

Improved Mobility and Independence of Night-Blind People Using Night-Vision Goggles

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PURPOSE. To investigate whether the use of night-vision goggles (NVGs) by night-blind people improves their mobility and sense of independence under dark circumstances.

METHODS. Twenty night-blind subjects with retinitis pigmentosa were requested to walk predetermined routes at night with and without NVGs. The number of unintended contacts with obstacles (hits) and the percentage of preferred walking speed (PPWS) en route were assessed in three different situations: a darkened indoor corridor; a moderately lit outdoor residential area; and a well-lit outdoor shopping area. Assessments were performed before and after a 5-week training period, during which the subjects practiced using NVGs in their own surroundings, registered their experiences in a journal, and filled out questionnaires.

RESULTS. The mean number of hits in the darkened corridor declined from eight to two when NVGs were used. Mean PPWS (34%) did not improve. In the residential area, mean hits declined from eight to practically zero and mean PPWS increased from 60% to 72% (after training to 78%). In the shopping area, subjects walked at 93% PPWS without any hits and showed no improvement with NVGs. Subjective scores revealed a good sense of orientation, feelings of safety and tranquility and an increase in independent mobility when NVGs were used.

CONCLUSIONS. Using NVGs seems to improve nighttime mobility in dark outdoor conditions by decreasing unintended contacts with obstacles and increasing walking speed. Use of NVGs increased independent activities in these subjects and was generally positively evaluated for everyday outdoor use. (*Invest Ophthalmol Vis Sci.* 2004;45:1725-1731) DOI:10.1167/iovs.03-1061

Night-blindness is caused by an impaired rod function of the outer sensory retina and is a symptom of a number of inherited retinal disorders. The congenital form, congenital stationary night blindness (CSNB) is not progressive and has no other accompanying disturbed visual functions. Retinitis pigmentosa (RP), the best-known type of retinal degeneration, is

progressive and involves both rods and cones. Because damage to the rod system usually predominates in the early stages of the disease, the first symptom of RP is often night blindness. It is followed by an increasing loss of peripheral visual field and deterioration of visual acuity in later stages. Night-blind subjects perceive the outdoor environment after sunset as almost completely dark. They bump into objects, their orientation is usually seriously hindered, and their walking speed is substantially reduced.¹⁻³ In addition, independent travel and other outdoor activities often become impossible. Night blindness therefore severely interferes with normal daily activities.

A luminance-enhancing vision aid may be of great help to night-blind individuals. In the past, light-enhancement devices were large, heavy monocular instruments,⁴ that later evolved into smaller,⁵ more compact, hand-held devices.⁶ These were then followed by head-mounted binocular instruments, known as night-vision goggles (NVGs). Today, a newer version of these spectacles, called the Multi-Vision (Trivisio, Taegerwilten, Switzerland), is available (Fig. 1). It has the added advantage of a higher resolution and an improved automatic light-adapting system. Two studies investigating the potential benefit of NVGs were performed recently.^{7,8} The one by Friedburg et al.⁷ found that night-blind subjects could improve their visual functions in a laboratory design using NVGs. The second study⁸ was conducted in a real-life situation, in which participants subjectively evaluated the device after walking a designated route. It reported that a small majority of participants was positive about the instrument. Although both studies provided new information, they did not show data about the influence of such a device on orientation and mobility in a realistic outdoor situation and they were both based on single experiences. To evaluate the usefulness of such a device adequately, we believe that more data should be assessed from real-life outdoor situations: not only from a single use, but also after a period with ample opportunity to practice using the instrument.

The purpose of the present study was to assess how much night-blind individuals benefit from using NVGs in everyday life. Data were collected on mobility performance (walking speed and the number of times obstacles were hit, referred to as hits) and personal judgments after prolonged use of a night-vision device.

METHODS

Subjects

Night-blind subjects who wished to improve their nighttime mobility were recruited by means of announcements and advertisements at visual rehabilitation centers and the Dutch Retina Association. Walking cane users were initially excluded, because we wanted to test the function of NVGs alone. Because the visual field of the goggles used in this study was only 30°, we mainly addressed subjects with RP. Most of these individuals already had constricted visual fields and therefore were not expected to experience any severe additional field loss. No control group was included. We considered the test group as its own control group, since the subjects all performed tests both with and without NVGs. Pretests on visual acuity, visual field, and dark adapta-

