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34(5):358–365, Wiley Periodicals, Inc.

Estimation of Phosphene Spatial Variability for Visual Prosthesis Applications

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Abstract: Visual prostheses are the focus of intensive research efforts to restore some measure of useful vision to blind or near-blind patients. The development of such technology is being guided to an extent by tools that simulate prosthesis behavior for healthy sighted subjects in order to assess system requirements and configurations. These simulators, however, typically assume purely deterministic phosphene properties and thus do not apply any variability to phosphene size, intensity, or location. We address this issue by presenting data on phosphene variability measured in a blind human subject fitted with an optic nerve prosthesis. In order to correct for normal limitations in human-pointing accuracy, the experimental conditions were repeated with sighted subjects. We conclude that identical optic nerve stimulations can result in phosphenes whose perceived locations vary by up to 5° of deviation angle and 10° of position angle. The consistency of phosphenes presented in the peripheral field of view can vary by an additional 3°. **Key Words:** Computer simulation—Optic nerve—Phosphenes—Prostheses and implants.

Visual prostheses are devices that restore visual sensation to blind or vision-impaired subjects by electrically stimulating functional tissue in the visual pathway. The potential for such technology was first suggested by Brindley, who observed that electrical stimuli in the visual cortex of blind subjects produced sensations of small, well-localized light flashes termed "phosphenes" (1). At present, investigators are assessing the viability of visual prostheses that electrically stimulate cells in the retina (2–5), the optic nerve (6,7), and in the visual cortex (8,9). In all cases, the objective is to convert real-time images from a subject-mounted camera into patterns of phosphenes that can be interpreted and recognized by the subject. These efforts have yielded successful elementary systems that have allowed blind or visually impaired retinitis pigmentosa (RP) patients to locate objects, track movement, and determine object orientation, albeit under tightly controlled experimental condition (2,4,10). Ongoing research seeks to make these devices more functionally practical in subjects' day-to-day lives.

Recent research in visual prosthetics has been focused on improving both instrumentation and surgical implantation techniques (11,12). As investigators continue to tackle various technical issues (such as electrode impedance, electrode spatial density, biocompatibility, and chronic stability), a parallel development pathway is being pursued that identifies optimal algorithms for converting real-time visual information into electrical stimuli. This has been achieved by developing virtual reality (VR)-based models that simulate the psychophysical interaction between the visual prosthesis and the implanted volunteer. These models potentially allow healthy sighted subjects to evaluate different stimulation algorithms and electrode configurations, reducing the need to work directly with blind subjects.

Investigators have used images masked by circular grids to determine the number, density, and size of phosphenes that would be necessary in a putative visual prosthesis for restoring certain measures of mobility, facial recognition, object recognition, and word recognition (13–18). More recently, such models have been used to quantify saccade and

doi:10.1111/j.1525-1594.2009.00878.x

Received September 2008; revised June 2009.
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pursuit performance (19), as well as to determine the extent to which subjects can enhance their visual prosthesis performance through training (20). One limitation of these models is that they assume idealized virtual phosphenes; the visual stimuli are purely deterministic with respect to size, shape, location, color, and persistence. However, phosphene reproducibility in visual prosthetics remains poorly understood, and neglecting its effects in designing VR models will limit their utility. Quantitative measures of phosphene variability have not been widely reported in the literature. Rizzo et al. found that subjects presented with pairs of identical stimuli reported "similar" phosphenes in 66% of trials (21). Furthermore, phosphene reproducibility may be affected by how closely stimuli are spaced together in time (22).

One possible factor in the apparent variation of phosphene positions observed in visual prosthesis patients may be pointing errors. A typical scenario requires the visual prosthesis patient to point to the perceived location of small phosphenes (typical diameter <10°) that appear in the visual field for a fraction of a second (23). The imprecision inherent in pointing to the location of a small, dim, brief flash of light may cause errors that are misinterpreted as true variations of apparent phosphene positions. In designing high fidelity VR visual prosthesis models, it will be important to incorporate an accurate estimate of phosphene position variability that is not biased by pointing errors.

The goal of the present work is to quantify the extent to which variations in reported phosphene locations can be attributed merely to pointing inaccuracies. This was achieved by comparing pointing errors exhibited by sighted subjects with the variations in phosphene locations reported by a blind subject with a chronically implanted optic nerve visual prosthesis.

METHODS

The present study with sighted subjects was designed to replicate the experimental conditions that were previously used to test a blind volunteer with a chronically implanted optic nerve visual prosthesis (7,23). All volunteers freely gave their consent after being fully informed, and were free to withdraw at any time. This study adhered to the Declaration of Helsinki and was approved by the Ethics Committee of the School of Medicine and University Hospital of the Université Catholique de Louvain.

