, the subjects sat 50 inches (1.27 m) away, where the screen spanned 66°(H) × 54°(V). In study A, 60 targets were presented in a random sequence at eccentricities of 20°, 27°, or 35° in random directions, and in study B the eccentricities were 15°, 22°, and 29°. There were no 29° targets in the vertical direction. Targets at all these eccentricities were outside the VF of all subjects and therefore could not be detected with natural vision when looking straight ahead at a fixation point at the center of the screen (Fig. 2). Each target was composed of a black frame (triangle, square, or circle selected randomly), inside of which was a random low-contrast letter on a white background. In both studies, the target size was either 3° or 5°. Target size and contrast were such that only the frame could be detected by the edge detector and recognized in the minified contour view. When the device was used, subjects had to look through the display to view the targets foveally to identify the letter.

Subjects were allowed to move their eyes and heads freely during the search. On each trial, starting from the fixation point, subjects were instructed to find and identify targets presented on a gray blank background. Recording was initiated as soon as a target was presented. Subjects pressed a mouse button, which terminated the recording and made the letter vanish, as soon as they located the target foveally and recognized the letter. They then reported the letter verbally. Any trial in which the letter was incorrectly identified would have been discarded in the analysis procedure, but this did not occur.

In a pseudorandomized order, subjects carried out the visual search tasks under three cue conditions: the auditory-cue search (performed

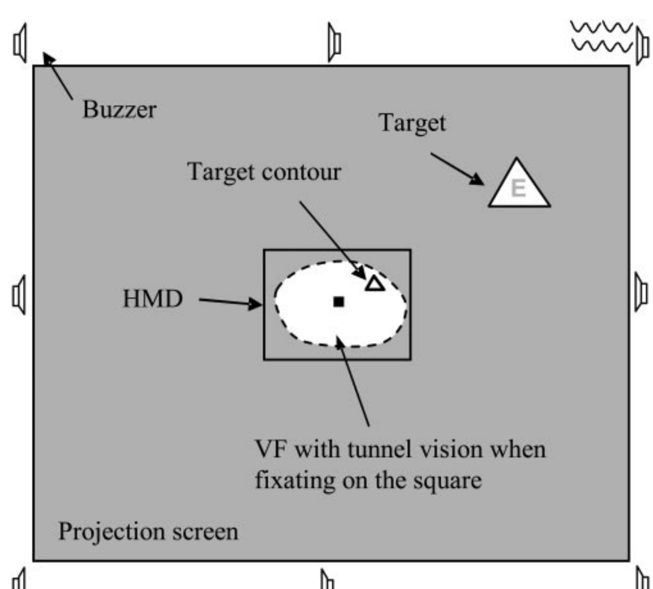

Figure 2. A diagram of the visual search task performed by subjects with tunnel vision. Targets were presented outside their VFs. Auditory cues were provided by buzzers placed around the projection screen to indicate the approximate directions of targets but not their eccentricities. The minified contour images seen in the HMD provided cues for the direction and the eccentricity of targets.

with the help of given sound), the contour-cue search (using the HMD device), and the without-cue search (performed without any cue). The auditory cue was a chirped sound lasting 5 seconds from one of eight piezoelectric buzzers placed around the projection screen (Fig. 2), indicating the approximate direction to a target but not its eccentricity. Presenting minified contour images, the HMD provided contour cues for the direction and eccentricity of targets. For larger and smaller search areas, the minification factors were approximately 6 × and 4×, respectively. In both cases, the whole search area could be seen in the HMD when the center of the search area coincided with the display center.

Evaluation of Visual Search

Visual search performance was evaluated based on search time, search efficiency (directness), and gaze speed. Search time was measured from the initial gaze movement to the point at which a target was foveated. Figure 3 shows an example of horizontal and vertical gaze movements during one trial. Flat segments can be seen at the beginning and the end of the search. The flat segment at the beginning represents a reaction time delay. The flat segment at the end includes the time for fine visual discrimination of the low-contrast letter and reaction time (to press the mouse button). The section between the two flat segments (between S and E in Fig. 3) was extracted for performance analysis, from which search time was directly measured. On average, search sections were 67% ±12% of the entire recording in our study.

We defined a measure, *directness*, for evaluation of search efficiency. As illustrated in Figure 4, the dashed curve schematically represents a gaze trajectory. S denotes the start point, and E denotes the end point. P_i and P_{i+1} are two consecutive sample points along the path. At point P_i, the straight path to point E would be vector P_iE. The angle between the actual movement vector P_iP_{i+1} and the optimal direction P_iE is denoted θ. Cos(θ) served as a measure for how much the actual movement deviated from the correct direction. The directness score of a whole search path was the average cos(θ) weighted by the step length. A perfect path would have a directness of 1 regardless of the distance between S and E or gaze speed. Tests with normally sighted subjects performing the same task gave directness scores of approximately 0.95.