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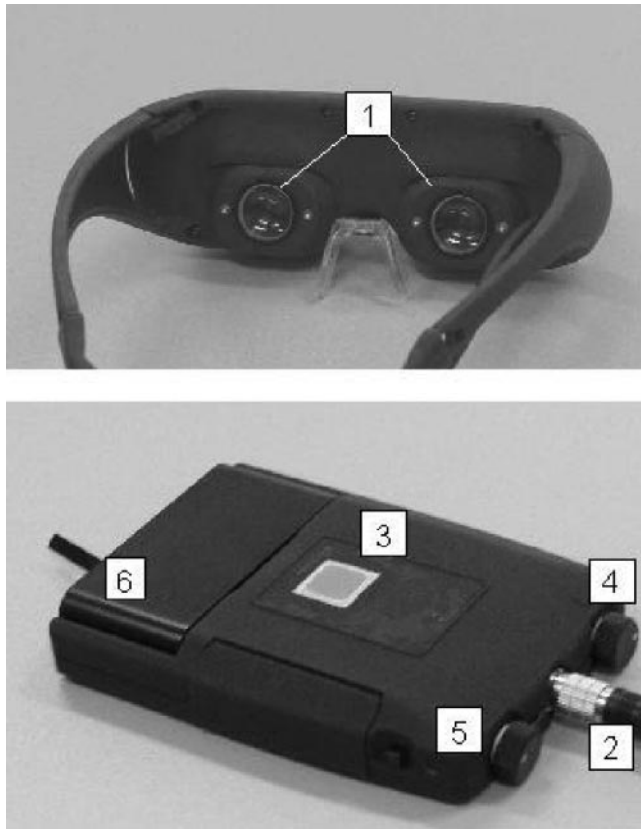


FIGURE 1. NVGs with attached power unit: (1) liquid crystal video (LCD) screens, (2) connecting cable, (3) push-button for power, (4) brightness control, (5) contrast control, and (6) rechargeable battery.

tion were conducted at the regional vision rehabilitation centers. Our study group ($n = 20$) consisted of 4 (20%) women and 16 (80%) men. All subjects had RP. Age distribution, visual acuity, visual field, and light sensitivities are presented in Table 1. One subject was an active cane user, but did not use his cane during the time of the research. Written informed consent was obtained from all subjects before the study and the Institutional Review Board of the University Hospital of Groningen approved the study protocol. The study was consistent with the principles outlined in the Declaration of Helsinki.

Night-Vision Goggles

Twenty Multi-Vision night-vision devices (Trivisio; Fig. 1), were available for the duration of the study. (Fifteen of the devices were borrowed from Trivisio and five were owned by the research laboratory.) The Multi-Vision system consists of goggles (122 g, $155 \times 50 \times 50$ mm) connected to a power unit (380 g, including battery, $155 \times 105 \times 25$ mm), a microcamera (sensitivity 0.015 lux) located at the center of the goggles that records images of the visual world (horizontal diameter 30°), and a connecting cable that transfers the signals to the power unit for signal processing. The black-and-white image is presented at an enhanced luminance level within the goggles to both eyes on two super video graphics array (SVGA) displays with 480,000-pixel color resolution (equals 1,440,000 pixels). Contrast and brightness can be manually adjusted on the power unit. If ambient light is insufficient, additional illumination can be achieved by switching on two built-in infrared-light sources. Pupil distance and nose position can be altered to align the images with both eyes. The accompanying rechargeable battery enables an operating time of up to 2 hours (~ 1.5 hours when the infrared light is switched on).

Routes

The two indoor laboratory walking routes consisted of a darkened corridor with floor-level illumination (at +20 cm) between 10^{-3} and 10^{-2} lux, and a route length of 36 meters. Ten artificial rectangular obstacles were placed along the route at different heights (foot, knee, shoulder, and head). The four outdoor walking routes (>0.5 hour after sunset) in the residential area each covered 330 meters and had floor-level illumination between 10^{-2} and 10^{-1} lux. The four routes at the outdoor shopping areas were 187 meters long and had illumination levels between 10^{-1} and 10 lux. The outdoor routes had comparable amounts of obstacles: curbs, public gardens, lampposts, and poles, for example.

Test Protocol

All subjects were consecutively invited to our laboratory in Groningen, twice during the dark winter season of 2002 to 2003. The first visit started with instructions on the use of the Multi-Vision. Then, the individual preferred walking speeds (PWSs) were assessed by measuring the walking speed of each participant three times along an unobstructed, straight path (17 m).⁹ This was followed by orientation and mobility tests first without and second with use of NVGs along the three dark walking routes (indoor corridor, outdoor residential area, and shopping area). Every test route differed and thus was unknown to the participant. An initial walking route with NVGs without scoring was performed before starting the first test. Furthermore, the order of routes randomly changed between subjects. During the test routes, subjects had to follow a predetermined route, of which we had measured the exact distance. To follow the route, subjects were instructed by the investigator to turn either to the right or left at the next crossing. This information was given long before a particular junction was reached, so the subjects had to find their own way.

All the subjects were lent a Multi-Vision to use during the 4 to 6 weeks between visits. They were requested to practice using the device in their own surroundings every evening and to register their experiences in a journal. The subjects also received weekly mobility instructions and feedback from a professional mobility trainer. After this training period, the subjects returned to Groningen for their second visit. There, the orientation and mobility tests were repeated and personal experiences discussed. All subjects were requested to fill out a questionnaire regarding their nighttime walking experiences at start and after the training period.

