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Evaluation of a prototype Minified Augmented-View device for patients with impaired night vision*

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Abstract

An evaluation was carried out of the first prototype (LV-3) of a new night vision device, which incorporates visual field expansion through minification (Minified Augmented-View), to provide feedback for continuing development. Six subjects with night blindness completed visual function measurements and indoor mobility assessments without a device, with the LV-3 and with a commercially available comparison device (the Multi-Vision) at light levels representative of well lit and poorly lit streets. Device performance and potential benefits in real-world situations were evaluated at four outdoor locations (well lit to very dark). Results indicate that the see-through nature and spectacle-frame mounting of the LV-3 address some of the cosmetic and ergonomic disadvantages of currently available devices; however insufficient light sensitivity of the prototype camera limited LV-3 performance. With improved camera sensitivity and full implementation of the Minified-Contours Augmented-View concept in the next prototype, patients might be able to make better use of the novel field expansion and vision multiplexing features to aid outdoor night mobility.

Keywords: augmented reality, field expander, head mounted device, mobility performance, night blindness, retinitis pigmentosa

Introduction

Night blindness (impaired vision at low light levels) is the hallmark of any disease that affects rod photoreceptor function, for example retinitis pigmentosa, choroideraemia and congenital stationary night blindness (Kanski, 2003). Typically the impairment is first noticed outdoors at night or in very dark indoor areas, even when vision under photopic conditions may still be relatively unaffected. Mobility performance of patients with night blindness is adversely affected by reduced illumination (Black *et al*., 1996; Geruschat *et al*., 1998), causing major difficulties with independent night mobility (Turano *et al*., 1999) and limiting participation in activities requiring outdoor night travel.

Since the early 1970s, various night vision enhancement devices have been proposed as aids for patients with night blindness. At first devices were based on military light-intensifier technology and were large, hand held (although a canvas head mount was developed), monocular and heavy (Berson *et al*., 1973a). Although lighter, more compact, versions were developed (Berson *et al*., 1973b, 1974; Hoover, 1983; Morrissette *et al*., 1983), they were still monocular with a monochromatic green display, and met with poor user acceptance (Morrissette *et al*., 1983). More recently there has been renewed interest in the development of lightweight, binocular, head mounted, goggle-type devices using low-light sensitive video cameras (Friedburg *et al*., 1999; Rohrschneider *et al*., 2000; Spandau *et al*., 2002). However these newer binocular devices are conspicuous, cosmetically unattractive, prevent eye contact, and have a relatively limited field of view (about 30–40°), although they do improve night mobility in outdoor environments (Rohrschneider *et al*., 2000; Spandau *et al*., 2002).

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MicroOptical Engineering Corporation and the Schepens Eye Research Institute are collaborating in the development of an innovative night vision device for patients with night blindness. The long-term aim is to implement Peli's Minified-Contours Augmented-View concept (Peli, 2001; Vargas-Martin and Peli, 2002), using a novel display technology developed by MicroOptical. New display technology allows embedding of a micro-display and its optical viewing system in a spectacle frame and lens (Spitzer *et al*., 1998), thus enabling the development of a spectacle-mounted device which has the potential to be cosmetically more attractive and less conspicuous than other currently available night vision devices. If the display is turned off, the glasses will function as ordinary eyewear with no obscuration of the visual field (except for a small reduction in light transmission in the display area). As the display is see-through and monocular, the user will have a natural view of the scene at all times (in addition to the display image), whereas in existing commercially available devices, users see only the image-intensified view of the scene presented on a opaque display within the goggles. The spectacle-mounted design will also permit normal eye contact, an important part of social interaction, if the user encounters other people while wearing the device.

Many patients with night blindness also have restricted peripheral visual fields. Their mobility difficulties are not only because of reduced sensitivity at night, but also the field restriction. Even in daylight, a patient with 20° (diameter) or less of residual visual field will encounter mobility difficulties (Black *et al*., 1996; Haymes *et al*., 1996; Geruschat *et al*., 1998). Visual field expansion can be achieved through minification; although the minification reduces resolution, the field expansion provides visual information about objects that would otherwise be outside the patient's visual field. Berson *et al*. (1974) reported an improvement in mobility performance under scotopic conditions for two subjects with night blindness and visual fields of $< 10°$ when a wide-angle (fish-eye) lens was attached to the objective of a Generation II night vision pocketscope, providing field expansion of 4–5×. However, to the best of our knowledge, visual field expansion has not been implemented in any commercial products.

The Augmented-View concept to be implemented in the new device is based on visual field expansion through minification (Peli, 2001). In the full implementation of the Minified-Contours Augmented-View design (*Figure 1*), the minified displayed image will contain only the edge contours of the scene (edge-contour mode), which will be superimposed over the patient's natural view and it will be possible to look through the contour view to the real world (Peli, 2001; Vargas-Martin and Peli, 2002). Thus, this design should enable vision multiplexing i.e. merging of the natural (high resolution) view of the scene with the minified wide field of view to maintain the normal interplay between central and peripheral vision, an important aspect of the Augmented-View concept (Peli, 2001).

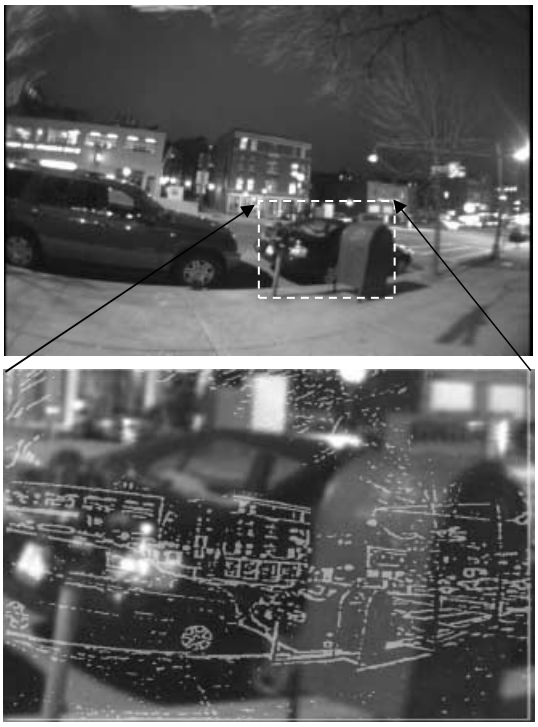

Figure 1. Illustration of the Augmented-View concept. The upper image shows a full view of a street scene taken at night with the camera used in the LV-3 device; the white rectangle inset represents the size of the field of the display. In the partial implementation of the concept (Minified Augmented-View) used in the prototype LV-3 device, a minified gray-scale image of this scene was presented on the device display. The lower image shows the Minified-Contours Augmented-View concept that will be implemented in future versions of the device, where a minified edge-contour image of the scene (shown here without minification) will be superimposed on the natural see-through view (shown here as the car and mail box, etc. behind the edge-contour image). For the purpose of illustration the edge-contour image is shown over the image obtained with the night vision camera; however a person with night blindness at low light levels would see less detail with their natural vision.

As a precursor to developing the new night vision device, the Minified-Contours Augmented-View concept was pilot tested with a small number of subjects with severely restricted visual fields using a range of commercial off-the-shelf devices (Vargas-Martin and Peli, 2002): subjects thought that the concept could be useful for navigation and obstacle avoidance while walking. Development of the new device was then implemented. This paper reports the evaluation of the first prototype LV-3. At the time of the evaluation, the edge-contour mode was not fully developed; therefore the LV-3 prototype that we tested included only a

partial implementation of the Augmented-View concept, displaying a gray-scale minified image rather than an edge-contour image (i.e. a Minified Augmented-View, rather than a Minified-Contours Augmented-View). Although we were unable to evaluate the edge-contour mode, it was nevertheless important to obtain feedback on cosmetic, ergonomic, and functional aspects of the device in order to guide further development of the final prototype LV-4. Furthermore, in the LV-4 prototype the option of using either the edge-contour mode or the gray-scale image mode is planned; therefore it was useful to obtain preliminary feedback on the utility of the gray-scale image.

The gray-scale mode provides a complete minified image superimposed on the natural view of the scene, whereas the edge-contour mode superimposes only a minified outline on the natural view (*Figure 1*). Thus in very dark areas, where natural vision of patients with night-blindness is non-functional, the gray-scale image might be preferred as it provides more information than the edge-contour image. Also, under these conditions, the LV-4 in gray-scale mode could operate as a conventional night vision device using digital zooming to achieve a 1:1 image. While the gray-scale image is not totally opaque, it might be difficult to see through this type of image at low light levels. Therefore, in the LV-3 prototype, vision multiplexing may be achieved by alternating attention between the two eyes, or by using slight head movement to shift the display eye out of the field of the gray-scale image (temporal multiplexing, as in the use of bioptic low vision telescopes).

