Vision Res. Vol. 32, No. 7, pp. 1367–1372, 1992
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0042-6989/92 $5.00 + 0.00

Research Note

Mobility Performance with a Pixelized Vision System

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Received 19 September 1991; in revised form 15 January 1992

A visual prosthesis, based on electrical stimulation of the visual cortex, has been suggested as a means for partially restoring functional vision in the blind. The prosthesis would create a pixelized visual sense consisting of punctate spots of light (phosphenes). The present study investigated the feasibility of achieving visually-guided mobility with such a visual sense. Psychophysical experiments were conducted on normally sighted human subjects, who were required to walk through a maze which included a series of obstacles, while their visual input was restricted to information from a pixelized vision simulator. Walking speed and number of body contacts with obstacles and walls were measured as a function of pixel number, pixel spacing, object minification, and field of view. The results indicate that a 25 × 25 array of pixels distributed within the foveal visual area could provide useful visually guided mobility in environments not requiring a high degree of pattern recognition.

Visual prosthesis   Mobility   Phosphene simulator

INTRODUCTION

Electrical stimulation of the visual cortex evokes a punctate sensation of light (a phosphene). When human visual cortex is stimulated by an array of surface electrodes, a pixelized visual sensation is created (Brindley & Lewin, 1968; Dobelle & Mladejovsky, 1974). The rate of information transfer via these patterns of phosphenes can be higher than that obtained with tactile methods, indicating that a phosphene based vision system could be useful for performing functional visual tasks (Dobelle, Mladejovsky & Evans, 1976; Dobelle, Mladejovsky & Girvin, 1974). However surface electrodes have not proven suitable for functional restoration of vision because of the limited number of phosphenes available and their non-contiguous distribution. Electrodes which penetrate into the cortex can evoke phosphenes at lower current intensities than surface electrodes (Bak, Girvin, Hambrecht, Kufta, Loeb & Schmidt, 1990; Bartlett & Doty, 1980), and could allow for more closely spaced phosphenes.

Based on these concepts, we are developing a cortical visual prosthesis to restore a limited but useful visual sense for the profoundly blind (Campbell, Jones, Huber, Horch & Normann, 1991; Normann, Campbell & Jones, 1989). The prosthesis is intended to provide visually-guided mobility: the ability to efficiently and safely navigate a purposeful course through a visually complex environment.

The visual sense created by this prosthesis will be limited in the number of phosphenes it can produce and their spacing (Normann, 1990). Nonetheless, we have shown that such a pixelized vision can provide good visual acuity (Cha, Horch & Normann, 1992a) and reading speeds (Cha, Horch, Normann & Boman, 1992b). Since these data are not sufficient for predicting mobility (Blasch & Apples, 1975), we have conducted psychophysical experiments specifically designed to evaluate mobility with a pixelized visual sense.

Several methods have been used to evaluate the usefulness of mobility aids for the visually disabled (Armstrong, 1975; Dodds, Carter & Howarth, 1983; Key, 1974). These methods use fixed patterns of test routes and obstacle positions, and therefore provide the opportunity for subjects to use memory when tested repeatedly. To avoid this problem, we have devised an indoor maze in which the test route and obstacle positions can be randomly varied for each trial.

Normally sighted human subjects wearing our pixelized vision simulator (Cha *et al.*, 1992a,b) walked through this maze. Walking speed and number of contacts with the obstacles and walls were measured to evaluate mobility performance as a function of pixel number, pixel spacing, object minification, and field of view.

The results demonstrated that a foveally projected visual sense consisting of 625 or more pixels with a field of view of about 30° allowed nearly normal walking speeds through the maze. The results could also be applied to the design of a mobility aid with a limited number of information channels (Bach-y-Rita, Collins, Saunders, White & Scadden, 1969; Collins, 1970).