TABLE 1. Characteristics of 20 Night-Blind Subjects with Retinitis Pigmentosa

Variable	Minimum	Maximum	Mean \pm SD
Age	23	61	47.6 ± 11.52
Visual acuity OU*	0.09	1.0	0.53 ± 0.26
LogMAR	-1.05	0.00	-0.35 ± 0.29
Visual Field OU* (Goldmann III/4 ^c -diameter)	6°	45°	21.65 ± 10.46
Visual Field Score†	10	62	39.95 ± 14.53
Elevation of dark adaptation threshold (l.u.) compared to mean normal values (Goldmann-Weekers adaptometer)	1.6	> 5.0	3.1 ± 0.97

*OU, oculus unitas (both eyes).

†Visual field score according to Colenbrander et al.¹⁴ is designed to indicate the severity of consequences of field defects. It involves a count score of 100 points distributed on a visual field grid; 50 points are confined to the central 10° of the visual field and another 50 points are confined to the periphery up to 60° . The points are located along 10 meridians, two in each of the upper quadrants, three in each of the lower quadrants.

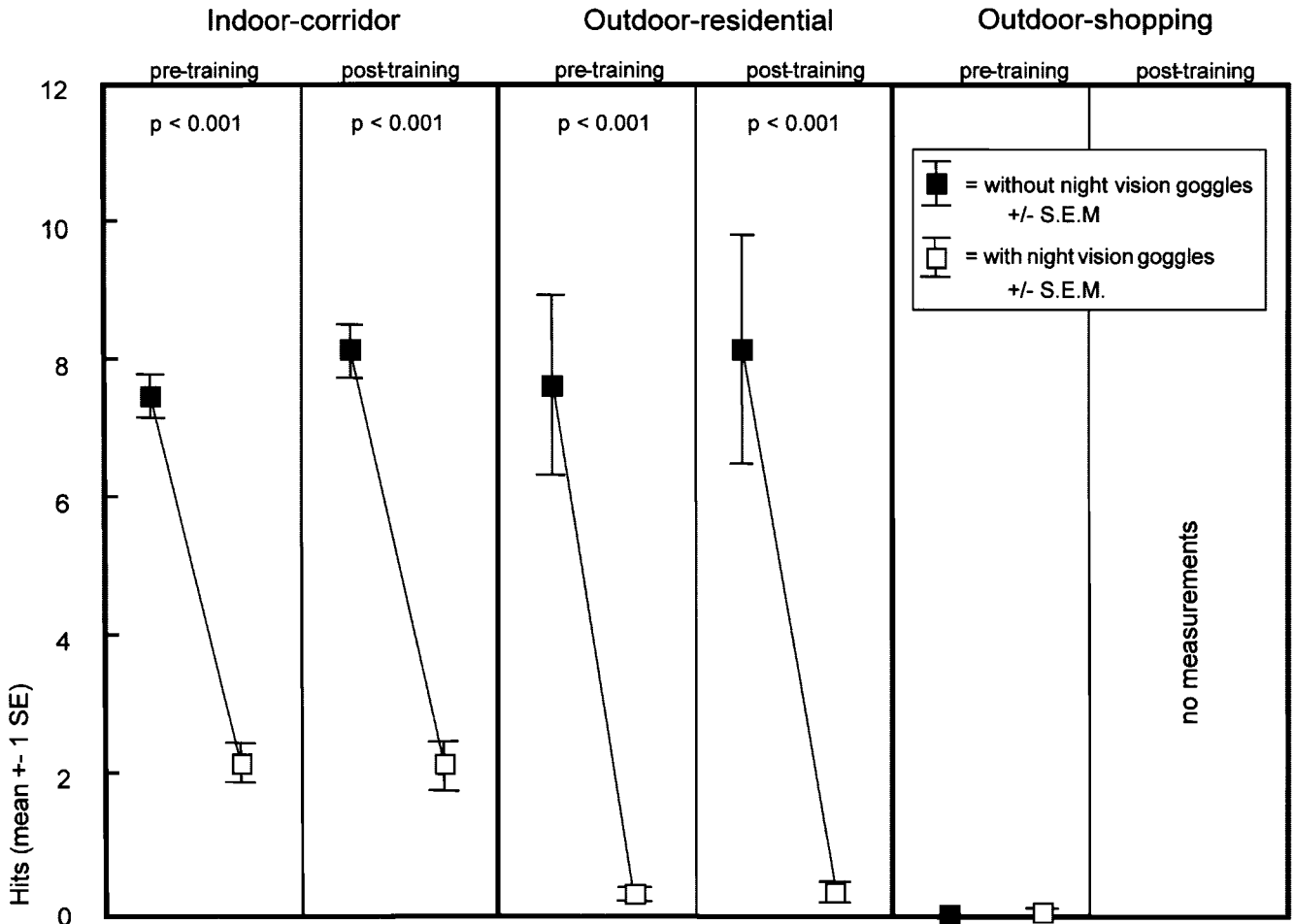


FIGURE 2. Number of obstacles hit. Indoor corridor: the mean of approximately eight hits decreased to two hits when NVGs were used. Outdoor residential area: mean of approximately eight hits decreased to almost zero when the goggles were used. Results at pre- and posttraining visits did not differ. Outdoor shopping area: practically no hits occurred without or with the use of the goggles.