In order to provide a meaningful assessment of the LV-3 prototype, the evaluation was carried out at functionally relevant illumination levels using subjects with night blindness. The evaluation included assessment of visual function, mobility on an indoor obstacle course, and outdoor observations with and without the device. To provide valid comparison data, subjects also completed all evaluations using a commercially available, binocular goggle-type night vision device (Multi-Vision, Trivisio, Switzerland). Early versions of this device (Rohrschneider *et al.*, 2000; Spandau *et al.*, 2002) and recent versions, similar to that used in this study (Pierrottet *et al.*, 2003; Hartong *et al.*, 2004), were found to improve night mobility in patients with night blindness.

Methods

The evaluation included clinical vision tests performed under different illumination levels with and without a device, an indoor obstacle course under two low illumination levels, and an outdoor stationary device evaluation at night. The indoor and outdoor assessments were carried out on separate days (with the exception of one subject) and the order of assessments varied between subjects.

Subjects

Six patients with night blindness participated in this study (*Table 1*). All subjects were in good general health, with no physical or mobility restrictions that would impair their ability to participate in the study. Subjects 1–5 first became aware of night blindness more than 20 years ago, used long canes for day and night mobility and all engaged in independent night mobility. Subject 6 became aware of night blindness more recently (6 years ago), and neither used a long cane nor engaged in independent night mobility. Before the study commenced, subjects read and signed an informed consent form approved by the Institutional Review Board (IRB).

Night vision devices

Two night vision devices were evaluated: the first generation prototype LV-3 of the new night vision device (MicroOptical Engineering Corp, MA, USA), and a commercially available comparison device, the Multi-Vision (M-V).

The prototype LV-3 system implemented the Minified Augmented-View concept (as described in the introduction), by presenting a minified view of the ambient scene obtained with a wide-angle camera. The system consisted of a pair of glasses integrated with an optical see-through monocular display (90 g) and a control unit

Table 1. Subject details. Vision data are baseline measures at standard illumination levels

Subject	Age	Gender	Diagnosis[a]	Corrected visual acuity (logMAR)	Contrast sensitivity (log unit)	Visual field horizontal diameter (degree)	Independent night mobility
1	50	M	RP	0.32	1.35	7.5	Yes
2	62	M	RP	0.02	1.65	10.5	Yes
3	40	M	Choroideraemia	0.16	1.60	9.9	Yes
4	46	F	RP	0.04	1.85	19.8	Yes
5	68	M	RP	0.22	1.35	11.3	Yes
6	26	F	RP	0.24	1.60	18.3	No

[a]RP, retinitis pigmentosa.

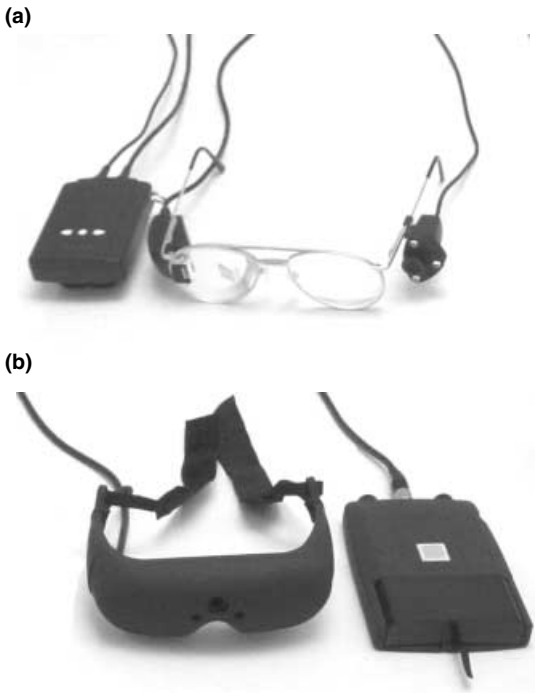

Figure 2. Night vision devices evaluated in this study: (a) the first prototype LV-3 of the new night vision device and (b) the Multi-Vision (M-V), a commercially available comparison device. The M-V camera is mounted in the center above the nose and 2 IR LEDs may be activated in very dark conditions to improve visibility. The LV-3 camera was mounted on the temple on the opposite side from the monocular display with three IR LEDs for supplemental illumination.

(175 g including battery) (*Figure 2a*). The viewing window was built inside either the left or right spectacle lens, with a regular prescription lens for the other eye. The system displayed a gray-scale video image on a transmissive active matrix liquid crystal display (AMLCD) microdisplay (video graphic array, 640×480 pixels). The camera was mounted on the temple of the spectacle frame on the opposite side from the display housing. The camera used in the LV-3 was optimized for small size and low power consumption by using a 1/4 inch complementary metal oxide semiconductor (CMOS) image sensor. Neither the sensor nor camera lens (a 2.9 mm, f/2 microlens) had an infrared filter; therefore the camera had some sensitivity at infrared as well as visible wavelengths. Although the camera had insufficient sensitivity at very low light levels, it was decided to proceed with the evaluation as the device was also to be tested at moderately low light levels (e.g. 16 lux) at which it might be expected that subjects could benefit from the field expansion. Eventually CMOS sensors will achieve the required sensitivity, but current technology requires a charge-coupled device (CCD) sensor for this application. To improve camera performance in dark conditions, three infrared light emitting devices (LEDs) were mounted around the camera. The LEDs could be turned on to provide supplemental illumination as required; however this feature was found to be of benefit only for very near objects (under 1 m), and the illumination was insufficient at the longer distances required for obstacle detection while walking. The field of view of the camera was 60°(H) by 40°(V), and that of the display, 16°(H) by 12°(V). Thus, the system presented about a 4× minified gray-scale view of the real world. Contrast enhancement was implemented digitally using customized gamma curves; seven levels of contrast and brightness of the display could be selected by pressing buttons on the control unit. All electronics were digital (direct camera to display interface) for low power consumption. In addition the prototype LV-3 provided 2, 4 and 8× digital zoom, but this feature was not evaluated.

The M-V system consisted of head mounted optically opaque goggles (122 g) and a control unit (380 g including battery) (*Figure 2b*). It had a CCD camera located in the center of the goggles and a super video graphic array liquid crystal display (SVGA LCD) display for each eye. The M-V system presented a 1:1 image of the ambient scene on the display. The field of view of the system was 32°(H) by 24°(V). The contrast and brightness of the display could be adjusted continuously by using two knobs on the control unit. Two infrared LEDs could be turned on to provide supplemental illumination.

Subjects were fitted with and trained in the use of each device in turn. Training was carried out under dim lighting conditions indoors. General training was given at the start of the experiment, and further practice time provided before each of the evaluations. Subjects who wore corrective lenses placed the M-V over their habitual spectacles. When the LV-3 was used, a Fresnel lens of the spherical equivalent power was placed on the rear of the display carrier lens, and the fellow eye was provided with a regular spectacle lens (with the habitual correction). The LV-3 was fitted with the display in front of the dominant eye. The contrast and brightness settings for each device were under the subjects' control: before each assessment at each light level, subjects adjusted the settings to optimize the displayed image.

Light levels

To determine reasonable illumination levels for the night vision device evaluations, two street lighting assessments were carried out starting an hour after sunset: one in downtown Boston and the other in a rural residential area in the town of Lincoln, MA, USA. The routes went past stores, hotels, restaurants, crosswalks, residences, etc. The light sources included sodium light, tungsten light, fluorescent light, and even gas light (in

the historic Beacon Hill area of Boston). An illuminance meter (Minolta TL-1, Minolta Corp., Ramsey, NJ, USA) was used to measure the lighting conditions. Measurements were taken about every 15 m with the illuminance meter held face up 1 m above the ground. In total, 342 points were measured in the two locations.

The illuminance level data were analysed by dividing the surveyed areas into three categories: busy well-lit shopping streets (downtown), quiet poorly-lit residential streets (downtown), and rural residential areas. *Table 2* summarizes the results. Based on these results, 16 and 2 lux were selected as the two main *low* light levels for conducting the vision tests and the indoor mobility assessments. These light levels were chosen to be representative of those typically found on the well lit and poorly lit streets at night in the Boston area (high and mid/low mesopic respectively); they were also included in the four light levels used in the outdoor assessment (described below). Lower light levels will also be encountered during outdoor night travel, especially in rural areas (*Table 2*); therefore one location with illumination below 1 lux was included in the outdoor assessment and indoor mobility was also assessed in very dark conditions (< 0.1 lux; scotopic), where patients with night blindness have virtually no vision.