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METHODS

Portable phosphene simulator

Pixelized vision was created by a portable simulator which optically emulated the pixelized visual sense expected to be produced by intracortical stimulation with a square array of evenly spaced electrodes. The simulator consisted of a small video camera, a miniature monochrome CRT monitor and optic lenses mounted on a pair of goggles. A perforated mask was placed over the monitor, creating an image consisting of discrete pixels, each of which appeared as a small (<2 min of arc), uniform spot of light. The only visual information available to subjects wearing the simulator was a monocular view of the television monitor. The angle the masked monitor screen subtended at the eye will be referred to the "image" size, while the area of visual space presented in the image, which was determined by the acceptance angle of the video camera and the size of the mask, will be referred to as the "field of view".

Two sets of perforated masks were used. "Fixed field" masks had a constant image size, 1.7°, and pixel spacing (the angular distance between neighboring pixels) varied with pixel number. "Fixed spacing" masks maintained a fixed, 0.053° pixel spacing, so image size decreased with decreasing pixel number. In addition, a "clear mask" with an image size of 1.7° was prepared as a control. External lenses adjusted the acceptance angle of the camera. A large acceptance angle gave a large field of view seen by the subjects, at the expense of greater minification of objects in the field of view. More details of the simulator are available elsewhere (Cha *et al.*, 1992a,b).

Four variables were studied: pixel number, pixel spacing, object minification, and field of view. The number of pixels ranged from 100 to 1024, and pixel spacing ranged from 0.053 to 0.17°. Field of view, calculated as the acceptance angle of the camera multiplied by the image size as projected to the eye, ranged from 2.0 to 45.5°. Object minification factors, calculated as the field of view divided by the image size, ranged from 3.82 to 26.75.

Mobility test course

An indoor maze was developed to allow repeated measures of mobility performance. An 8.4 × 7.0 m room was divided into 1.4 × 1.4 m square blocks with cloth screens as shown in Fig. 1. The pattern of open and closed screens set the route of the maze.

A cylindrical paper column obstacle, 5 cm in dia and 1.8 m in length, was suspended next to each screen. The position of the obstacle could be varied as shown by the arrows in the upper left corner of Fig. 1. Thus subjects walked through a maze with a series of randomly placed obstacles.