Scores: Objective

Orientation and mobility performance along the routes was scored as hits and percentage of preferred walking speed (PPWS). Hits were scored as the number of unintended contacts with obstacles along the walking route (i.e., curbs, poles, garden fences, and public gardens). This score reflects the level of “risk” on a route.¹⁰ PWS assumes that subjects walk at their optimal walking speed when they do not have to worry about obstacles or dangerous conditions en route. Walking speed (meters per second) on a test route is calculated as the percentage of the preferred walking speed (PPWS) and is a measure of “walking efficiency.”¹¹ The number of unintended contacts with obstacles and the time to cover a route were recorded by the investigator. All data were collected and converted on computer (SPSS for Windows; SPSS Science, Chicago, IL).

Scores: Subjective

Questionnaires consist of 22 questions considering “specific problems with mobility,” “bumping into obstacles,” and “independent travel.” The experienced trouble on these items was scored with help of a 5-point Likert scale: 1, never; 2, sometimes; 3, regular; 4, often; and 5, always. Research by Turano et al.¹² has shown that a similar questionnaire is a valid way to measure perceived ability for independent mobility in persons with RP. However, this questionnaire has not been validated for the particular nighttime condition. Therefore, we will confine our results to a descriptive evaluation of median scores.

The journal consists of judgments about difficulty, recognition, orientation, and feelings of safety and tension after every daily walking-route with use of NVGs. Values on these items were scored by use of an appreciation scale form 1 (very low appreciation) to 10 (very high appreciation).

Statistics

The significance of the differences in PPWS and hits with and without NVGs was tested using the nonparametric Wilcoxon test at the 0.01 level. The relation between the ophthalmic features and the results was tested at the 0.01 level with the Spearman’s correlation test. Visual acuity was expressed as logarithm of the minimum angle of resolution (logMAR)¹³ for the analyses. Visual fields were calculated as the visual field score according to Colenbrander.¹⁴ (The visual field score replaces the Esterman grids and is proposed by Colenbrander,¹⁴ accepted by the International Council of Ophthalmology (<http://www.icoph.org/pdf/visualstandardsreport.pdf>), and included in the fifth edition of the *AMA Guides to the Evaluation of Permanent Impairments*.¹⁵ See also Table 1.)

RESULTS

Data on mean hit scores are presented in Figure 2. When NVGs were used, the mean number of hits decreased from eight to two ($P < 0.001$) in the indoor corridor and from eight to practically zero ($P < 0.001$) on the residential routes. Results of