Head (Ascension, Burlington, VT) and eye (ISCAN, Burlington, MA) tracking systems were used to record subjects' head and eye positions

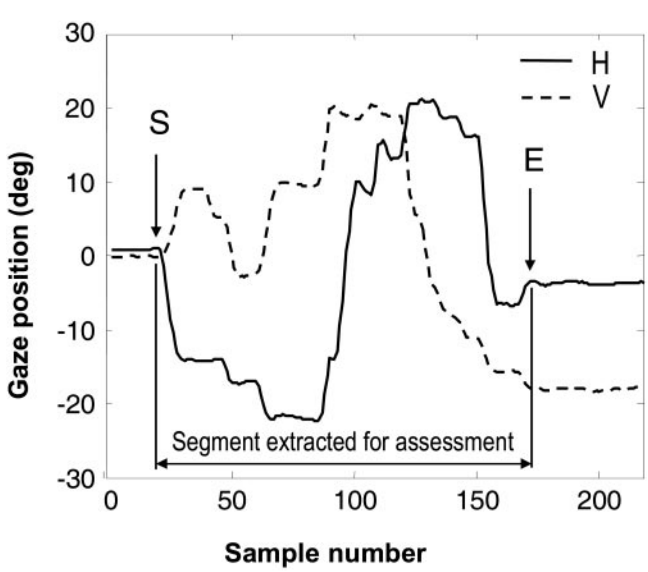

FIGURE 3. An example of horizontal and vertical gaze movements in a visual search trial. S and E indicate the moments at which the subject started to move his gaze and started to fixate on a target, respectively. The segment between them was extracted for performance analysis.

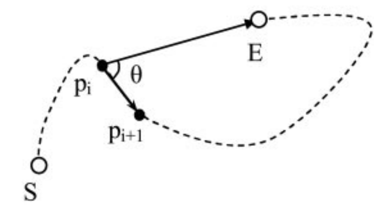

FIGURE 4. A diagram of the definition of the directness measure used in this study. The dashed curve represents a gaze trajectory. P_i and Pi_{+1} are two consecutive sample points on the trajectory. Directness of the whole search path is calculated as an average of cos(θ) weighted by step length over the whole path from S to E.

at 60 Hz that were later used to compute the gaze positions. We also calculated the angular speed of gaze movement with the minor head translation ignored. This approximation is appropriate because subjects sitting in a chair kept their trunks almost still during the search. The gaze speed of a trial was defined as the angular length of the search path divided by the search time. The angular length of a search path was the sum of the angular distances between consecutive gaze samplings during the search procedure (from S to E in Figs. 3 and 4). The average gaze speed of each subject under each cue condition was calculated and used in the data analyses.

Statistical Analysis

For each of the three subjects in study A, we performed *t* tests between different cue conditions; each subject's results are presented. For study B, we primarily conducted repeated-measures ANOVA and multiple regression analyses; results are presented by VF or eccentricity. Binocular VF values were used in the analyses because the subjects were able to see the projection screen with both eyes even when using the HMD device. An effect with $P \leq 0.05$ was considered statistically significant.

RESULTS

Search Time

The horizontal VFs of the three subjects who participated in study A were 8°, 10°, and 11°, respectively. As shown in Figure 5, all three subjects were able to find targets significantly faster using either auditory cues (39%~58%; $P \leq 0.003$) or contour cues (28%~74%; $P \leq 0.024$) than they could without cues.

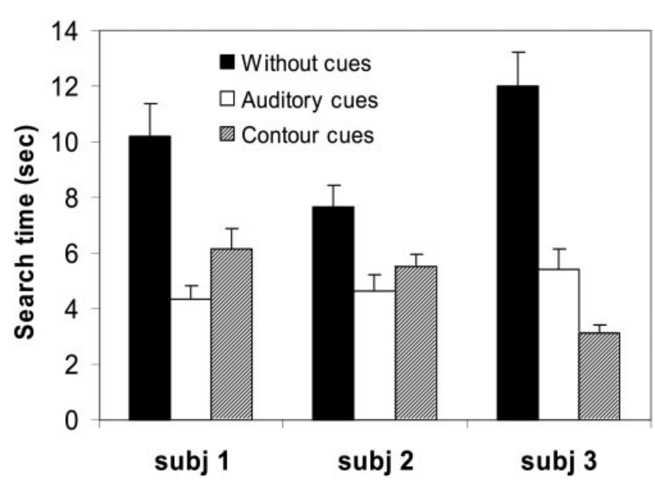

FIGURE 5. Visual search time of the three subjects in the larger area search (study A). Auditory cues and contour cues significantly reduced search time for all subjects. Error bars represent SEM.