Vision tests

The visual acuity, contrast sensitivity, and visual field of the subjects were measured under three light levels. Baseline measurements were conducted without night vision devices at standard illumination levels (Early Treatment for Diabetic Retinopathy Study (ETDRS) lighting cabinet illumination for visual acuity and contrast sensitivity, and office overhead fluorescent illumination for visual field measurements). All vision measurements were also taken under the two low light levels (16 and 2 lux) with and without each night vision device. Measurements with the LV-3 were taken for monocular viewing of the gray-scale display image. A cover was placed over the front of the display lens to ensure that only information from the display image (and not the see-through carrier lens) was available, while the fellow eye was occluded. Measurements with the M-V device were taken under binocular viewing conditions.

Visual acuity was measured with ETDRS visual acuity charts from 4 m, except when subjects were wearing the LV-3, when they were at 1 m so that several lines on the chart could be read on the minified display image. Letter contrast sensitivity was measured with Pelli-Robson charts at 1 m. Three different acuity charts and two Pelli–Robson charts were used to prevent memorization. Visual acuity charts and Pelli–Robson charts were hung in an ETDRS cabinet. They were illuminated either by the original fluorescent light for standard ETDRS light level (750 lux), or by four additional tubular incandescent lights, which were controlled by a dimmer, to provide the low light levels tested.

Visual field extent was measured at 1 m on a black tangent screen. A 10 mm white target was used for standard tests (without night vision device under standard office illuminance) and M-V tests, but a homemade 40 mm target was used for LV-3 tests to compensate for the 4×-minified display. The standard office light level was provided by ceiling recessed fluorescent room lights (375 lux) and low light levels were achieved by adjusting dimmer-controlled ceiling recessed incandescent lights.

Indoor mobility assessment

Obstacle course. Mobility performance with and without each night vision device was assessed on an indoor obstacle course set up along two corridors. The total length of the obstacle course (both corridors) was 44 m with similar obstacle density in each corridor (0.59 and 0.69 per m^2, respectively). The obstacles included 41 cardboard boxes placed on the ground along the two corridors that served as low lying obstacles (foot and knee), and 16 paper bags and plastic cups hung from the ceiling that served as high level obstacles (above shoulder). One of the corridors is shown in *Figure 3*. The corridors were of similar length, but differing widths; therefore the floor area was different in the two corridors (57.6 vs 33.5 m^2) and, in order to create similar obstacle densities, the total number of obstacles was also different (34 and 23). If obstacle density is too low, contacts with obstacles (a measure of mobility performance) can be relatively infrequent (as occurred on the 'simple' indoor course used by Geruschat *et al.* (1998)). A mobility course should be of sufficient

Table 2. Results of night street illumination measurements in the Boston area

	Downtown well lit shopping (145 points)	Downtown poorly lit residential (52 points)	Rural residential (162 points)
Median (lux)	13.1	3.3	0.3
Interquartile range (lux)	6.5–22.4	1.5–6.9	0.1[a]–0.5

Median and interquartile ranges are given as data were not normally distributed.
[a]0.1 lux was the lowest reading registered by our illuminance meter.

Figure 3. One of the two corridors on the indoor obstacle course. The illumination level was adjusted by dimmer controlled incandescent lights. The bright fluorescent lights seen in the picture were only used to take this picture.

complexity to challenge performance such that differences between subjects and conditions are discernible (Haymes *et al.*, 1996). An obstacle density that was higher than anything that might be encountered in a natural environment was therefore chosen, but this was similar to that used in a previous indoor mobility study of subjects with retinitis pigmentosa, in which there were significant differences in contact numbers at high (360 lux) and low (25 lux) illumination levels (Black *et al.*, 1996), and was similar to the density used in other indoor studies where vision variables affected mobility performance (Pelli, 1986; Lovie-Kitchin *et al.*, 1990; Kuyk *et al.*, 1998). The illumination levels in both corridors could be adjusted by using a group of dimmer controlled incandescent lights. For each walk along the course, the lighting was set with the median illuminance at 16 lux in one corridor and 2 lux in the other.

Each subject walked the complete course three times (once without and once with each of the devices) in alternate directions (to reduce the effect of memorization). Device condition (without device, with M-V or LV-3 device), illumination level in each corridor (16 or 2 lux) and direction of walking were counterbalanced (as far as possible) across subjects. Subjects completed the mobility assessments without long canes. Before walking the obstacle course with a device, subjects were given limited practice (5–15 min) walking around several similar obstacles laid out in a separate room under dimly lit conditions. At the start point of each corridor, subjects were given sufficient time to adjust the controls of the night vision device (when with device) or to adapt to the ambient illumination (when without device). Subjects were instructed to walk to the far end of each corridor (until told to stop) avoiding contact with all obstacles and with the corridor walls. An investigator followed close behind a subject at all times to ensure safety.

Mobility performance was assessed by recording time to walk along each corridor and the number of contacts with obstacles. Touching the walls was also recorded as a contact. At the end of each walk, subjects were asked to rate on a 5-point scale perceived difficulty with recognizing objects, determining obstacle distance, determining obstacle position (left or right), and avoiding obstacles in each corridor.

Walking times, measured with a stopwatch, were converted to walking speeds and expressed as a percentage of the subject's preferred walking speed (PPWS). Preferred walking speed was measured separately at the start of the experimental session as the subject walked (independently, without sighted guide) along a 20 m, unobstructed, well illuminated, and straight path without a night vision device (Clark-Carter *et al.*, 1986; Soong *et al.*, 2000). PPWS is an objective measure of functional mobility performance that has been used in a number of studies (Haymes *et al.*, 1994; Black *et al.*, 1996; Haymes *et al.*, 1996; Soong *et al.*, 2001; Hassan *et al.*, 2002) as it enables normalization of walking speed that controls for variations in age, height, weight and physical fitness of subjects that might otherwise affect walking speed (Haymes *et al.*, 1994).

To account for the difference in obstacle numbers in the two corridors, the number of contacts was normalized with respect to the number of obstacles and obstacle density in each corridor. As both corridors were long and narrow, there was about an equal probability, in such a highly restricted space, of subjects encountering every obstacle in each corridor as they walked from one end to the other. Therefore, it was hypothesized that the greater the number of obstacles the greater the chance of contacts occurring. Therefore, the data were normalized using the following equation:

$$\text{cmp\_con\_2} = \text{con\_2} \times \frac{\text{obs\_num\_1} \times \text{obs\_dens\_1}}{\text{obs\_num\_2} \times \text{obs\_dens\_2}}, \qquad (1)$$

where cmp_con_2 is the compensated number of contacts in corridor 2, con_2 is the original number of

contacts in corridor 2, obs_num_1 and obs_num_2 are obstacle numbers in the two corridors respectively, and obs_dens_1 and obs_dens_2 are obstacle densities in the two corridors respectively.

Dark obstacle-free course. Subjects also walked an obstacle-free route under very dark conditions through a conference lecture hall adjacent to the obstacle course. All lights, except a few emergency exit signs, were turned off so that the illumination was no more than 0.1 lux. The route included an up and a down ramp (with a railing on one side) respectively at the entrance and exit to the hall, an up and a down flight of highly uneven width stairs (with railings on one side) leading to/from the conference hall, and a flat open space across the front of the hall between the two flights of stairs. The total route was 32 m long. Subjects were given an opportunity to refuse to walk any section of the route, but all subjects completed the whole route without using a long cane. They were allowed to use railings for going up and down stairs. In some cases to give a sense of travel direction, one of the investigators stood at the end of the segment to be walked or subjects used other naturally occurring features of the environment, such as the exit signs. Again an investigator followed close behind to ensure safety. Each subject walked the route three times (in alternate directions) without a night vision device and with each device. For each condition, the conference hall walk was included at the end of the obstacle-course walk. Walking time to complete each segment (ramp, stairs, and flat space) of the route was recorded and then PPWS was calculated. After walking the route, subjects rated on a 5-point scale the level of difficulty encountered while walking each segment.

Outdoor stationary evaluation

A limited stationary outdoor assessment was conducted with and without the night vision devices to evaluate device performance and potential benefits of device use in real-world situations. Subjects did not walk outdoors with the night vision devices; instead they were guided to four outdoor sites (at least 1 h after sunset) where they were asked to make observations of the surrounding environment. The outdoor sites included a small park (location 1), a parking lot (location 2), a quiet residential street (location 3) and a busy shopping street (location 4) in downtown Boston, with median illuminances of <1, 2, 6, and 16 lux respectively.