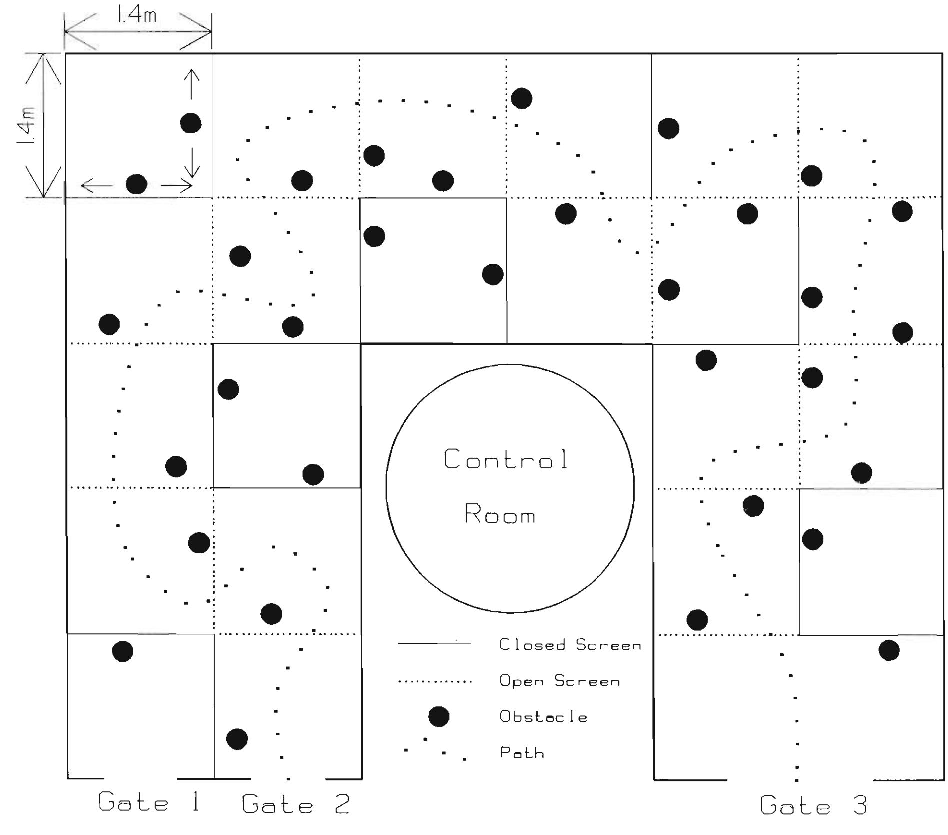

FIGURE 1. Indoor mobility course. The room was divided into 1.4 × 1.4 m square blocks with cloth screens. Dotted and solid lines indicate open and closed screens that create a particular path through the maze. Solid circles indicate suspended paper cylindrical obstacles, 5 cm in dia and 1.8 m in length, which could be moved to different positions in front of the screens as indicated by the arrows in the upper left corner of the figure. The course started at either gate 1 or gate 2 and ended at gate 3. The heavy dotted line indicates a pathway through the maze.

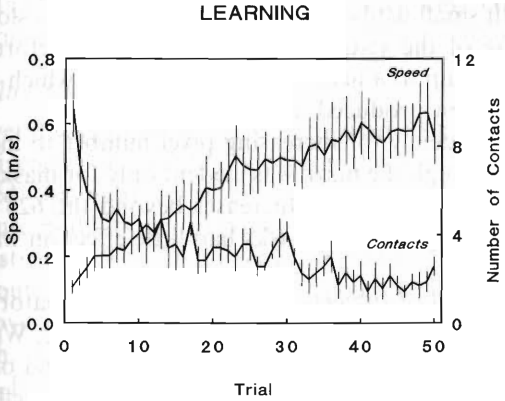

FIGURE 2. Learning curves. 7 subjects walked through the maze with a 32 × 32 pixel mask and a visual field of 13°. Walking speed and number of body contacts were measured for each trial. The solid lines indicate means of the 7 subjects' performance and vertical bars indicate standard errors.

The walls, screens, and floor were white, and the cylindrical obstacles were black. Three 2.5 cm wide black strips about 50 cm apart were placed horizontally on the walls and screens to provide a high contrast indicator of wall or screen location against the uniform white background. Black arrows on the walls and screens indicated the direction of the path through the maze. Overhead lighting provided nearly uniform luminance.

Psychophysical tests

Subjects were selected from the undergraduate student population at the University of Utah, and had an uncorrected visual acuity of 20/30 or better. Each subject participated in a 2 hr session per day, consisting of 8–10 trials.

For each trial, a maze was set randomly and the subject, wearing the simulator, walked through the maze as fast as he or she could while trying to avoid contacting the obstacles. The experimenter tracked the performance of the subject from the overhead control room. Total length of the maze was determined by multiplying the number of blocks by 1.4 m, the side dimension of a block. The average maze length was 24 ± 3 m, and contained 19 ± 2 obstacles. Travel time to traverse the maze and the number of body contacts with obstacles, walls, and screens were measured. Walking speed was determined by dividing the maze length by the travel time, and the number of body contacts was normalized to 19 obstacles.

Subjects were trained during the first 3 weeks to familiarize themselves with the pixelized visual sense and with the effects of minification (Demer, Porter, Goldberg, Jenkins, Schmidt & Ulrich, 1989). A 32 × 32 pixel mask was used with a camera acceptance angle giving a 13° visual field. Figure 2 shows average walking speed and number of contacts measured from 50 successive training trials with 7 subjects. About 40 trials were required before the average performance of the subjects was stabilized. After the subjects were trained, data were collected with 40 different experimental conditions.

Multivariate statistical analysis was performed on the pooled data from the 7 subjects using SPSS/PC+ (Norusis, 1990).

RESULTS

Data presented here are based on means from 5 trials per condition per subject for 7 subjects.

Walking speed and number of body contacts

During training, walking speed increased and number of contacts decreased with time (Fig. 2). Figure 3 illustrates the relationship ($r = -0.959$) between logarithm of walking speed and number of contacts after training in tests under different optical conditions. Thus either parameter may be used to evaluate mobility performance. We have chosen to use walking speed as our measure of mobility performance because it was more reliably determined than the somewhat subjective measurement of number of contacts with obstacles and walls.