Nine subjects (VF, 7°-16°) participated in study B. Improvements with contour cues varied between subjects. Figure 6 shows the search time improvement compared with VF in which the improvement, defined as the ratio of search time without cues divided by search time with contour cues, is plotted for each subject. Data points above the dashed line (i.e., ratios >1) represent the subjects who used less search time with contour cues than they did without cues. Visual inspection suggests that the nine subjects may be divided into a beneficiary group and a nonbeneficiary group by a VF criterion of approximately 10°.

Subjects were split into two groups, a small VF group (<10°) and a large VF group (≥10°). Repeated-measures ANOVA (excluding auditory cue data) revealed a significant effect of the VF group ($F_{1,7} = 8.0$; $P = 0.025$) and significant interaction between contour cues and VF group ($F_{1,7} = 10.2$; $P = 0.015$). As shown in Figure 7, the contour cues reduced the search time of the large-field group ($n = 6$) by 22% but increased that of the small VF group ($n = 3$) by 177% ($F_{1,7} = 7.3$; $P = 0.03$). For both groups, targets at smaller eccentricities took significantly less time than those at larger eccentricities ($F_{2,14} = 18.5$; $P < 0.001$). The interaction between eccentricity and contour cue treatment was also found to be significant ($F_{2,14} = 29.5$; $P = 0.008$), which indicated that the contour cues might help with searching for targets at smaller eccentricities more than at larger eccentricities. The Wilcoxon signed-rank test showed that the reduction in search time for the large-field group with the contour cues was approaching significance for 15° ($P = 0.075$) and was significant for 22° ($P = 0.028$) but not for 29° ($P = 0.463$). A nonparametric test was used here because of the small number of subjects ($n = 6$).

There was no significant effect of eccentricity on search time with auditory cues ($P = 0.122$), so the search time averaged across eccentricities for each group is also plotted in Figure 7. On average, the auditory cues significantly reduced search time by 54% ($F_{1,8} = 49.9$; $P < 0.001$).

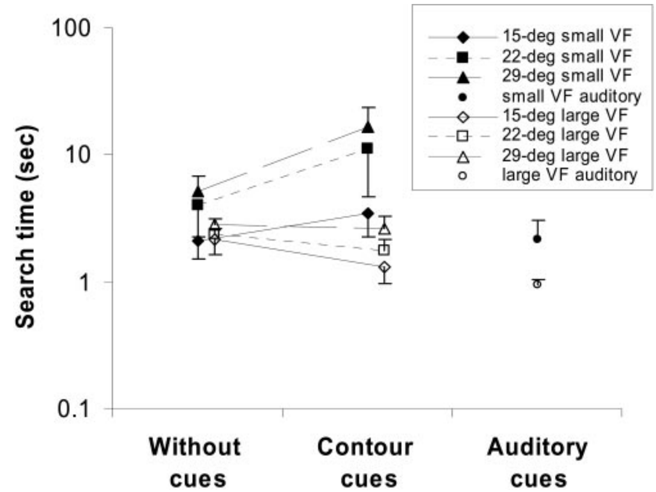

FIGURE 7. Search times of smaller area search (66° × 54°, study B). With contour cues, the small VF group (VF, <10°; $n = 3$; *solid symbols*) needed more time, but the large VF group (VF, ≥10°; $n = 6$; *open symbols*) needed less time than without cues. Auditory cues significantly reduced search time. Times with auditory cues are plotted for all eccentricities combined. Error bars represent SEM.

Directness of Search Path

The directness of the search path for the three subjects in study A is shown in Figure 8a. Compared with the without-cue search, the directness of the three subjects was significantly doubled with auditory cues ($P < 0.001$) and with contour cues ($P \leq 0.015$).

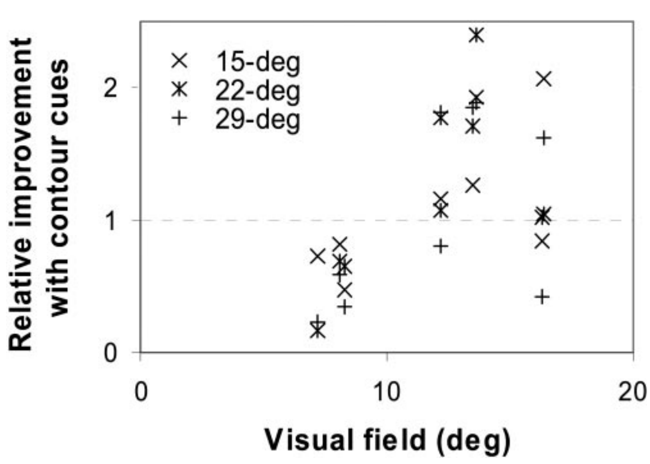

FIGURE 6. Relative improvement with contour cues in study B. Data points are ratios of search time without cues divided by time with contour cues for 3 tested eccentricities. Visual inspection suggests that when the VF was larger than 10°, the contour-cue search was usually faster than the without-cue search.