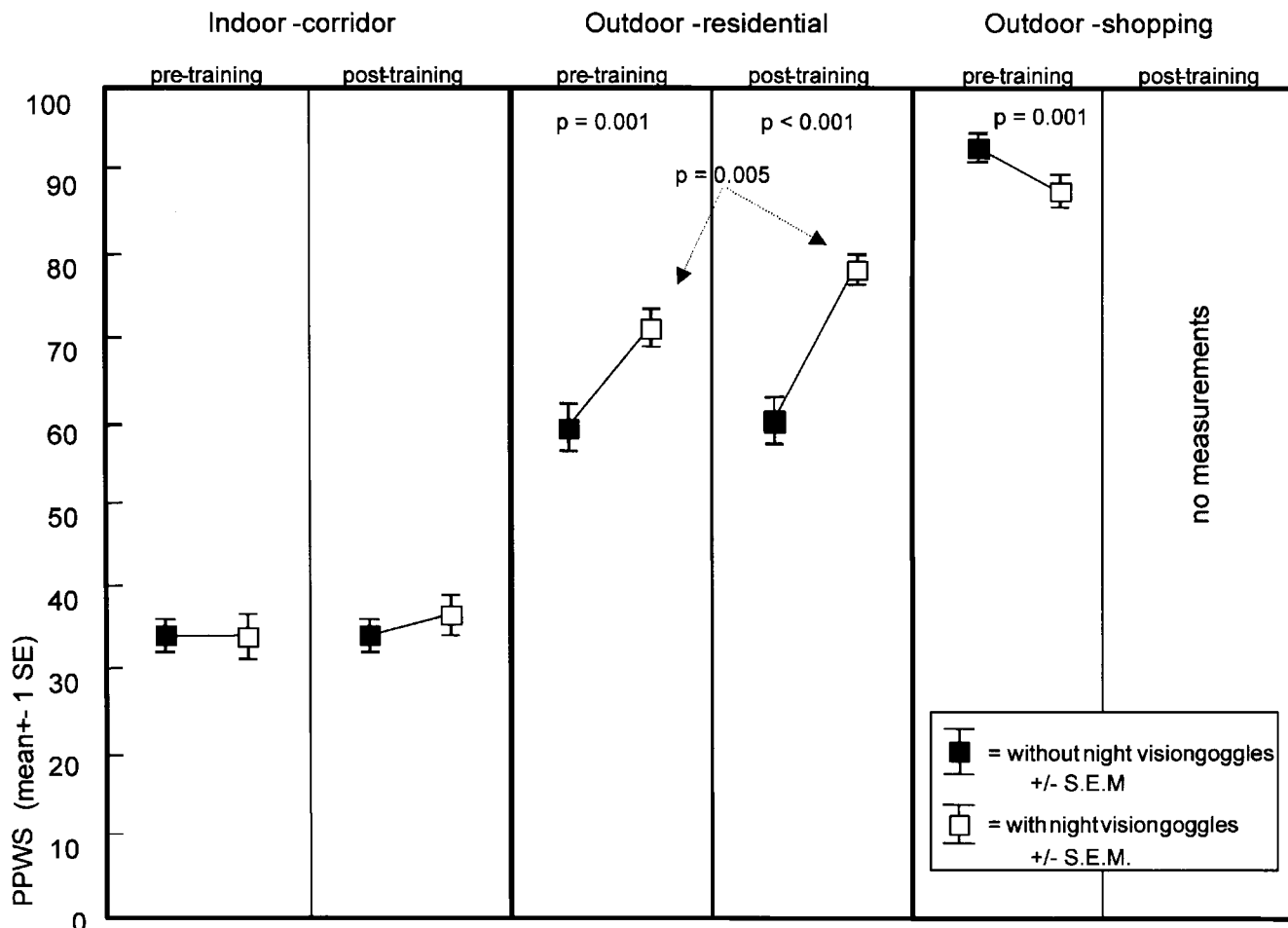


FIGURE 3. Percentage of PPWS. Indoor corridor: mean PPWS of 34% did not improve when NVGs were used. Outdoor residential area: mean PPWS of 60% increased to 72% when NVGs were used the first time and to 78% after training. Outdoor shopping area: mean PPWS of 93% decreased to 88% when the goggles were used.

these hit scores did not differ between the first and second visits. No hits occurred in the shopping area, whether or not NVGs were used.

Data on PPWS are illustrated in Figure 3. The mean PPWS was 1.48 m/s. Mean PPWS along the indoor corridor was 34% (0.51 m/s). This did not improve with use of NVGs at either the pre- or the posttraining visit. The PPWS along the residential routes was 60% (0.87 m/s), increasing to 72% (1.06 m/s; $P = 0.001$) when NVGs were used during the first visit, and 78% (1.16 m/s; $P < 0.001$) after training. PPWS without NVGs did not differ between the first and second visit. The mean rise in PPWS with use of NVGs after training was significant ($P = 0.005$). The PPWS at the shopping area was 93% (1.37 m/s), and slightly less (88%, 1.30 m/s) when the goggles were used.

The walking speed without NVGs in the shopping area at first visit was approximately normal and there were no hits on obstacles, which indicates that there was no impaired mobility due to vision problems. Because the goal of the study was to test the NVGs in situations in which vision is impaired, we decided not to perform tests in the shopping area during the second visit.

The increase in walking speed ($r = 0.572$) and for a great part the hit-score ($r = 0.54$) was related to the dark-adaptation thresholds but not to age, sex, visual acuity (logMAR), or visual field score (Table 2).

The subjective scores of data in the journals revealed a good sense of orientation, recognition, and feelings of safety

and tranquillity during mobility when the goggles were used. The scores increased until the third week of use (mean scores >9 on a scale of 1 to 10; Fig. 4) and then remained at that level.

Responses to the questionnaires also showed fewer problems with nighttime walking, changes in light conditions, and bumping into obstacles when the NVGs were used (Fig. 5). In addition, the subjects noted that they traveled independently more often at night from the time when they started wearing the goggles (change in response was from "traveling always with guidance" to "traveling sometimes with guidance"). Difficulties that were experienced using the Multi-Vision system were noted as "glittering light sources," "problems with distance estimation," and "a constricted field of view." The subjects indicated that adaptation was established within a period of 2 to 3 weeks. At the second visit, 17 (85%) of the subjects were positive and 3 (15%) negative about using the Multi-Vision.

DISCUSSION

In accordance with earlier studies,¹⁻³ we found that many night-blind individuals bumped into obstacles while they walked unaided in the dark. Not using vision aids is likely to increase the risk of incidents with resultant morbidity.¹⁶⁻²⁰ As expected, in our study night-blind subjects indicated a very low

TABLE 2. Relationship between the Results and Sex, Age, Visual Acuity, Visual Field, and Dark-Adaptation Threshold

	Hits without NVGs	Decrease in Hits with NVGs	PPWS without NVGs	Increase in PPWS with NVGs
Sex	-0.130	-0.120	-0.260	-0.260
Age	-0.077	-0.095	0.090	-0.432
LogMAR	-0.384	-0.421	0.099	-0.483*
Visual Field Score	-0.331	-0.289	0.440	0.073
Dark-adaptation threshold	0.549*	0.535*	-0.207	0.572†

Comparisons are by Spearman's nonparametric correlation test.

* $P < 0.05$.

† $P < 0.01$.

frequency of independent activities or travel under nighttime conditions. NVGs, developed for use by night-blind people, have been available for some time. However, very little research has been performed to assess their practical value. To provide more extensive information on NVGs with regard to mobility and a sense of independence, we collected both objective and subjective data from night-blind people after a prolonged use of the instrument under realistic outdoor conditions.