Factors determining mobility performance

Field of view was increased by increasing camera acceptance angle and/or increasing image size. Changing the camera acceptance angle changed the minification ratio of the object: as camera angle increased, visual field size increased and the apparent size of objects decreased. Changing image size did not affect object minification: increasing the number of pixels with the fixed spacing masks increased the image size but not the apparent size of individual objects. Object minification also affected the number of pixels available to describe a given object: for a given pixel spacing, as the size of individual objects decreased, the number of pixels per object decreased.

Since the four variables that determined the visual conditions (number of pixels, pixel spacing, object minification and field of view) could not be varied independently of each other, we evaluated the data by using multivariate statistical analysis in the form of partial and multiple correlations. Walking speed and the number of body contacts were analyzed with respect to pixel number, pixel spacing, object minification factor,

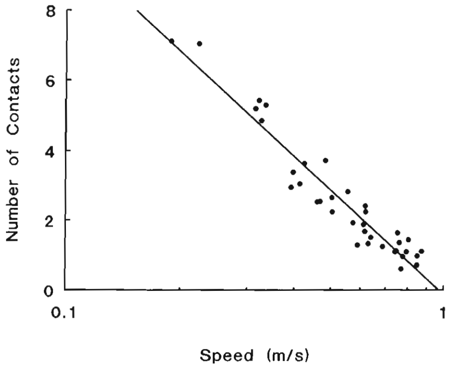

FIGURE 3. Number of contacts with walls or obstacles vs walking speed (plotted logarithmically). Walking speed was the average speed (7 subjects, 5 trials/subject) through the maze and the number of contacts were normalized with respect to 19 obstacles. The correlation coefficient (r) between these two variables was 0.941.

TABLE 1. Partial and multiple correlation coefficients between speed through the maze and number of pixels (NPXL), pixel spacing (SPXL), image minification factor (MIN) and size of the visual field (VF)

Speed	r
NPXL	0.436
SPXL	−0.177
MIN	0.468
VF	0.685
$(\mathrm{MIN})^2$	0.382
$(\mathrm{VF})^2$	0.545
log(NPXL)	0.654
log(SPXL)	−0.207
log(MIN)	0.538
log(VF)	0.791
NPXL + VF	0.756
NPXL + MIN	0.654
NPXL + log(VF)	0.851
log(NPXL) + VF	0.854
log(NPXL) + MIN	0.807
log(NPXL) + log(VF)	0.915

and size of the field of view. The results are summarized in Table 1.

Field of view size and number of pixels had higher correlations with performance than pixel spacing or object minification factor. The best single variable correlation with walking speed was the logarithm of the size of the field of view ($r = 0.791$). Combining the logarithms of field of view size and number of pixels produced a correlation coefficient of 0.915, accounting for 83.7% of the variance in walking speed.

Field of view and number of pixels

Figure 4 shows walking speed as a logarithmic function of the size of the field of view and number of pixels. Solid symbols show data from the fixed field masks, in which the image size of the mask was held constant at 1.7°, and pixel spacing increased as the number of pixels decreased. Data collected with fixed spacing masks are shown by open symbols. The plot is shown from two different view points for clarity.

With small fields of view, walking speed was slow. As the size of the visual field was increased, performance improved up to a field of view of 30°, after which object minification produced a decline in speed.

The tendency for increasing pixel number to increase speed through the maze was evident only for masks with low numbers of pixels. Increases beyond the 625 pixels present in the 25 × 25 masks had little effect on walking speed.

The speed of subjects not wearing the simulator while walking through the maze averaged 0.83 m/sec. Walking speed with a 25 × 25 pixel mask and a 30° field of view was near this value. This condition provides an effective visual acuity of 20/600 (Cha *et al.*, 1992a).

Regression analysis of the data shown in Fig. 4 gave the following relationship:

$$\mathrm{SPD} = 0.166 \cdot \log(\mathrm{NPXL}) + 0.345 \cdot \log(\mathrm{VF}) - 0.278,$$

where SPD = walking speed, NPXL = pixel number and VF = visual field.