Blind subject

The blind subject was a female RP patient who was left with only light sensation by age 40 and was totally blind by age 57 (23). She was implanted with the visual prosthesis in 1998 at age 59, and the data used in the present study were acquired from her between March 1998 and February 1999. The prosthesis consisted of an intracranially implanted four-contact self-sizing spiral cuff electrode wrapped around the optic nerve of her right eye. Details of the stimulation device and the implantation surgery are available elsewhere (6,23). Electrical stimuli were controlled externally via a radio frequency link and charge density was kept below 150 $\mu C/cm^2$ through electrodes of contact area 0.2 mm^2. Individual stimuli were trains of up to 17 charge-balanced pulses at frequencies of 10–320 Hz. All pulse widths and amplitudes in a given train were identical; pulse widths ranged from 21 to 400 μs with maximum amplitude 3.8 mA. Stimuli could be delivered in either a unipolar (between electrode and ground) or bipolar (between two electrodes) configuration.

The subject was seated facing into a Plexiglas pointing hemisphere of radius 45 cm (see Fig. 1). Head position was maintained via a chinrest such that the subject's right eye (the implanted one) was at

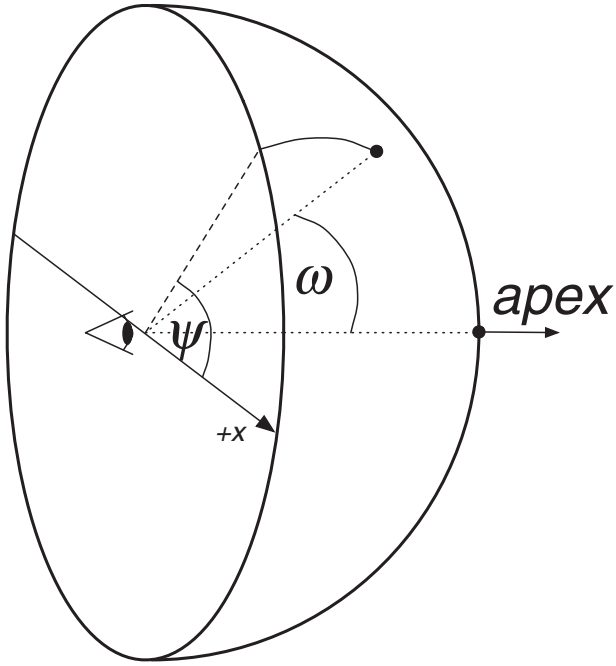

FIG. 1. Pointing hemisphere and coordinate system. Subjects' right eyes were placed at the center of the hemisphere and the subjects were told to fixate on the apex. Locations on the hemisphere were recorded as deviation (ω—the angle to the apex) and position angle (ψ—angle in the *x*–*y* plane, relative to the positive *x*-axis).

the center of the hemisphere. The subject placed her left finger on a tactile marker located at the hemisphere's apex and was told to fixate her gaze to that same location. Her right eye was monitored via camera, and trials in which her gaze deviated from the apex were discarded.

For each stimulus presentation, the subject described the location, brightness, and composition of any resulting phosphene. She communicated phosphene size and location by drawing on the hemisphere with her right index finger; these motions were transcribed onto paper by the experimenter and were later digitized. Subjective brightness was rated on a scale from 1 (very very weak) to 9 (very very strong) (23).

Data records were selected in which given electrical stimuli had been delivered to the volunteer on at least three separate occasions. Stimuli were only considered if the range of subjective brightness values from the individual stimulations was less than or equal to three units on the 1-to-9 scale. This eliminated outliers that may have been contaminated by the presence of spontaneous phosphenes.

Sighted subjects

For comparison, a control group of sighted subjects was tested in a similar experimental setup to that of the blind subject. The group consisted of 14 sighted right-handed subjects (six males aged 35.8 ± 17.2 years; eight females aged 38 ± 12.6 years). All subjects were healthy and had vision that was either normal or correctable thereto.