Figure 8b shows that the directness in study B was better than that in study A. Three repeated-measures ANOVAs were conducted separately for different cue conditions. Directness significantly decreased with eccentricity for the without-cue ($F_{2,16} = 4.5$; $P = 0.028$) and the contour-cue ($F_{2,16} = 6.8$; $P = 0.007$) conditions, but in the auditory-cue condition, eccentricity did not have a significant effect on directness ($F_{2,16} = 0.6$; $P = 0.56$). Compared with the without-cue search, the directness of the subjects in study B was significantly improved by 63% with auditory cues ($F_{1,8} = 29.6$; $P = 0.001$) and by 62% with contour cues ($F_{1,8} = 9.9$; $P = 0.014$). Pearson correlation between directness and VF was significant for the auditory-cue search ($r_8 = 0.79$; $P = 0.012$) but only approached significance for the without-cue search ($r_8 = 0.6$; $P = 0.085$) and the contour-cue search ($r_8 = 0.66$; $P = 0.053$). These positive correlations confirm the expected result that subjects with larger VFs searched with higher efficiency than subjects with smaller VFs.

Gaze Speed

Gaze speed was similar in both studies. Gaze speed averaged across eccentricities and subjects were 80, 70, and 30 deg/s in study A, and 63, 71, and 33 deg/s in study B for the without-cue, auditory-cue, and contour-cue searches, respectively. Apparently, gaze speed was slow with the augmented-vision device. For study B, the Pearson correlation between VF and gaze speed was not significant ($|r| < 0.38$; $P > 0.31$) for all cue conditions. In other words, subjects with smaller VFs scanned at about the same speed as subjects with larger VFs. Eccentricity had no significant effect on gaze speed ($P > 0.44$) for all cue conditions.

Regression Analysis

To investigate the factors related to visual search time, we conducted regression analyses based on the data of study B. The analysis was not performed for study A because of the small number of subjects.

Directness and gaze speed appeared to be highly associated with search time, as shown in Figure 9, which plots the search times versus the product of directness and gaze speeds. Each data point represents an eccentricity (15°, 22°, or 29°) under a

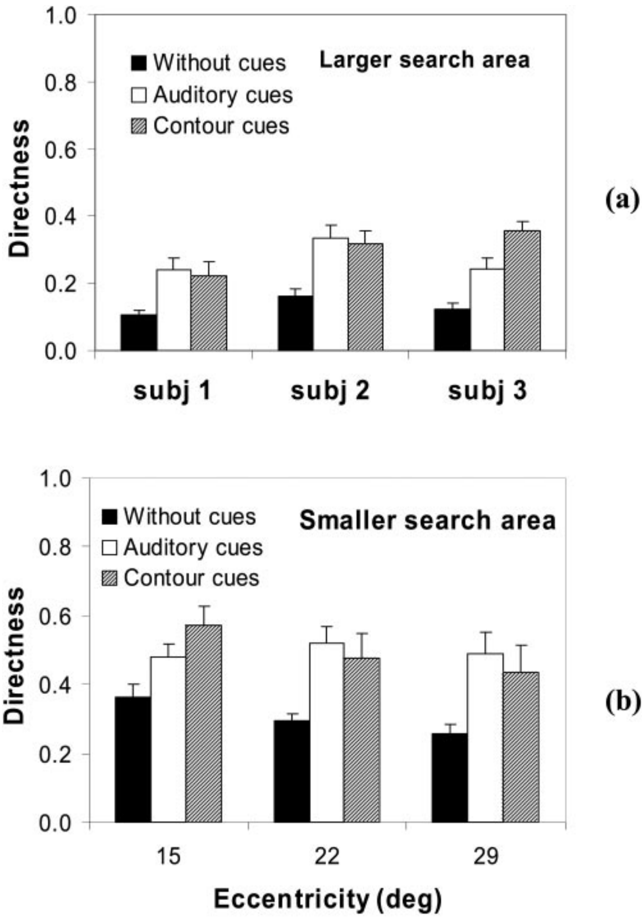

FIGURE 8. Directness of visual search. (**a**) Directness of the three subjects in the larger area search (study A). (**b**) Mean directness of the nine subjects in the smaller area search (study B). Overall, the directness in study B was better than that in study A, in which the search area was approximately twice as large. In both studies, directness with either auditory or contour cues was better than without cues. Error bars represent SEM. Note that the directness of normally sighted people is nearly 1.0.

cue condition (without cues and with auditory or contour cues). We proposed the following model to describe the relationship. Natural logarithms were applied to convert multiplication to addition so that simple linear regression analysis could be performed.

$$\ln(t) = k_0 + k_1 \times \ln(dir) + k_2 \times \ln(spd) \quad (1)$$

where t is the measured search time under a cue condition for an eccentricity, dir is the measured directness, spd is the angular gaze speed in deg/s, and k_0, k_1, and k_2 are coefficients. Regression results were $k_0 = -0.77$, $k_1 = -0.92$, and $k_2 = -1.36$. This model could explain 90% of the variance in the observed search time ($R^2 = 0.90$; $df = 78$). Search time was significantly related to directness ($P < 0.001$) and gaze speed ($P < 0.001$).