The equation predicts walking speed with standard error of 0.078 m/sec, but does not predict the decline in performance due to object minification with large camera acceptance angles.

DISCUSSION

The present study investigated the feasibility of achieving visually-guided mobility with a visual prosthesis based on electrical stimulation of the visual cortex. The prosthesis would create a pixelized visual sense consisting of punctate spots of light (phosphenes) in the subject's visual space. Previous work by us and others has quantified how visual acuity and reading speed depend on number of pixels and pixel spacing relative to the size of the pixelized image (Cha *et al.*, 1992a,b; Hemingway & Erickson, 1969; Legge, Pelli, Rubin & Schleske, 1985). Here we considered these variables and the size of the field of view in relation to the task of

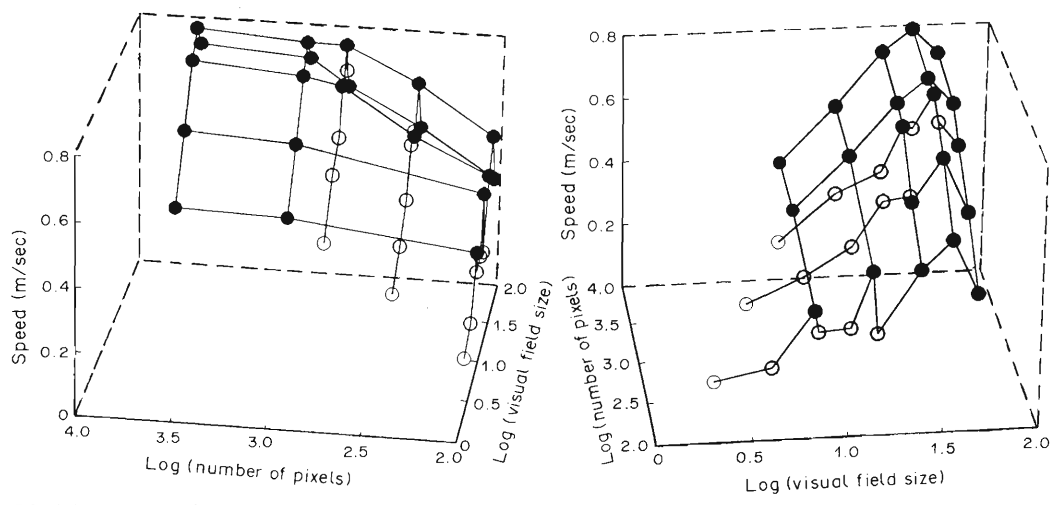

FIGURE 4. Mobility performance. Walking speed through the maze is plotted as a logarithmic function of number of pixels (100–4096) and field of view (2.0–45.5°). Solid symbols show data from fixed field masks, and open symbols show data from fixed spacing masks. Lines connect points with constant number of pixels or constant field sizes. Each point is the mean from 7 subjects, 5 trials/subject. The plot is shown from two different angles of view to facilitate visualization of the effects of each of the two independent variables.

orientation and navigation through a visually complex environment.

Mobility test course

Several test methods have been used to evaluate the effectiveness of mobility aids for the visually handicapped. An outdoor mobility route has been used to measure mobility performance in real-life environments (Armstrong, 1975; Dodds *et al.*, 1983) and an artificial test route consisting of a series of poles has been used to improve the objectivity of measures (Brown, Brabyn, Welch, Haegerstrom-Portnoy & Colenbrander, 1986; Key, 1974). These methods used a fixed test route, making them unsuitable for repeated tests on the same subject. In contrast, the method used in the present study varied path as well as obstacle position for each trial, allowing us to measure performance repeatedly on a course with essentially a constant degree of difficulty.

Learning

Learning played an important role in mobility skill with the simulator. During the short period of training, walking speed increased 5-fold as the subjects learned how to deal with small, highly minified visual images and how to use head movements efficiently.