Using NVGs on the outdoor residential test route clearly improved orientation and mobility and was expressed as a decrease in hits and an increase in walking speed.

Results were already highly significant at the first visit and therefore were independent of mobility training. Most striking was the immediate change in obstacle avoidance by every subject, resulting in practically no contacts with curbs, poles, fences, or other obstacles. Use of the goggles therefore is considered to improve safety while walking, since the risk of

injuries or accidental falls caused by hits is likely to be reduced. At the second visit, walking speed and hit score without use of NVGs had not changed. However, with the use of NVGs, the general walking speed improved further after just a few weeks of practice, indicating an additional positive effect of training on mobility with NVGs.

At the start of the study, we did not know at which level of artificial streetlight vision would be sufficient for night-blind people. Our test showed the street-lighting levels at the shopping street (between 10^{-1} and 10 lux) were strong enough for "normal" mobility (no hits on obstacles and a normal walking speed). Also, our results showed no benefit from NVGs in this particular condition, which is in line with a recent evaluation study on NVGs by Bowers et al. (Bowers AR, et al. *IOVS* 2003,44:E-Abstract 2772).

The indoor corridor was the darkest of the three test conditions, and the walking speed there was extremely low. Because there was no improvement in walking speed when the goggles were used, the low walking speed was probably mostly due to the numerous artificial obstacles placed over the short distance. Binocular depth perception is not possible with the Multi-Vision, since both eyes receive an image from the same camera. This seemed to cause people to walk slowly in anticipation of reaching an object. This problem with distance estimation together with the intensive scanning needed to detect the obstacles, randomly placed at head and feet height, also is probably the reason that the hit score did not reach zero in the indoor corridor as it did in the outdoor environment. Furthermore, its field of view is rather small, which at the short distances existing under indoor conditions, limits the opportunities to anticipate obstacles along the route. We presume that an overview is achieved easier on outdoor streets with larger distances. In other words, the instrument is considered to be less effective under indoor conditions.

For the measurements in all conditions it should be noted the without NVGs route always proceeded the with NVGs route, which may have biased our test results in favor of the goggles. It would have been more correct if we had changed these conditions. Yet, we believe a great consequence from a learning effect is implausible, because all performed test routes were different and thus new to the participant. Also, an initial walking route without scoring with NVGs was performed before starting the first test, which is considered as the primary practice route. Furthermore, at the second visit, walking speed and hit score without use of NVGs had not changed, indicating no effect from learning.

The mainly positive subjective evaluations given by night-blind people after several weeks of intensive use imply that the instrument is not only effective, but is also appreciated in practical use. The questionnaires and journals also revealed more independent travel during the dark evening hours. This does not, however, mean that there is no room for improve-

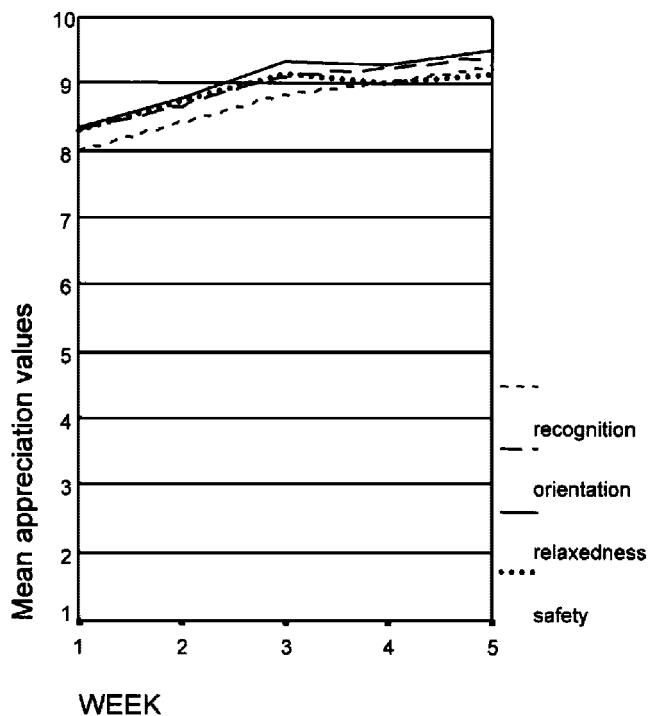


FIGURE 4. Mean scores per week as indicated in the subjects' journals for recognition, orientation, and feelings of tranquility and safety, while walking in the dark and using NVGs. Subjective appreciation of all four aspects ranged between 8 and 8.5 from the start of the training period and increased further until week 3 to more than 9. The scale is from 1 (low appreciation) to 10 (highest appreciation).