Subjects were seated comfortably in a dark room facing into a clear plastic hemisphere identical to that used with the blind subject. As with the blind subject, head position was maintained via a chinrest such that the right eye was at the center of the hemisphere. A semitranslucent screen was placed immediately behind the hemisphere. Virtual phosphenes (see "Virtual phosphene characteristics" section) were beamed onto the back of this screen by an LCD projector and were therefore also visible to the volunteer, who faced the front of the screen through the hemisphere. The projector produced a small amount of residual background light (1.06 cd/m^2) even when projecting a pure black screen. The hemisphere was unmarked with the exception of several small registration points that were used to calibrate the system. Subjects were able to see these dimly lit marks as well as the hemisphere itself due to the background light emitted by the LCD projector; virtual phosphenes were not projected near these marks. Subjects indicated phosphene locations using a commercially available position-tracking device (IsotrakII, Polhemus, Inc., Colchester, VT, USA) consisting of a reference position box and a handheld stylus with a push-button switch. Phosphene locations were indicated by touching the stylus to the hemisphere and pressing the push button in a single motion. The deviation and position angles were recorded, with a hardware resolution of 0.36°. The change in method for transcribing observed phosphene locations between the blind and sighted subjects was in order to automate and accelerate the experimental protocol and is not expected to affect precision. The entire system was calibrated immediately prior to each session by projecting two different alignment templates onto the screen and adjusting the hemisphere accordingly to align its registration points.

Subjects were dark adapted for 20 min immediately prior to beginning the experiment. After this period, the left eye was covered with a patch of gauze that remained in place for the duration of the experiment. Subjects used their right eyes for all trials.

Virtual phosphene characteristics

The virtual phosphenes were small, well-localized flashes of light that were varied according to location and brightness. All phosphenes were white circles of diameter 3° projected onto the screen for 16.7 ms (i.e., one period of the projector frame rate of 60 Hz). The software warped the phosphene shapes such that all virtual phosphenes appeared to the subjects as circles of diameter 3° regardless of their location in the visual field; the degree of warping was a function of phosphene deviation angle. Phosphene brightness levels were set to be one, two, four, or eight times the perception threshold, which was determined individually for each subject. There were 105 virtual phosphene locations, each repeated four times (by brightness level) for a total of 420 (see Table 1). Based on the luminance measurements, contrast across the four brightness settings ranged from 10.2 to 61.3%.

TABLE 1. *Virtual phosphene locations*

Deviation angle (ω)		Position angle (ψ)		Total
0°		0°		1
7°	12°	5°, 35°, 65°	+ n·90°	24
17°	22°	5°, 35°, 50°, 65°	+ n·90°	32
27°	32°	5°, 20°, 35°, 50°, 65°, 80°	+ n·90°	48
Total				105

Note: $n = 0, 1, 2, 3$. Phosphene positions were offset from common circle landmarks (i.e., position angle = 0°, 180°) to avoid the registration points drawn on the hemisphere. Each of these 105 virtual phosphenes was presented at four different brightness levels to each of the sighted subjects.

TABLE 2. *Pointing precision in the blind subject*

	Central stimuli		Peripheral stimuli	
	Bright	Dim	Bright	Dim
n. Trials	743	321	355	36
σ—Deviation (ω)	6.06	5.70	10.58	10.34
σ—Position angle (ψ)	8.41	10.11	12.24	10.96
ρ	–0.304	0.067	–0.532	0.060

Phosphenes were grouped according to median perceived location of each stimulus (based on deviation angle) and brightness (based on subjective 1–9 scale rated by patient). Central: $\omega \leq 20°$; Peripheral: $\omega > 20°$; Bright: (score > 3); Dim: (score ≤ 3). Spatial distributions of user-indicated phosphene locations were fitted to bivariate normal distributions along the deviation and position angle axes. The table indicates the measured standard deviation (σ) along each axis, as well as the correlation (ρ). The n. Trials measurement indicates the total number of stimuli detected by the subject in each category.

Sighted subject protocol

Subjects were instructed to keep their right eyes trained on a hemisphere marker located at the hemisphere's apex. The virtual phosphenes were presented in a different pseudorandom order for each subject, with a 3-min break taken after every 105 stimuli. Each stimulus (i.e., each virtual phosphene presentation) began with a randomized delay (between 1.5 and 2.5 s) followed by the virtual phosphene presentation. Subjects were told to respond as quickly and as accurately as possible by touching the position-tracking stylus onto the hemisphere and pressing the push button. Trials in which the phosphene went undetected after 4 s were considered as absent perception and were not included in the data analysis.

Coordinate system

Positions on the hemisphere were recorded using the spherical coordinate system shown in Fig. 1. Deviation (ω) measures the angle to the apex, whereas position angle (ψ) measures the angle in the *x–y* plane, relative to the positive *x*-axis. A detailed review of coordinate systems for vision research is presented by Bishop et al. (24).

RESULTS

The data from the sighted and blind subjects were compared by classifying all stimuli into one of four categories: bright/central, dim/central, bright/peripheral, and dim/peripheral. Central phosphenes were defined to be those with deviation angle $\omega \leq 20°$; peripheral phosphenes had $\omega > 20°$. For the blind volunteer, dim phosphenes were defined to be those that were scored as less than or equal to three on her subjective 1-to-9 scale. For sighted volunteers, dim phosphenes were defined to be those at brightness levels of 1x or 2x of the perception threshold.