As mentioned, directness increased with VF and decreased with eccentricity (except for auditory-cue search; see "Directness of Search Path"). To examine the relationship between search time and VF, we tested a model similar to equation 1 describing the relationship between search time and eccentricity, VF, and gaze speed

$$\ln(t) = b_0 + b_1 \times \ln(ecc) + b_2 \times \ln(vf) + b_3 \times \ln(spd) \quad (2)$$

where t and spd have the same definitions as in equation 1, vf is the binocular horizontal VF size in degrees, ecc is the target eccentricity, and b_0, b_1, b_2, and b_3 are coefficients to be derived. Because neither eccentricity nor VF had any significant correlation with gaze speed, as reported, eccentricity, VF, and gaze speed can be considered orthogonal variables.

Because the effect of eccentricity on directness varied between cue conditions (Fig. 8b), we conducted three separate multiple regression analyses. Table 1 lists the results of regression analyses based on the model described in equation 2. The model explained 63%, 67%, and 79% of the variance in the search time for without-cue, auditory-cue, and contour-cue searches, respectively. Eccentricity, VF, and gaze speed were all significantly correlated with search time ($P \leq 0.006$) except for the eccentricity factor in auditory-cue search ($P = 0.143$), which was consistent with the result from the previous ANOVA.

Based on the model, larger eccentricity required longer search time for both without-cue and contour-cue searches. However, the strength of the eccentricity effect was stronger for contour-cue searches ($b_1 = 1.52$ vs. 0.75). This suggests that there may be an eccentricity at which the search times for contour-cue searches and without-cue searches will be the same. This crossover point can be thought of as the eccentricity threshold, below which contour-cue searches take shorter time than without-cue searches. We derived the eccentricity threshold using the following equation:

$$b_{0w} + b_{1w} \times \ln(ecc) + b_{2w} \times \ln(vf) + b_{3w} \times \ln(spd_w) > b_{0c} + b_{1c} \times \ln(ecc) + b_{2c} \times \ln(vf) + b_{3c} \times \ln(spd_c)$$

and

$$(b_{1w} - b_{1c})\ln(ecc) > b_{0c} - b_{0w} + (b_{2c} - b_{2w}) \times \ln(vf) + b_{3c} \times \ln(spd_w) - b_{3w} \times \ln(spd_w) \quad (3)$$

where the notations have the same definition as in equation 2, and subscripts w and c denote the without-cue search and

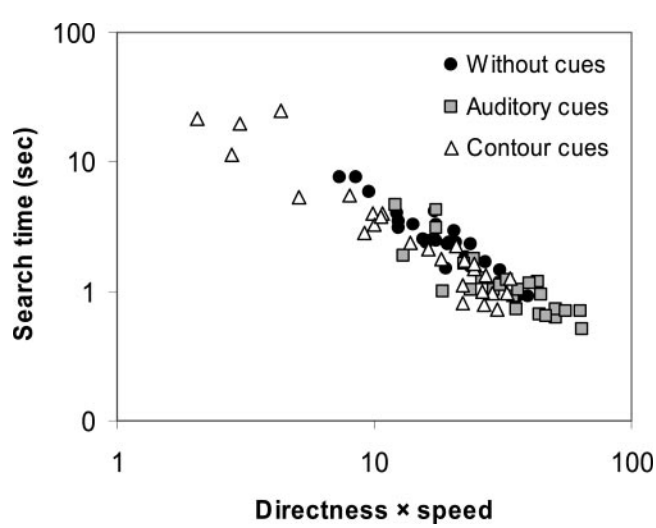

FIGURE 9. Search time versus product of directness and gaze speed. Data points are from the nine subjects in study B for 15°, 22°, and 29° eccentricities in without-cue, auditory-cue, and contour-cue searches.