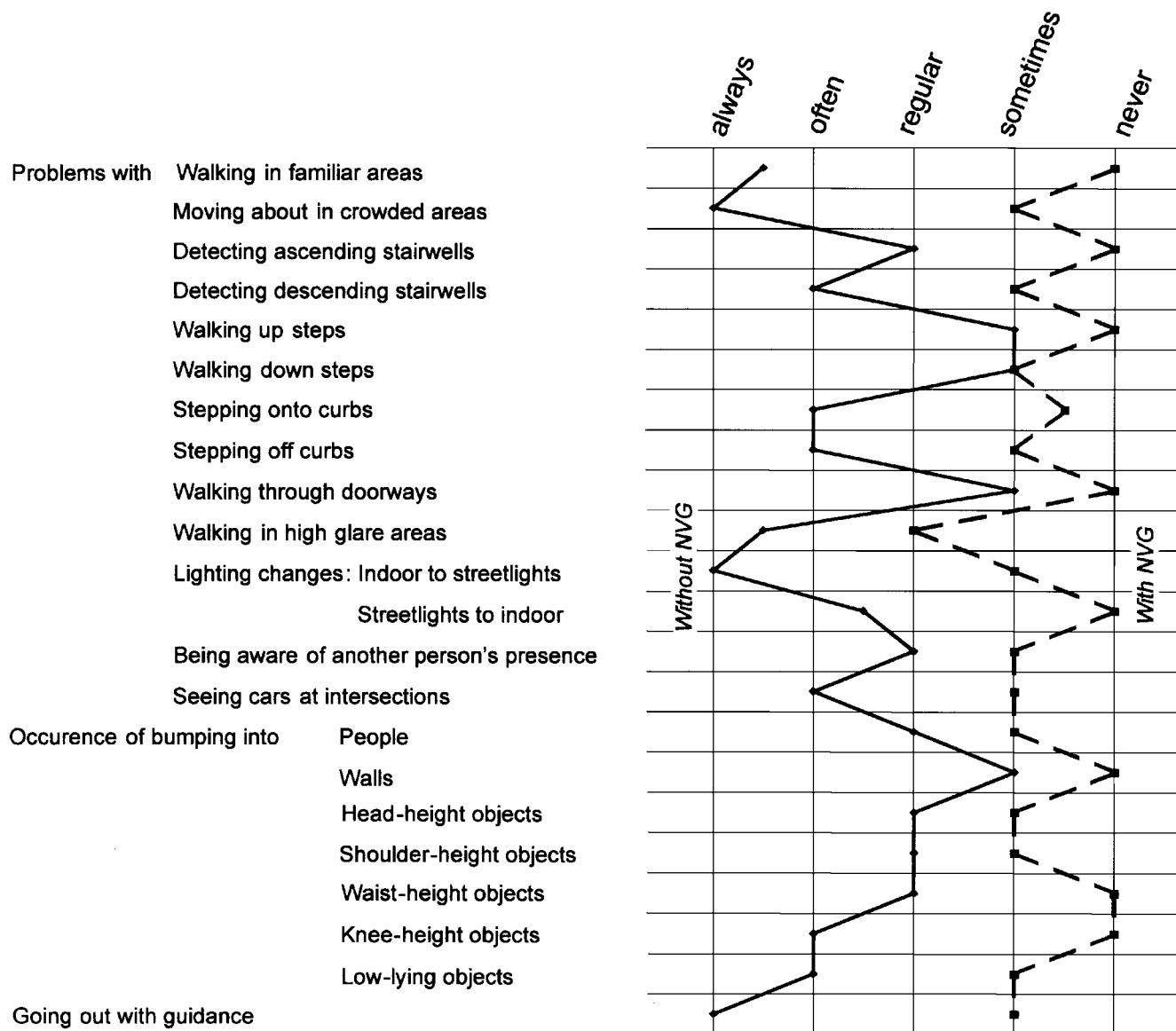


FIGURE 5. Median of answers to questionnaires regarding nighttime mobility without (solid line) and with (dashed line) NVGs.

ment. The most pronounced problem with the Multi-Vision involved experiences with light sources (e.g., car headlights, lit shop windows), which were perceived as unpleasant sparkling light spots within an otherwise intact view. Another frequently reported difficulty was the fact that no depth perception could be experienced using the instrument. Participants reported that they became accustomed to the two-dimensional view in many situations after several weeks of practice, but that this definitely did not apply to situations in which they had to estimate the distance to approaching cars. Some subjects also mentioned difficulties with the restricted visual field. Although these individuals already had constricted fields due to their disease, with use of NVGs, the perceived view can be increased only by head movement. Without the goggles, eye movements could accomplish this increase easier and faster. During mobility training, the participants were trained to enlarge their visual field by scanning the environment with systematic movements of the head. Experiences and the successful application of this scanning method, however, differed between the subjects. To increase comfort and facilitate utilization, future improvements to NVGs should include develop-

ment of a better automatic light-adapting system, the implementation of binocular vision, and the enlargement of the visual field.

Our study was designed primarily to indicate the potential effectiveness of NVGs. As we were restricted by the number of devices available and the limited period with dark evenings in the winter season, we could include only 20 participants. We selected participants with constricted central visual fields, because the study by Rohrschneider et al.⁸ showed a better outcome within this group. We cannot, therefore, make any statements regarding the potential benefits for night-blind people with normal visual fields (e.g., those with congenital stationary night blindness) or for people with impaired central visual fields.