The results were quantified using the precision metric, which measures the spatial distribution of a group of pointing positions around their mean. This was achieved by fitting a bivariate normal distribution to the data along the position angle and deviation axes, which are orthogonal. This procedure is similar to the method of using fitted ellipses to quantify the data (25). All trials from each of the four brightness/deviation angle categories were pooled to compute the respective precision metrics. In fitting these distributions, the position angle data were scaled by the sine of the corresponding deviation angle in order to normalize the position angle and deviation angle data to the same scale.

Blind subject

Trials with the blind subject yielded 214 unique stimuli, each repeated between three and 34 times. Trials in which the subject did not see phosphenes were not included in the analysis. The precision metrics for these stimuli are summarized in Table 2 and Fig. 2. The subject's responses to the repeated stimuli tended to be more tightly clustered for Central phosphenes than for Peripheral ones by an average of 3.4° in both the deviation and position angle directions. Conversely, there was little difference between Bright and Dim stimuli. In all cases, responses tended to be more closely clustered along the deviation axis versus the position angle axis by an average of approximately 2°. Whereas a moderate negative correlation between the deviation and position angle axes was observed for Bright phosphenes, no such correlation was seen for the Dim stimuli. Note that there were only nine unique stimuli in the Peripheral/Dim category for a total of just 36 trials.

Sighted subjects

Each of the 14 subjects was presented with 420 pseudorandomized white phosphenes. Phosphene

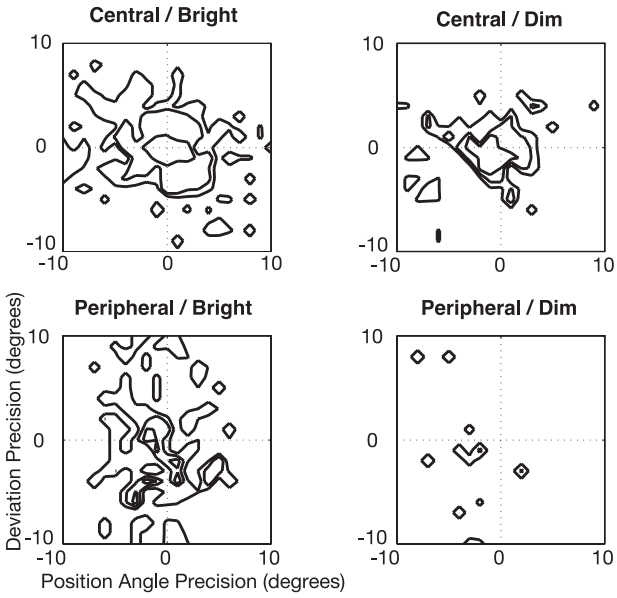

FIG. 2. Pointing distributions for the blind subject, grouped by Bright/Central, Dim/Central, Bright/Peripheral, and Dim/Peripheral. In each case, the mean pointing position is at the origin, and the three concentric contours enclose 25, 50, and 75% of the data.

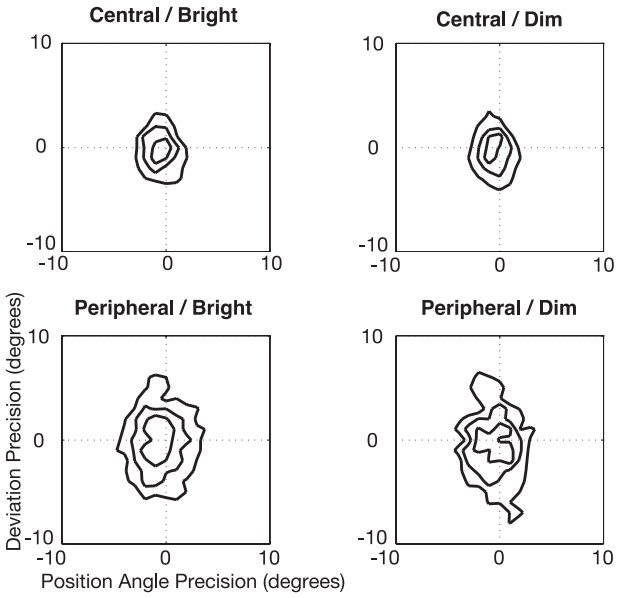

FIG. 3. Pointing distributions for sighted subjects, grouped by Bright/Central, Dim/Central, Bright/Peripheral, and Dim/Peripheral. In each case, the mean pointing position is at the origin, and the three concentric contours enclose 25, 50, and 75% of the data.

detection rates ranged from 96% for Central/Bright phosphenes to 33% for Peripheral/Dim ones. As the location of the pointing targets (i.e., the phosphenes) was precisely known, it was possible to calculate the observed pointing accuracy, defined as the angle between the mean pointing location and the target location. This metric ranged from 0.8° for Central/Dim phosphenes up to 2.6° for Peripheral/Bright phosphenes. Accuracy was found to decrease approximately in proportion to deviation angle, with a mean slope of approximately 0.07° per degree of deviation angle.