TABLE 1. Results of Regression Analyses Based on Equation 2

Search Condition	R^2	b_0 Constant	b_1 Eccentricity	b_2 VF	b_3 Gaze Speed
Without cue	0.63	4.92 (P = 0.003)	0.75 (P = 0.006)	−0.71 (P = 0.005)	−1.11 (P < 0.001)
Auditory cue	0.67	6.14 (P < 0.001)	0.36 (P = 0.143)	−1.12 (P < 0.001)	−1.04 (P < 0.001)
Contour cue	0.79	4.42 (P = 0.006)	1.52 (P < 0.001)	−1.38 (P = 0.001)	−1.39 (P < 0.001)

Eccentricity, VF, and gaze speed were significant factors affecting search time in all cue conditions expect eccentricity in auditory-cue search.

contour-cue search, respectively. After substituting the coefficients listed in Table 1 into equation 3, it becomes

$$-0.77 \times \ln(ecc) > -0.5 - 0.67 \times \ln(vf) - 1.39 \times \ln(spd_c) + 1.11 \times \ln(spd_w)$$

and

$$\ln(ecc) < 0.65 + 0.87 \times \ln(vf) + 1.81 \times \ln(spd_c) - 1.44 \times \ln(spd_w) \quad (4)$$

Note that the greater-than sign becomes a less-than sign because the coefficient of ln(ecc) is negative in the derivation of equation 4. Figure 10 plots the eccentricity threshold and VF size, assuming the gaze speed of the without-cue search is always 63 deg/s—the actual average gaze speed without cues in study B. In the figure, the solid line represents that gaze speed with contour cues is 33 deg/s—the measured average gaze speed with contour cues. The dashed line represents (for an assumption) that gaze speed with contour cues could be increased to 38 deg/s. As shown, the dashed line is above the solid line. It means that as gaze speed with the device increases, the eccentricity threshold becomes larger. In other words, the device would then be helpful for patients to search for targets within a larger eccentricity, such as from point A to point B. Similarly, it also suggests that when the gaze speed increases, the VF required to gain benefit from the device would become smaller. In other words, the device could become helpful for patients with smaller VFs, such as from point C to point D. We believe that gaze speed can be improved through practice or training with the device.

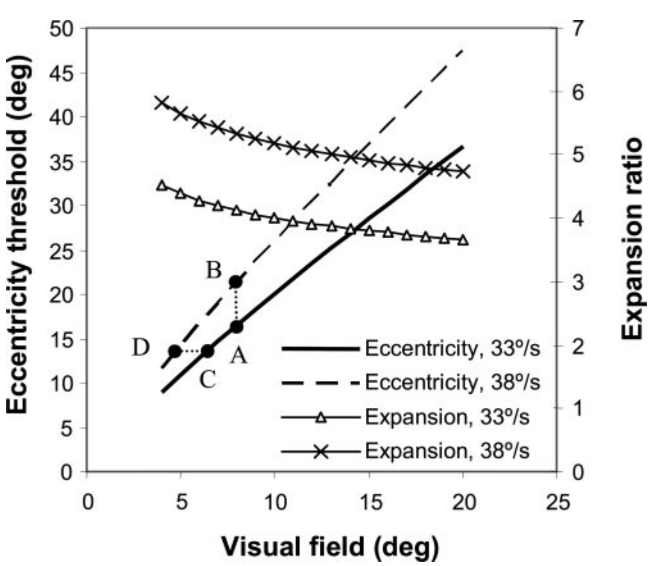

FIGURE 10. Predictions based on regression model equation 2 and calculated using equation 4. Eccentricity threshold indicates an area within which patients could search faster with the device than without it. An increase in gaze speed with contour cues may permit a larger beneficiary area (e.g., A to B) and make the device useful for patients with smaller VF (e.g., C to D). The ratio of eccentricity threshold to VF radius is plotted with × signs and *open triangles*, which represent the expansion ratio of the HMD device. The device might provide larger expansion ratios to patients with smaller VFs than those with larger VFs.

Based on the predicted eccentricity threshold, we further examined the ratio of eccentricity threshold to VF radius (because eccentricity is also a radius measure), which we define as the expansion ratio (ER). This ratio represents, relative to the VF, the area within which patients would find targets faster when using the contour cues than without.ER as a function of VF for study B is also plotted in Figure 10 with × signs and triangles for the two gaze speeds. It can be seen that patients with smaller VFs have larger ERs than those with larger VFs. This result does not contradict our finding that patients with larger VFs benefited from the device while the patients with smaller VFs did not. Because ER is a relative measure, the same tested eccentricities required higher ERs for patients with smaller VFs than patients with larger VFs. For instance, the regression model predicts that at a gaze speed of 33 deg/s, a patient with a VF of 7° would achieve an ER of 4.2, which is larger than that of a patient with a VF of 12° (ER of 3.9). However, the patient with the 7° VF could benefit from the device for targets within an eccentricity of 14.7° (4.2 × 7/2), which is smaller than that of the patient with the 12° VF, within an eccentricity of 23.4° (3.9 × 12/2). Therefore, when eccentricity of 15° is tested, we would likely observe that the patient with the 7° VF cannot benefit from the device but that the patient with the 12° VF can.