At each location, subjects rated on a 5-point scale the perceived difficulty of seeing each of six pre-selected objects without a night vision device and the amount of help in seeing provided by each device. The objects were obstacles that would typically have to be detected and avoided during normal outdoor night travel, including buildings, pedestrians, cars, trash cans, trees, low railings and steps projecting onto the sidewalk. Three of the objects were within 4 m and the other three were beyond 4 m from the point at which the subject stood. Subjects were also asked to rate their confidence to undertake independent mobility in each location without a device (but with long cane, if used) and how much each device would increase their confidence (when used in addition to long cane). Before rating, subjects were given time to look around and become familiar with each location, ensuring sufficient dark adaptation for the evaluations without device, and correct adjustment of controls for the evaluations with device. The without device assessment was always performed first, while the order of the with-device conditions was alternated across subjects and experiment sites. The order of experiment sites was also counter balanced across subjects.

Questionnaires

After having used the two devices during the indoor and outdoor assessments, subjects completed a short questionnaire rating (on a 5-point scale) comfort, weight, cosmetic appearance, ease of use, image quality, and field of view, etc for each device. They also made a side-by-side comparison of the two devices, and were asked which device they would chose (or neither) as a nighttime mobility aid if they were allowed to take one of the devices home. Subjects were given the opportunity to comment freely on each device and how they thought it could be improved.

Statistical analysis

Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 11.5. For the *continuous* variables (PPWS, number of contacts and vision measures), because of limited sample size, differences between devices (without device, LV-3, M-V) and illumination levels were analysed using both parametric tests (repeated measures ANOVAs, paired t-tests) and non-parametric tests (Friedman, Wilcoxon signed-ranks). The results were similar for the parametric and non-parametric analyses. The results of the parametric analyses are therefore presented, as they enable a simultaneous assessment of the two main variables (device and illumination level) as well as an assessment of interactions between them.

For the *ordinal* data from the 5-point rating scales, differences between devices and illumination levels were analysed using non-parametric tests (Friedman, Wilcoxon signed-ranks). A probability value of <0.05 was used to indicate a significant effect for all tests.

Results

Visual function

Figure 4 shows the results of vision measurements, visual acuity (VA), visual field (VF) and contrast sensitivity (CS), at different illumination levels without and with each night vision device. As expected, visual performance without a night vision device declined significantly with decreasing illumination level (repeated-measures ANOVA VA: $F_{2,10} = 43.7$ $p < 0.001$; VF: $F_{2,10} = 14.8$ $p = 0.001$; CS: $F_{2,10} = 39.7$ $p < 0.001$). Compared with standard illumination levels, VA declined 0.2 logMAR at 16 lux ($p = 0.007$) and 0.33 at 2 lux ($p = 0.001$); VF diameter shrank by 6.1° (or 46%) at 2 lux ($p = 0.02$), while the difference in VF diameter of 2.5° (or 20%) at 16 lux approached significance ($p = 0.07$); CS declined 0.21 log units at 16 lux ($p = 0.02$) and 0.47 at 2 lux ($p = 0.001$).

With night vision devices under low light levels there was a significant main effect of illumination level on CS and VF but not VA (repeated measures ANOVA, VA: $F_{1,5} = 2.3$ $p = 0.2$; VF: $F_{1,5} = 29.2$ $p = 0.003$; CS: $F_{1,5} = 55.7$ $p = 0.001$), a significant main effect of device on all three measures (VA: $F_{2,10} = 157.7$ $p < 0.001$; VF: $F_{2,10} = 31.0$ $p < 0.001$; CS: $F_{2,10} = 24.1$ $p < 0.001$) and a significant interaction between the two factors for VA and CS (VA: $F_{2,10} = 16.2$ $p = 0.001$; CS: $F_{2,10} = 11.8$ $p = 0.002$), but not for VF ($F_{2,10} = 2.5$ $p = 0.13$). Compared with viewing without a device, *post hoc* analyses showed that M-V improved VA by 0.14 logMAR at 2 lux, but did not significantly change VA at 16 lux ($p = 0.3$; *Figure 4a*). For LV-3, because of the 4× minification of the display image, we expected a reduction in VA of 0.6 logMAR relative to the without-device measurement. After accounting for this expected reduction, the LV-3 did not further decrease VA at 2 lux ($p = 0.2$), but did significantly reduce VA by a further 0.24 logMAR at 16 lux from the VA recorded without the device ($p = 0.02$) (*Figure 4a*). As expected from the minification, LV-3 substantially expanded subjects' VF by 16.6° (or 178%) at 16 lux ($p = 0.002$) and 18.4° (or 287%) at 2 lux ($p = 0.002$). M-V also expanded the VF (just significantly) by 1.2° (or 15%) at 16 lux ($p = 0.04$) and 4.0° (or 64%) at 2 lux ($p = 0.04$) (*Figure 4b*).

The M-V significantly improved CS by 0.27 log units at 2 lux ($p = 0.04$), compared with the without-device condition, but there was no significant improvement at

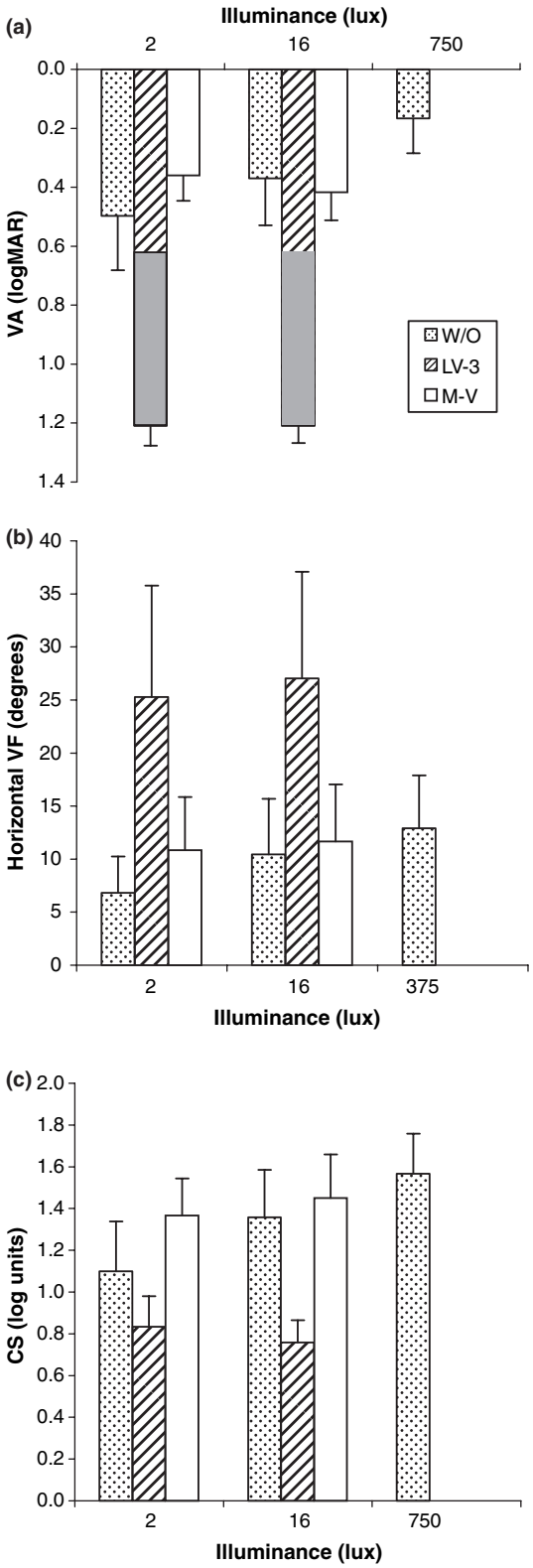

Figure 4. Mean vision measurements without a device (w/o) at standard illumination levels, and with/without night vision devices at dim illumination levels (2 and 16 lux). (a) Visual acuity (gray bar on the LV-3 columns represents the expected visual acuity reduction of 0.6 logMAR because of the 4× minification); (b) visual field; and (c) contrast sensitivity. Error bars represent one S.D.