Two important characteristics of visual images produced by the simulator are pixelization and minification. As the visual field was expanded optically, visual objects were minified by a factor of 3.8 or more. The minified objects made untrained subjects feel uncomfortable because of loss of depth perception. The subjects hardly moved during the first trial, and so were encouraged to grasp the obstacles along the maze as part of a familiarization trial. This allowed them to develop depth perception by getting familiar with the relation between apparent and real sizes of objects at arm's length.

Head movements also helped depth perception. The image displacement produced by voluntary head movement provided information about how far the obstacles were from the viewing position. Efficient head movement also provided additional advantages by expanding the effective visual field and by improving visual acuity (Cha *et al.*, 1992a, b).

Once subjects were familiar with the environment, they could perform well if the field of view was sufficiently large. The subjects seemed to use the simulator as an obstacle detector, so they were able to get around comfortably in a familiar environment that did not require pattern recognition.

The importance of familiarity with the surroundings for mobility was confirmed in informal outdoor experiments we conducted with the trained subjects after the indoor tests were completed. The outdoor test course was a typical residential area containing trees, lamp posts, walkways and stairs. The subjects were tested with a 25 × 25 pixel mask and a 30° visual field. Subjects familiar with the route could walk along it at normal walking speeds; however subjects unfamiliar with the area often had problems in orientation. Perceptual anticipation based on past experience has been shown to be important in this context (Barth & Foulke, 1979). Once subjects became familiar with their surroundings, they could navigate with greater confidence using the simulator.

Visual factors determining mobility

Important factors contributing to mobility include visual field size, contrast sensitivity, and visual acuity (Marron & Bailey, 1982). The visual sense created by an intracortical visual prosthesis is expected to provide good visual acuity (Cha *et al.*, 1992a) but only a small visual field (Dobelle, Turkel, Henderson & Evans, 1979). Restricted visual fields would seriously restrict mobility (Brown *et al.*, 1986; Fonda, 1981; Pelli, 1987; Pelli & Serio, 1984).

To overcome the problem of restricted visual field size, two strategies were used in this experiment: (1) field expansion by increasing camera acceptance angle and (2) head movements. A field expander can help mobility by increasing the field of view (Hoeft, Feinbloom, Brilliant, Gordon, Hollander, Newman, Novak, Rosenthal & Voss, 1985; Holm, 1970; Kozlowski, Mainster & Avila, 1984), at the cost of reduced acuity as objects in the visual field are minified. Figure 4 shows that mobility improved as the visual field was expanded until a point was reached where the minification factor exceeded 18.

Below this limit, however, visual acuity did not seem to play an important role in walking speed through the maze. This is evident from Table 1, where pixel spacing, the primary determinant of acuity, showed only a very weak correlation with walking speed.

Head movements improve spatial resolution (Cha *et al.*, 1992a) and are very important in reading (Cha *et al.*, 1992b). In the present study, head movements clearly improved mobility performance. However inefficient head movements caused loss of body balance. Low vision patients using telescopic spectacles have problems in vestibulo–ocular reflex because of the magnification of images (Demer *et al.*, 1989). Early during the learning period, subjects in the present study may have lost their balance due to inappropriate vestibulo–ocular reflexes caused by the effects of minification.

Although contrast sensitivity is a significant factor in mobility (Marron & Bailey, 1982), the brightness of individual phosphenes can be modulated by stimulation current (Brindley & Lewin, 1968; Dobelle & Mladejovsky, 1974), so we held this factor constant by using a high contrast display.

CONCLUSIONS

A visual prosthesis for the blind should provide the user with an acceptable level of visually guided mobility. Our psychophysical experiments indicate that a 25 × 25 pixel array with 30° of visual field could provide good obstacle avoidance and a sense of confidence to patients in familiar environments. Current microelectrode fabrication technology could develop such a visual cortical prosthesis (BeMent, Wise, Anderson, Najafi & Drake, 1986; Campbell *et al.*, 1991; Najafi & Wise, 1986;

Normann *et al.*, 1989), which could then be placed in a single gyrus of the primary visual cortex in man (Normann, 1990).

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Acknowledgement—This project was supported by the W. M. Keck Foundation.