DISCUSSION

Our experiments provide evidence that, in a laboratory setting, the augmented-vision HMD device improved visual search task performance of some patients with tunnel vision. Obvious and significant improvements in directness of visual search were found in the larger and the smaller search area settings (studies A and B, respectively). The improvement in search time was substantial for searching over the larger area (90° wide). It was comparable to the improvement observed with auditory cues. Auditory information in the real world, when available, usually provides helpful cues for people with VF loss. For searching over the smaller area (66° wide, study B), the device shortened the search time for most patients with VF larger than approximately 10° only. However, our regression analyses suggest that the eccentricities tested in study B might be too large (difficult) for patients with smaller VFs. They might have shown improvement in search time with the device had we tested smaller eccentricities, such as 10°, which would still be outside their VFs. Intuitively, one may expect that field expanders would be especially helpful for patients with small VFs.

Based on our results, this intuition appears to be correct for the HMD device when considering a measure relative to their residual VF. In terms of ER, patients with smaller VFs might benefit from the device more than those with larger VFs (Fig. 10).

VF can rarely be described properly with a single number. First, the functioning VF depends on the testing methods. For example, glaucoma patients may have depressed function in the periphery but not an absolute scotoma, so a Goldmann test and a Humphrey test often yield different results. Second, some patients with RP may have separated functional areas in periphery called residual islands. These islands may be useful for the detection of targets. We evaluated a subject with RP who had a half-ring–shaped island extending from eccentricity 40° to 60° in the lower field (Goldmann II4e) and a central VF of 7° (tangent screen 18-mm white target). He withdrew from the study because of health reasons after participating in a without-cue search session in study A. His performances (search time 1.9 seconds, directness 0.5) was much better than those of the three subjects in study A (compare with Fig. 5 and Fig. 8a). It appeared that many targets were detected by his island. Therefore, our results may not be simply transferable to patients with complex VFs. The usefulness of the islands or depressed peripheral vision for visual search tasks and mobility requires further investigation.

Lowe et al.[19] reported that they did not find obvious indications that their field expander (a reversed telescope with 3× minification) benefited their subjects with restricted VF in visual search, and they argued that adaptation would improve performance with the field expander. In other words, their subjects needed additional time to learn to deal with the changed visual direction. We believe that the change in the perception of visual direction negatively affects performance with virtually all visual aids that are based on magnification, minification, or prismatic displacement. In our study, subjects commented that the registration mark implemented in the device was very effective in reducing that problem. It is even possible that patients would not have to use the registration mark if they could make coarse but sufficient estimates of the locations of real targets, move their gaze there, and perform a local search ignoring the display. One of the advantages of the augmented-vision HMD device is that excellent eye-head coordination is not required.

Despite the help of the registration mark, we do not think the impact of the change in perceived visual direction was completely eliminated in our experiments. In searches over the larger area (study A), the great benefit of field expansion provided by the device outweighed the negative effect of change in perceived visual direction. However, when the search area was smaller (study B), this negative effect became noticeable, whereas the search time without cues dramatically reduced (overall from 10 seconds in study A to 2.9 seconds in study B).

Other investigators have argued that training and adaptation are critical for success in the use of field expanders.[17,19] In our study, subjects were unable to fully adapt to changed visual direction because of limited use before the experiment (typically less than 1 hour, except for subject 3 in study A, who had a couple of hours of previous experience). This could be one of the reasons subjects moved their gaze much more slowly in contour-cue search than they did in without-cue search (30 deg/s vs. 80 deg/s in study A, and 33 deg/s vs. 63 deg/s in study B), and the need to search for target contours within a small display (16°) could be another reason. It appears that there is much room for improvement in gaze speed. Based on our finding that directness and gaze speed were the two key factors associated with search time (see equation 1, and note that the equation can be applied to searches with and without the device) and on the fact that the device improved directness unambiguously (Fig. 8), a larger improvement in search time with the device might be expected if gaze speed can be increased through training. Furthermore, faster gaze speed may lead to a larger ER or eccentricity threshold (Fig. 10), which means that patients could benefit from the device up to a larger eccentricity within a given search area. We think faster gaze speed should be achieved by adapting to changed visual direction, being familiar with the device, and developing good search strategies instead of simply acting more quickly.

VA was not found to affect performance. None of the subjects reported any difficulty seeing the minified contour images in the HMD or the letters in the targets on the screen. Therefore, it seemed that the device did not impose any resolution limitation for subjects within the VA range (0.00 to 0.4 logMAR, or 20/20 to 20/50).

In our study, targets were presented on a blank gray background to make them stand out. Once the real targets or contours of the targets were within VF, they could be easily detected. This is not always the case in the real world, where targets may have to be found among many distracters. The form of edge image may or may not affect the conspicuity of targets.[24,25] The usefulness of the augmented-vision HMD device in the real world is now under investigation.