16 lux ($p = 0.21$; *Figure 4c*). However the LV-3 significantly reduced CS by 0.6 log units ($p = 0.004$) at 16 lux (relative to without device), while the reduction of 0.27 log units at 2 lux approached significance ($p = 0.07$). The CS measurements were taken at the same distance without and with each device; thus the spatial frequencies of the letters on the Pelli–Robson chart would be shifted towards higher frequencies when displayed as a minified image on the LV-3 display. For four normal observers viewing without the LV-3, when viewing distance was increased from 1 to 4 m, contrast sensitivity reduced by 0.1–0.15 log units. Therefore the reduction in CS with the LV-3 was greater than would be expected because of the minification alone.

Indoor obstacle course

Percentage preferred walking speed. There were significant main effects of illumination level and device on PPWS on the indoor obstacle course (repeated-measures ANOVA: $F_{1,5} = 28.2$, $p = 0.003$ and $F_{2,10} = 13.7$, $p = 0.001$, respectively), but there was no significant interaction between these factors ($F_{2,10} = 2.1$, $p = 0.2$). Overall, subjects walked 3.3% slower at 2 than 16 lux ($p = 0.003$), and walking speeds were slowest with the LV-3 ($p = 0.01$) (*Figure 5*).

Without a device, subjects walked under the dim illumination levels at only 33% of their preferred speed in daylight, and at 2 lux they were a further 7% slower than at 16 lux ($p = 0.04$), which suggests they encountered greater difficulties at the lower light levels (*Figure 5*). Neither of the night vision devices improved subjects' walking speed, instead wearing a device resulted in the same or slower walking speeds. Compared with the without-device condition, at 2-lux illumination they walked significantly more slowly with LV-3 (12% slower, $p = 0.01$) and at the same speed with M-V ($p = 0.97$). Under 16 lux, they walked more slowly with both devices: significantly more slowly with LV-3 (15% slower, $p = 0.004$) and almost significantly with M-V (8.3% slower, $p = 0.08$).

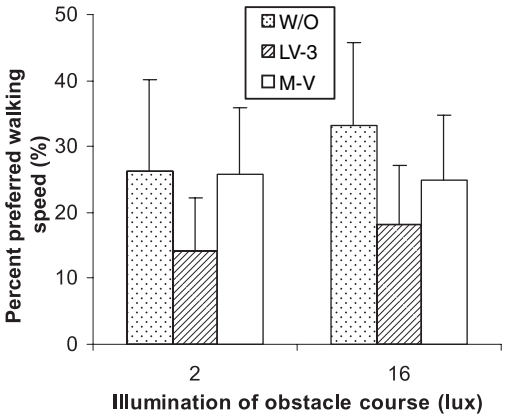

Figure 5. Mean percent preferred walking speed with/without (w/o) night vision devices at the two dim illumination levels. Walking speed is expressed as a percentage of the preferred speed in daylight on an unobstructed straight course. Error bars represent one S.D.

Number of contacts. Repeated-measures ANOVA revealed significant main effects of illumination level ($F_{1,5} = 7.5$, $p = 0.04$) and device ($F_{2,10} = 52.3$, $p = 0.002$) on total number of contacts (all obstacles) on the indoor obstacle course (*Figure 6a*), but there was no significant interaction between these factors ($F_{2,10} = 0.2$, $p = 0.8$). The effects of illumination level and device on number of contacts were similar to those reported for PPWS. Overall, 1.4 more contacts were made under 2-lux than 16-lux illumination ($p = 0.04$), and performance was just significantly worse with the LV-3 than without a device (3.3 more contacts, $p = 0.03$) or with the M-V (3.9 more contacts, $p = 0.04$).

Unexpectedly, performance with M-V was not significantly better than without a device (*Figure 6a*). The subjects only made 0.6 fewer contacts overall (all obstacles) with M-V than without device ($p = 1.0$). When using the M-V, informal observations of scanning behaviours indicated that subjects tended to look at the ground and did not scan sufficiently well to detect the high level obstacles within their restricted visual field. When only low-level obstacles were included in the analyses (*Figure 6b*), M-V did reduce the overall number of low obstacle contacts by 1.3 and the effect approached significance ($p = 0.07$), with a trend towards a greater reduction in the number of contacts at 2 lux (1.8 fewer, $p = 0.06$) than 16-lux (0.7 fewer, $p = 0.3$).

Subjective evaluation of perceived difficulties. *Table 3* summarizes the perceived difficulty in obstacle recognition and avoidance with and without each device on the indoor mobility course. At 2-lux illumination, there were significant differences between devices in the ratings of perceived difficulty ($p = 0.01$ for each task). Compared with the without device condition, perceived difficulty reduced by at least 1.5 levels on each task at 2 lux when using the M-V, but was unchanged, or increased (for determining obstacle distance) with the LV-3. At 16 lux there was a significant device effect only for obstacle distance determination, with perceived difficulty being highest for LV-3 and least for M-V ($p = 0.03$). Without a device there was a significant reduction in the median difficulty ratings for obstacle recognition at 16 lux compared with 2 lux ($p = 0.03$), and a trend towards a reduction in difficulty ratings for determining obstacle position ($p = 0.07$), obstacle distance ($p = 0.1$) and seeing an obstacle in time to avoid it

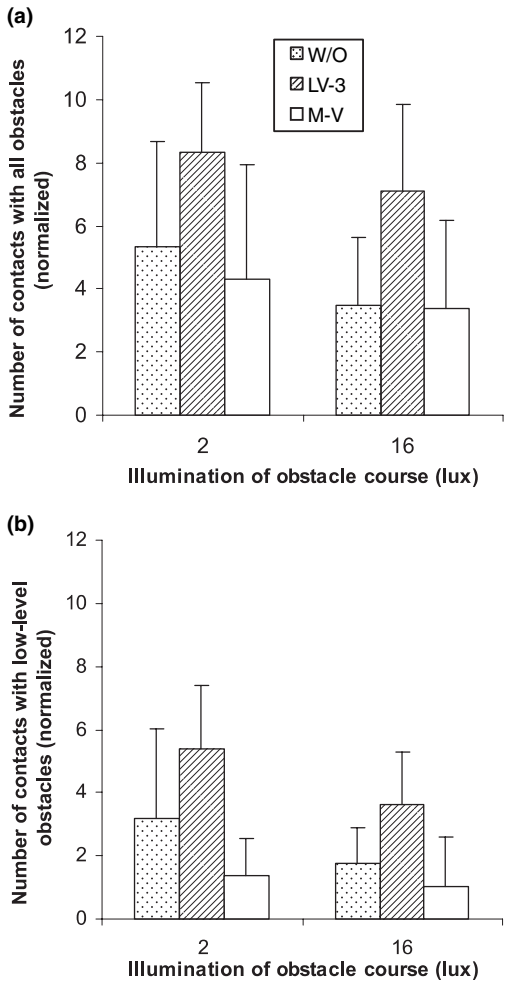

Figure 6. Mean number of contacts with obstacles on the indoor mobility course with/without (w/o) night vision devices at the two dim illumination levels. (a) contacts with all obstacles; (b) contacts with low-level obstacles. Error bars represent one S.D.

($p = 0.1$; *Table 3*). With the LV-3 there was also a trend for a reduction in the difficulty rating at 16 lux compared with 2 lux for obstacle recognition ($p = 0.05$) and seeing an obstacle in time to avoid it ($p = 0.06$). By comparison, difficulty ratings were more similar at the two light levels for the M-V device ($p > 0.3$, with a maximum difference in median difficulty rating of only 0.5).

Dark obstacle-free course

For the obstacle-free walk through the very dark conference hall, repeated-measures ANOVAs revealed a significant main effect of device on PPWS on the total route, the stairs down, ramp and flat segments of the route (total route: $F_{2,10} = 10.5$, $p = 0.003$; stairs down: $F_{2,10} = 5.8$, $p = 0.02$; flat segment: $F_{2,10} = 26.0$, $p < 0.001$), but not the stairs up ($F_{2,10} = 0.7$, $p = 0.5$). Except for the up-stairs segment, PPWS was significantly slower with the LV-3 than the M-V (*Figure 7*). Unlike on the obstacle course, neither device significantly changed PPWS from without device levels, the only exception being that the LV-3 significantly reduced walking speed on the ramp and flat segment compared to without the device (12.8% slower, $p = 0.02$).

Very similar results emerged from the analyses of subjects' ratings of mobility difficulty for the walk through the conference hall. There was a significant effect of device on the rating of mobility difficulty for all segments (Freidman test, $p = 0.05$ for up stairs, $p = 0.02$ for down stairs, $p = 0.03$ for ramp and flat segment) with higher perceived difficulty for the LV-3 than the M-V (*Figure 8*). The difficulty ratings were not significantly different with and without the LV-3 (Wilcoxon signed ranks test, $p > 0.07$), while the M-V significantly reduced perceived difficulty of walking only on the ramp and flat segments ($p = 0.04$; *Figure 8*).