This study found no relationship between the results (objective and subjective) and visual acuity, visual field, sex, or age. The only relationship found was that subjects with more impaired light-sensitivities had more hits while walking unaided and, therefore, showed a larger reduction in the number of hits plus a higher increase in walking speed when using the goggles. The subjective improvement in independent mobility,

however, did not differ between people with different levels of impairment.

Other available night-vision aids are the white cane and the wide-beam flashlight.⁶ A comparison between NVGs and these instruments can be interesting and might be a subject for future research. From our study results, we consider NVGs as an alternative vision aid that has also been proven effective.

In our opinion, a potential NVGs candidate is a night-blind subject who declares him- or herself unable to move safely and independently under dark conditions. These individuals should be given the opportunity to practice using the instrument for 2 to 3 weeks to assess individual benefit.

In conclusion, at dark, outdoor conditions in which night-blind subjects have been shown to have considerable mobility problems, the NVGs seemed to improve mobility by decreasing hitting of obstacles and increasing walking speed. Use of the goggles increased independent nighttime activities in our subjects and was generally positively evaluated for everyday outdoor use. In very well-lit outdoor environments as exists in shopping streets, luminance is sufficient for normal mobility, and NVGs were of no additional value. The instrument may be less effective in indoor environments in terms of gain in walking speed, though it decreased the number of hits on obstacles considerably.

References

1. Geruschat DR, Turano KA, Stahl JW. Traditional measures of mobility performance and retinitis pigmentosa. *Optom Vis Sci.* 1998;75:525-537.
2. 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.
3. Black A, Lovie-Kitchin JE, Woods RL. Mobility performance in retinitis pigmentosa. *Clin Exp Optom.* 1997;80:1-12.
4. Berson EL, Mehaffey L III, Rabin AR. A night vision device as an aid for patients with retinitis pigmentosa. *Arch Ophthalmol.* 1973;90:112-116.
5. Berson EL, Rabin AR, Mehaffey L III. Advances in night vision technology: a pocketscope for patients with retinitis pigmentosa. *Arch Ophthalmol.* 1973;90:427-431.
6. Morrisette DL, Marmor MF, Goodrich GL. An evaluation of night vision mobility aids. *Ophthalmology.* 1983;90:1226-1230.
7. Friedburg C, Sery L, Sharp LT, Trauzettel-Klosinski S, Zrenner E. Evaluation of night vision spectacles on patients with impaired night vision. *Graves Arch Clin Exp Ophthalmol.* 1999;237:125-136.
8. Rohrschneider K, Spandau U, Wechsler S, Blankenagel A. Utilization of a new night vision enhancement device (DAVIS) (in German). *Klin Monatsbl Augenheilkd.* 2000;217:88-93.
9. Soong GP, Lovie-Kitchin JE, Brown B. Preferred walking speed for assessment of mobility performance: sighted guide versus non-sighted guide techniques. *Clin Exp Optom.* 2000;83:279-282.
10. Marron JA, Bailey IL. Visual factors and orientation-mobility performance. *Am J Optom Physiol Opt.* 1982;59:413-426.
11. Clark-Carter DD, Heyes AD, Howarth CI. The efficiency and walking speed of visually impaired people. *Ergonomics.* 1986;29:779-789.
12. Turano KA, Geruschat DR, Stahl JW. Perceived visual ability for independent mobility in persons with retinitis pigmentosa. *Invest Ophthalmol Vis Sci.* 1999;40:865-877.
13. Bailey IL, Lovie JE. New design principles for visual acuity letter charts. *Am J Optom Physiol Opt.* 1976;53:740-745.
14. Colenbrander A. The functional vision score. In: Kooijman AC, Looijestijn PL, Welling JA, van der Wildt GJ, eds. *Low Vision: Research and New Developments in Rehabilitation.* Amsterdam: IOS Press; 1994:552-561.
15. *Guides to the Evaluation of Permanent Impairment.* 5th ed. Chicago: American Medical Association; 2000.
16. Ivers RQ, Cumming RG, Mitchell P. Visual impairment and falls in older adults: the Blue Mountains Eye Study. *J Am Geriatr Soc.* 1998;46:58-64.
17. Klein BE, Klein R, Lee KE. Performance-based and self-assessed measures of visual function as related to history of falls, hip fractures, and measured gait time. The Beaver Dam Eye Study. *Ophthalmology.* 1998;105:160-164.
18. Ivers RQ, Norton R, Cumming RG. Visual impairment and risk of hip fracture. *Am J Epidemiol.* 2000;152:633-639.
19. Ivers RQ, Cumming RG, Mitchell P. Visual risk factors for hip fracture in older people. *J Am Geriatr Soc.* 2003;51:356-363.
20. Klein BE, Moss SE, Klein R. Associations of visual function with physical outcomes and limitations 5 years later in an older population: the Beaver Dam eye study. *Ophthalmology.* 2003;110:644-650.