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References

1. Marron JA, Bailey IL. Visual factors and orientation-mobility performance. *Am J Optom Physiol Opt*. 1982;59:413–426.
2. Lovie-Kitchin J, Mainstone J, Robinson J, Brown B. What areas of the visual field are important for mobility in low vision patients? *Clin Vision Sci*. 1990;5:249–263.
3. Kuyk T, Elliott J, Fuhr PS. Visual correlates of obstacle avoidance in adults with low vision. *Optom Vis Sci*. 1998;75:174–182.
4. Kuyk T, Elliott JL, Fuhr PS. Visual correlates of mobility in real world settings in older adults with low vision. *Optom Vis Sci*. 1998;75:538–547.
5. Turano KA, Geruschat DR, Stahl JW, Massof RW. Perceived visual ability for independent mobility in persons with retinitis pigmentosa. *Invest Ophthalmol Vis Sci*. 1999;40:865–877.
6. Szlyk JP, Fishman GA, Alexander KR, Revelins BI, Derlacki DJ, Anderson RJ. Relationship between difficulty in performing daily activities and clinical measures of visual function in patients with retinitis pigmentosa. *Arch Ophthalmol*. 1997;115:53–59.
7. Szlyk JP, Seiple W, Fishman GA, Alexander KR, Grover S, Mahler CL. Perceived and actual performance of daily tasks: relationship to visual function tests in individuals with retinitis pigmentosa. *Ophthalmology*. 2001;108:65–75.
8. Haymes S, Johnston A, Heyes A. Relationship between vision impairment and ability to perform activities of daily living. *Ophthalmic Physiol Optics*. 2002;22:79–91.
9. Turano KA, Rubin GS, Quigley HA. Mobility performance in glaucoma. *Invest Ophthalmol Vis Sci*. 1999;40:2803–2809.
10. Turano KA, Broman AT, Bandeen-Roche K, et al. Association of visual field loss and mobility performance in older adults: Salisbury Eye Evaluation Study. *Optom Vis Sci*. 2004;81:298–307.
11. Nelson P, Aspinall P, Papasouliotis O, Worton B, O'Brien C. Quality of life in glaucoma and its relationship with visual function. *J Glaucoma*. 2003;12:139–150.
12. Noe G, Ferraro J, Lamoureux E, Rait J, Keeffe JE. Associations between glaucomatous visual field loss and participation in activities of daily living. *Clin Exp Ophthalmol*. 2003;31:482–486.

13. Kozlowski JM, Jalkh AE. An improved negative-lens field expander for patients with concentric field constriction. *Am J Optom Physiol Opt*. 1985;103:326.
14. Drasdo N. Visual field expanders. *Am J Optom Physiol Opt*. 1976; 53:464–467.
15. Kennedy WL, Rosten JG, Young LM, Ciuffreda KJ, Levin MI. A field expander for patients with retinitis pigmentosa: a clinical study. *Am J Optom Physiol Opt*. 1977;54:744–755.
16. Hoeft WW, Feinbloom W, Brilliant R, et al. Amorphic lenses: a mobility aid for patients with retinitis pigmentosa. *Am J Optom Physiol Opt*. 1985;62:142–148.
17. Szlyk JP, Seiple W, Laderman DJ, Kelsch R, Ho K, McMahon T. Use of bioptic amorphic lenses to expand the visual field in patients with peripheral loss. *Optom Vis Sci*. 1998;75:518–524.
18. Loshin DS, Juday RD. The programmable remapper: clinical applications for patients with field defects. *Optom Vis Sci*. 1989;66: 389–395.
19. Lowe J, Drasdo N. Using a binocular field expander on a wide-field search task. *Optom Vis Sci*. 1992;69:186–189.
20. Bowers AR, Luo G, Rensing NM, Peli E. Evaluation of a prototype Minified Augmented-View device for patients with impaired night vision. *Ophthalmic Physiol Optics*. 2004;24:296–312.
21. Vargas-Martin F. Survey of a free cost viewfinder for visual field expansion. *International Congress Series*. 2005;1282:1080–1084.
22. Peli E. Vision multiplexing: an engineering approach to vision rehabilitation device development. *Optom Vis Sci*. 2001;78:304–315.
23. Vargas-Martin F, Peli E. Augmented-view for restricted visual field: multiple device implementations. *Optom Vis Sci*. 2002;79:715–723.
24. Sanocki T, Bowyer K, Heath M, Sarkar S. Are edges sufficient for object recognition? *J Exp Psychol Human Perception Performance*. 1998;24:340–349.
25. Apfelbaum H, Apfelbaum D, Woods R, Peli E. The effect of edge filtering on vision multiplexing. In: *SID05 Digest of Technical Papers*. 2005;1398–1401.