Table 3. Median and interquartile ranges for ratings of perceived difficulty in obstacle recognition and avoidance on the indoor mobility course, with and without each night vision device

	Task			
Device	**Recognize obstacle**	**Determine obstacle position**	**Determine obstacle distance**	**See obstacle in time to avoid it**
2 lux illumination				
Without device	4 (4–4.75)	4.5 (4–5)	3.5 (3–4.75)	5 (3.5–5)
LV-3	4 (3.25–4)	4.5 (4–5)	5 (4.25–5)	4.5 (4–5)
M-V	2 (1–3)	3 (2.25–3)	2 (2–2.75)	2.5 (2–3)
Significance of device effect (Friedman)	0.01	0.01	0.01	0.01
16 lux illumination				
Without device	3 (2.25–3)	3 (2.25–3.75)	3 (2.25–3)	3 (3–3)
LV-3	3 (3–3.75)	4 (4–4.75)	4.5 (4–5)	3.5 (3–4.75)
M-V	2.5 (1.25–3)	3 (2.25–3)	2 (2–2.75)	2.5 (2–3)
Significance of device effect (Friedman)	0.14	0.10	0.03	0.3

The higher the score the more difficult is the task (1, no difficulty; 2, a little; 3, some; 4, moderate; 5, extreme difficulty).

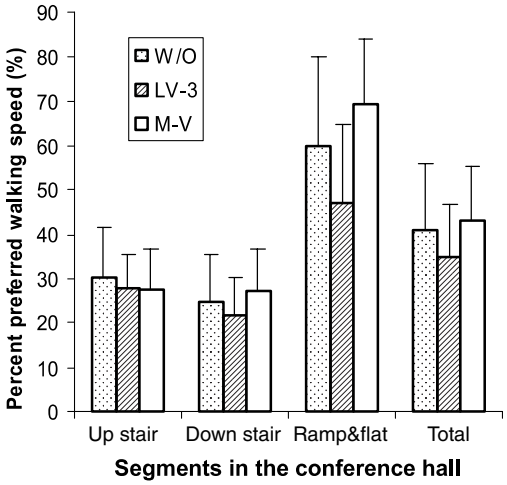

Figure 7. Mean percent preferred walking speed with/without (w/o) night vision devices in a very dark conference hall (<1 lux). Walking speed expressed as a percentage of the preferred speed in daylight on an unobstructed straight course. Error bars represent one S.D.

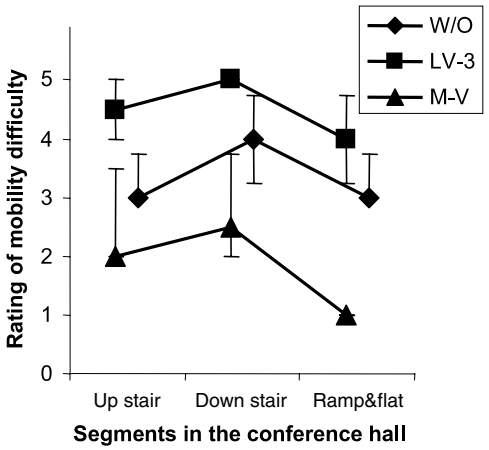

Figure 8. Median ratings of perceived mobility difficulty for different segments of the walk through the very dark conference hall. The higher the score the greater the difficulty (1 = no difficulty, 2 = a little, 3 = some, 4 = moderate, 5 = extreme difficulty). Error bars represent interquartile range.

Outdoor stationary evaluation

Subjects rated difficulty of seeing without a device and amount of help with a device for three near and three far objects at each outdoor location. There were no significant differences in ratings for the objects at the two distances (Wilcoxon signed ranks test, $p > 0.1$); therefore ratings were pooled across the six objects at each location. Subjects also gave an overall rating of perceived difficulty without a device and amount of help with a device at each location. The median rating score from the pooled data and the overall rating were highly correlated (Spearman, $r = 0.96$, $p < 0.001$) and, not surprisingly, results of the statistical analyses were the same irrespective of which

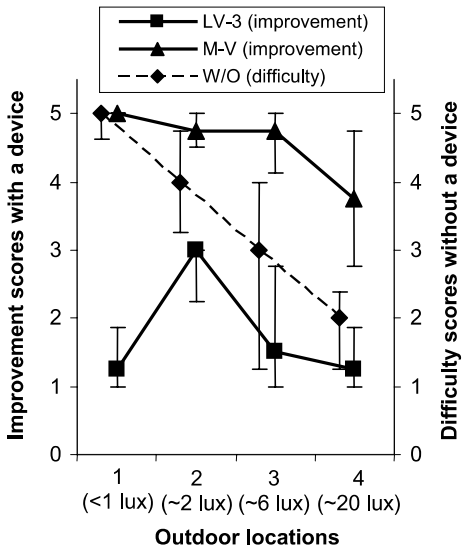

Figure 9. Median ratings of perceived difficulty without device (diamonds connected by dashed line) and improvement with each device (triangles and squares connected by solid lines) in seeing at four outdoor locations. Higher scores represent greater difficulty/improvement (1 = no; 2 = little; 3 = somewhat; 4 = moderate; 5 = extreme difficulty or improvement). Error bars represent interquartile range.

measure was used. The results presented are for the data pooled across the six objects.

There were significant differences in the median ratings of difficulty without device at the four locations (Friedman test, $p = 0.002$). As illumination level increased from location 1 to 4, median difficulty decreased (*Figure 9*), suggesting that the four locations provided a good representation of the illumination levels at which different degrees of difficulty are likely to be experienced during outdoor night mobility.

There were also significant differences in the improvement of seeing with the M-V across the four locations (Friedman test, $p = 0.02$). All subjects were extremely satisfied with the assistance provided by M-V at the darkest location (location 1, <1 lux). As illumination levels increased, ratings gradually declined from location 1 to 4 with increasing between-subject variation (increasing interquartile range, *Figure 9*). Nevertheless subjects still felt that the M-V was a moderate help even at the brightest location (location 4). By comparison the LV-3 was considered almost no help for seeing at three of the outdoor locations with the only exception being location 2, where the illumination was about 2 lux and subjects had moderate difficulty seeing without a device. Differences in ratings of the LV-3's help across locations only approached statistical significance (Friedman test, $p = 0.08$).

The median scores for self-rated confidence in independent night mobility without a night vision device (but with long cane, if used) were significantly different across

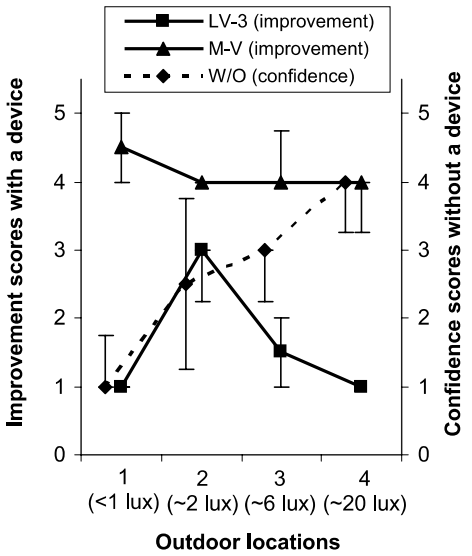

Figure 10. Median ratings of mobility confidence without device (diamonds connected by dashed line) and improvement in confidence with each device (triangles and squares connected by solid lines) to undertake independent mobility at four locations. Higher scores represent greater confidence/improvement (1 = no; 2 = little; 3 = somewhat; 4 = moderate; 5 = extreme confidence or improvement). Error bars represent interquartile range.

locations (Friedman, $p = 0.004$), with confidence increasing from the darkest location to the brightest location (*Figure 10*). Comparing with *Figure 9*, a clear correlation is noted, i.e. the greater the difficulty in seeing, the less the confidence to undertake independent mobility (Spearman's $r = 0.67$, $p < 0.001$). Subjects believed that using the M-V would greatly improve their mobility confidence at all locations (even the brightest location) and there were no significant differences in ratings across the four locations (Friedman, $p = 0.56$). By comparison subjects gave only very low ratings of improvement in mobility confidence with the LV-3, except at location 2 where they felt that the LV-3 provided some help with seeing (*Figure 9*), and they also felt that the device would somewhat improve their mobility confidence (*Figure 10*; Friedman, $p = 0.05$). In fact, the improvements in seeing with devices (*Figure 9*) and the improvements in confidence (*Figure 10*) were significantly correlated (LV-3: Spearman, $r = 0.81$, $p < 0.001$; M-V: Spearman, $r = 0.41$, $p = 0.04$).

Device questionnaire

Based on their experiences in the indoor and outdoor assessment, subjects completed a questionnaire about various aspects of the two devices. The LV-3 was rated as good (median score ≥4) for the comfort and weight of the device, whereas the M-V received poor ratings (score ≤2) on these aspects (*Figure 11*). On the contrary, the M-V scored highly for ease of learning to use, image clarity, brightness and contrast, and ease of control (although for the latter it was not significantly different from the LV-3 rating), whereas the LV-3 received poor ratings for image clarity and contrast. In addition the LV-3 also scored poorly in terms of ease of walking while wearing the device (again difference not significant). Surprisingly, subjects did not rate the LV-3 significantly better in terms of field of vision of the device, which may be because the subjects did not interpret the meaning of the question correctly, confusing it with field of view of the display. These differences were reflected also in the responses to the final questionnaire in which subjects indicated a preference for the M-V in terms of device performance and ease of use, but a preference for the LV-3 based on comfort of wearing (*Table 4*). When asked which of the two devices they would like to keep, five of six subjects chose M-V and only one chose the LV-3.

Before the subjects completed this study, they were asked to give comments about limitations of each device and how it could be improved. Despite the open-ended nature of the question, several common themes emerged. In addition to aspects already covered in the closed questions, three subjects commented that the LV-3 display suppressed the vision of the fellow eye in the dark (so it was difficult to switch attention to the fellow eye), three subjects reported that there was a noticeable delay problem with M-V when the head moved, and two subjects felt the field of view of the M-V was limited. The field of view limitation was also reported as a problem with an earlier version of the M-V device (Spandau *et al.*, 2002) and may relate to the limitation imposed on the field that can be scanned by eye movements alone (without head movement) when wearing the device compared with walking without the device.

Discussion

Light levels

The illuminance levels of 2 and 16 lux, that were selected as representative of lighting on quiet poorly-lit and busy well-lit streets, proved also to be light levels at which there were functionally significant differences in visual performance (objective and subjective) and mobility performance without night vision devices. Reduction in visual acuity and contrast sensitivity at low light levels, similar to that found in this study, is well documented for patients with night blindness (Hyvarinen *et al.*, 1981; Hoover, 1983; Spellman *et al.*, 1989; Alexander *et al.*, 1991, 1992; Sucs and Uvijls, 1992; Friedburg *et al.*, 1999); however the shrinkage in overall visual field extent with decreasing illumination recorded has, to the

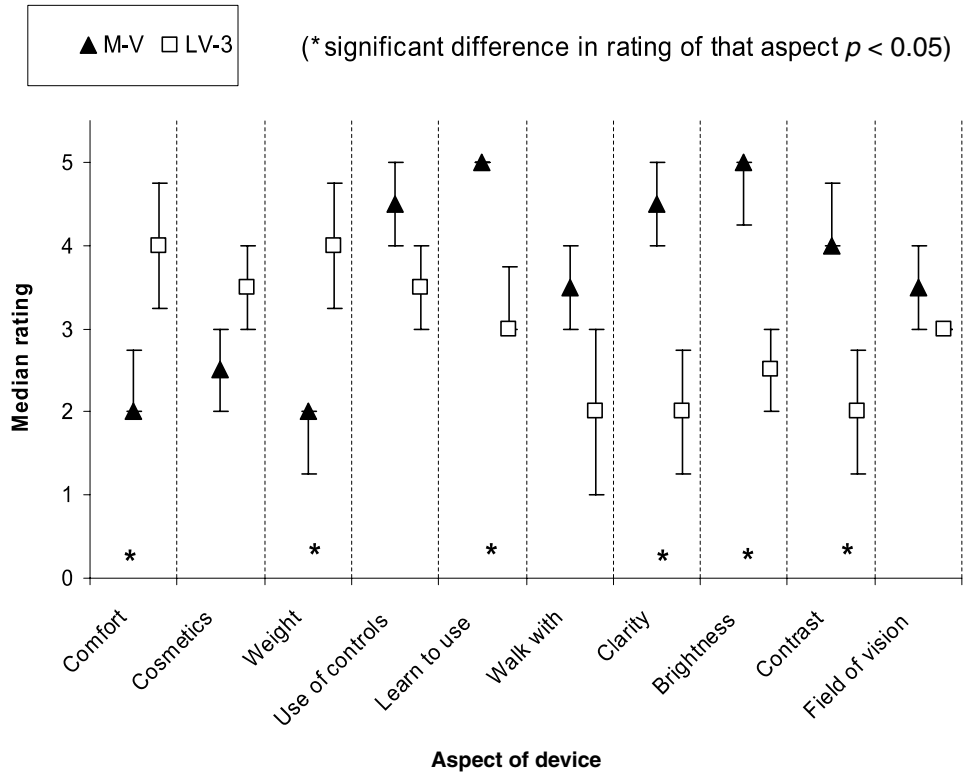

Figure 11. Median ratings for various aspects of device performance based on experiences during the indoor and outdoor assessments (1 = very poor; 2 = poor; 3 = fair; 4 = good; 5 = very good). Error bars represent interquartile range.

	Easier to learn to use	Easier to operate	More comfortable to wear	More help in seeing	Overall, choose which device?
LV-3	0	0	6	0	1
M-V	5	5	0	6	5
No preference	1	1	0	0	0

Table 4. Number of subjects indicating a preference for either the LV-3 or the M-V in the side-by-side comparison

best of our knowledge, only previously been cited anecdotally (Ehrlich, 1987).

Although there was a reduction in visual function on objective clinical tests at 16 lux, subjective ratings indicated little perceived difficulty with seeing and moderate confidence to undertake independent mobility at the well-lit outdoor 16 lux location (*Figures 9* and *10*). By comparison, the reduction in visual function was greater on clinical testing at 2 lux and, on the less well-lit streets (location 2, median 2 lux), perceived difficulty with seeing was higher (median rating – moderate) and confidence was lower (median rating – a little). On indoor tests at 16 lux, the M-V device improved neither visual function nor mobility performance. However at 2 lux, the M-V device did improve visual performance and decreased the number of contacts with low-lying objects. These results suggest that a conventional night vision device (such as the M-V) might only be a significant help on poorly lit streets. By comparison, for patients with restricted fields in addition to night blindness, it would be expected that the field expansion feature of future LV-3 type night vision devices might aid mobility at higher light levels (although, for reasons discussed below, this could not be properly tested with the prototype evaluated in this study).

As well as functioning at the moderately low light levels discussed above, it is also important for night vision devices to function in near dark conditions, as these are the light levels at which, in the outdoor assessment, the subjects reported extreme difficulty with seeing and no confidence to undertake independent night mobility (*Figures 9* and *10*).

Prototype LV-3 device

Subjects rated the prototype LV-3 highly for comfort, fit and weight, but were less positive about device performance and image quality. They perceived some visual

benefit of the device outdoors at the location where the lighting was in the 2-lux range, but no benefit at the darkest location where the prototype camera did not have enough sensitivity to capture an image, and no benefit at the better-illuminated locations where device performance was unable to match natural vision. Nevertheless one subject indicated that he would choose the LV-3 rather than the M-V device, as he liked the option of being able to use whatever natural vision he retained at the reduced light levels (by looking through the display, moving his eye out of the field of the display or switching attention to the other eye), which was not possible with the M-V as it blocked the natural view. Furthermore, our outdoor illumination measurements indicated that there are many situations in which outdoor lighting levels within a city center are likely to be sufficient for the patient's natural vision to be useful: 30% of illuminance measurements were higher than 16 lux in downtown Boston. Under these conditions, an occluding display such as the M-V may hinder patients' mobility.

The LV-3 device expanded the visual field of all subjects, but generally the expansion was less than the theoretically predicted 4×. Visual acuity and contrast sensitivity with the device were reduced more than would be expected from the minification alone. The main factors limiting visual performance and field expansion with the LV-3 were: poor camera sensitivity at low light levels (< 2 lux), insufficient range on the contrast enhancement and limited resolution of both the camera and the display. These aspects of device performance are being addressed in the next stage of development.

Mobility performance on the indoor obstacle course was very poor when wearing the LV-3 (slow walking speeds, high number of obstacle contacts and difficulties with determining object positions). Furthermore, on the obstacle-free walk along the flat section in the dark conference hall, walking speed was significantly slower with the LV-3 than without. Apart from the camera's poor low-light sensitivity, which limited device performance on some parts of the obstacle course (and on the entire conference hall walk), a big factor impacting mobility performance was the spatial distortion of obstacle position resulting from the minification. Although subjects understood the concept of the minification, had practiced reaching out to objects seen on the minified display and had practiced walking around obstacles in a dark room while wearing the device before starting the indoor mobility course, this training period may have been too brief to sufficiently habituate the user to the challenge of using a minified image for obstacle avoidance.

At the low light levels on the indoor course, subjects found it very difficult to vision multiplex (alternate attention) between the gray-scale minified video image and their natural vision. If they had been able to multiplex, their natural view of the scene might have helped with adaptation to the device and determining the true position of obstacles. The gray-scale image affected the entire visual field of our subjects: they commented that the light emitted by the display interfered with dark adaptation and they were usually unable to swap their attention to use the low-light natural view from the other eye. Furthermore, the LV-3 display was fitted in front of the dominant eye, which may also have contributed to difficulties in alternating attention to the non-dominant eye. In daylight conditions one subject found it impossible to alternate attention to the fellow eye when the display was mounted in front of the dominant eye, but had no problems when it was in front of the non-dominant eye. The next generation of the prototype device will offer users the option to use the edge-contour image, which will enable vision multiplexing by looking through the contour view to the real world. We anticipate that it will be easier to apply vision multiplexing with the edge-contour mode than with the gray-scale image mode as the illuminated pixels of the contours occupy only a small portion of the display area, rarely obscure any detail of the real-world view for any length of time and do not significantly affect the level of (dark) adaptation of the eye. The light adaptation and eye dominance difficulties encountered with vision multiplexing between the two eyes when using the LV-3 should be eliminated by the use of the edge-contour image in the next prototype.

Due to the minimal level of training and problems with vision multiplexing with the gray-scale image, the results of the LV-3 evaluation might have underestimated the full benefit of the novel field expansion feature that is believed to be fundamental to the Minified-Contours Augmented-View concept (see Introduction) of the new night vision device (Peli, 2001; Vargas-Martin and Peli, 2002). More extensive training, as well as full implementation of the edge-contour image to facilitate vision multiplexing, may be necessary to use the field expansion feature more effectively. If vision multiplexing is easier, then the field-expansion feature could be used in a more dynamic fashion enabling better interplay between the field-expanded view and the natural view than with the gray-scale image (i.e. attention could be swapped rapidly and intermittently from the natural view to the minified, field-expanded view to gain advance warning about obstacles or orientation information from outside of the field of vision). Preliminary testing within a virtual environment indicates that subjects with restricted visual fields are able to successfully use the minified edge-contour image to aid visual search for objects outside of the habitual visual field, and that they quickly learn the relationship

between the apparent position of an object on the minified display and its true position (Luo and Peli, 2004). Furthermore, since carrying out the LV-3 evaluation, we have demonstrated that inclusion of a center mark on the device display facilitates adaptation for people with a visual field extent less than that of the display (Luo and Peli, 2004); this feature will be incorporated in the next generation prototype LV-4 device. It is suggested that the field expansion aspect of the Minified-Contours Augmented-View concept merits further investigation in a longer-term study of the LV-4 device.

Multi-Vision (M-V) device

Subjects were very enthusiastic about the way the M-V device made 'night look like day' and gave high positive ratings for device performance, but they did not like the heavy weight and poor fit of the device. They also noticed that lack of colour information was a problem at pedestrian crossings with signal lights where both the red (do not walk) and white (safe to cross) signals appeared white on the display and were not distinguishable by shape. On the clinical tests of visual function used in this study, visual performance improved significantly with the M-V (compared to without) at 2 lux, but not at 16 lux. Although the ranges of contrast and brightness adjustments were sufficiently wide on the M-V, visual acuity was restricted by the limited resolutions of display and camera. Low contrast letters on the Pelli–Robson chart may have been washed out by the automatic exposure control of the camera and the contrast enhancement of the control box. Nevertheless our findings suggest that the performance of the M-V device tested is superior to that of an earlier version where visual acuity with the device was better than without only up to 0.01 cd m^{-2} (0.03 lux) and contrast sensitivity up to 0.1 cd m^{-2} (0.3 lux) (Friedburg *et al.*, 1999); however visual performance at light levels above 0.1 cd m^{-2} was not evaluated in that study.

Subjective ratings of the potential of the M-V device to improve confidence to undertake independent mobility were high for all outdoor locations and little perceived difficulty was reported for obstacle detection and avoidance on the indoor course. However these highly positive subjective ratings did not appear to be reflected in the modest improvement in mobility performance on the indoor course when using the device. The density of obstacles on the indoor course was much higher than would be experienced outdoors and subjects were asked to walk the course without using their long cane. Therefore they were presented with an artificial situation and had to utilize different mobility strategies than they normally would. Factors related to device usage while mobile, such as problems with parallax (from the monocular camera view) and judging obstacle distance, system delay during head movement which degrades image quality, and the need to adjust habitual scanning patterns (make greater use of head movements) probably were not taken into account by the subjects in the stationary outdoor ratings, but were nevertheless reported after the indoor mobility assessment. Instead it appears that subjects' ratings might have been influenced by their initial enthusiasm for the perceived improvement in vision with the device, while mobility performance was limited by the lack of experience of using the device and course complexity. The mismatch between subjective and objective findings reinforces the importance of training and adaptation in order to fully evaluate the effects of a device on mobility performance. Mobility performance is likely to improve following a period of training and use of the device in realistic outdoor settings; however, with the exception of one investigation (Hartong *et al.*, 2004), those night vision device studies that have included an outdoor mobility assessment (Morrissette *et al.*, 1983; Rohrschneider *et al.*, 2000; Spandau *et al.*, 2002) have not included a period of home-use of the device prior to the evaluation.

For the walk through the dark conference hall, the M-V provided much better levels of visual function than subjects could possibly achieve with their natural vision at the scotopic light levels. Perceived difficulty with mobility was significantly lower with than without the device on the ramp and flat sections, yet walking speed was not significantly faster with the device. This suggests that for the ramp and flat segments, although the extra visual information provided by the M-V improved confidence to walk (which is important from the user's perspective), it was not required for mobility. The ramp and flat sections were relatively short and subjects knew that they were obstacle-free, so having determined the direction of travel, little visual information was necessary for mobility; thus walking speed with and without the M-V was about 60% of the preferred walking speed in good lighting (*Figure 7*), as compared with $< 30\%$ on the indoor obstacle course where visual information was essential to mobility (*Figure 5*). After sufficient training and adaptation to using a night vision device, the extent to which the device is likely to improve mobility will depend on the visual requirements of the mobility task as well as the extent to which non-visual information is used to aid mobility, such as tactile information from use of stair railings or long cane.

Conclusions

Although the results of this study were limited by small sample size and the lack of training and time for

adaptation to the use of the night vision devices, the aims of the study are fulfilled in that the information necessary to direct future development of the next prototype LV-4 is provided. Subjects' preference for the better comfort, fit and lighter weight of the LV-3 device in comparison to the M-V device confirms that some of the cosmetic and ergonomic disadvantages of other currently available devices have been successfully addressed. The next stage of development will focus on improving camera sensitivity, and the image quality and contrast. The Minified-Contours Augmented-View concept will be fully implemented by including the edge-contour image and will also use a custom-designed spectacle frame with a wider range of fitting adjustments to provide an even better ergonomic design. With improved camera sensitivity and the edge-contour image, patients should be able to make better use of the field expansion and vision multiplexing features to aid outdoor night mobility than was possible with the prototype LV-3. The next prototype LV-4 will provide flexibility for patients to use their natural vision when light levels are sufficient and when they are not, the edge-contour or full gray-scale image modes. Additionally they will have the option of viewing a minified image or using digital zoom to reduce the minification and display a 1:1 image. A more extensive evaluation of the next generation device is planned, which will include device training, a period of home use of the device and a mobility evaluation on an outdoor course at night.

Acknowledgements

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MicroOptical Engineering Corp provided the prototype LV-3 device. Visys, Germany (now Trivisio, Switzerland) provided the Multi-Vision device.

Disclosures

Dr Rensing is an employee of MicroOptical Engineering Corp., which has a financial interest in the LV-3 technology. Dr Peli has a financial interest in the multiplexing technology through a patent and is a consultant to MicroOptical. Dr Bowers and Dr Luo have no financial interests in the devices evaluated in this study.

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