Precision data from the sighted subjects are shown in Table 3 and Fig. 3. Responses to Central phosphenes tended to be equally distributed along the position angle and deviation axes, with an average standard deviation of 2.0°. Responses to Peripheral stimuli tended to be more closely clustered along the position angle axis than the deviation axis by an average of 1.1°. In all cases, there was a negligible negative correlation between the two axes.

Pointing precision—sighted versus blind

In order to unbias the blind subject's phosphene precision data, we sought to subtract the precision of the sighted subjects from that of the blind subject. Because the data for the blind and sighted subjects have been modeled by bivariate Gaussian distribu-

TABLE 3. *Pointing precision in sighted subjects*

	Central stimuli		Peripheral stimuli	
	Bright	Dim	Bright	Dim
n. Trials	1101	721	1679	576
σ—Deviation (ω)	2.00	2.29	3.55	3.69
σ—Position angle (ψ)	1.62	2.27	2.45	2.51
ρ	–0.036	–0.119	–0.040	–0.037

Phosphenes are grouped according to stimulus location (based on deviation angle) and brightness (set as a multiple of each subject's perception threshold). Central: $\omega \leq 20°$; Peripheral: $\omega > 20°$; Bright: (4× and 8× threshold); Dim: (1× and 2× threshold). Spatial distributions of user-indicated phosphene locations were fitted to bivariate normal distributions along the deviation and position angle axes. The table indicates the measured standard deviation (σ) along each axis, as well as the correlation (ρ). The n. Trials measurement indicates the total number of stimuli detected by the subject in each category.

TABLE 4. *Difference of pointing precisions between sighted and blind subjects, computed as the square root of the difference of the squares of the σ values from Tables 2 and 3*

	Central stimuli		Peripheral stimuli	
	Bright	Dim	Bright	Dim
σ—Deviation (ω)	5.72	5.22	9.97	9.66
σ—Position angle (ψ)	8.25	9.86	11.99	10.67

tions, it is possible to simply subtract the variances along the position angle and deviation axes. These data are shown in Table 4 and represent an upper bound on that portion of the blind subject's phosphene variability that cannot be explained by normal human-pointing inaccuracies. A comparison of Tables 2 and 4 reveals that normal pointing inaccuracies can only account for approximately 0.5° of the variability observed in the blind subject.

DISCUSSION

The purpose of this work is twofold. First, we have presented (for the first time) statistics that quantify the repeatability of phosphenes in a visual prosthesis patient. Second, we have calculated an upper bound on actual phosphene variability by comparing the performance of sighted patients performing an equivalent experiment. The results have implications both for explaining phosphene variability in visual prosthesis patients and for enhancing VR simulations of visual prostheses. Our analysis is based on the assumption that the variability in pointing positions indicated by both sighted and blind volunteers is well modeled by bivariate Gaussian distributions along the position angle and deviation axes. Furthermore, we assume that the pointing errors in the sighted subject are a reasonable appropriate approximation for those of the blind subject. The reliability of this second assumption will be examined later; to the extent that it is not the case, the findings of this work represent an upper bound on phosphene variability in the blind subject.

The results presented here reflect the phosphene variability experienced by a single optic nerve prosthesis volunteer. The only other volunteer implanted with the optic nerve prosthesis has experienced only dim, diffuse phosphenes (owing to the cuff electrode's apparent inability to stimulate through the dural sheath surrounding the optic nerve in the intra-orbital cavity) and has therefore not yielded information on phosphene variability (26). Variations in perceived phosphene locations may be attributable to any number of factors. These include physical factors such as head position and microscopic movements of the cuff electrode relative to the optic nerve, as well as psychological factors such as attention, mood, and fatigue. Because such factors are not likely to vary substantially from subject to subject, it is reasonable to hypothesize that the phosphene variability reported here would be representative of other optic nerve prosthesis patients. Phosphene reproducibility in subjects with other types of visual prostheses has been sparsely (and only qualitatively) discussed in the literature (21); reports from other investigators would greatly enhance VR-based visual prosthesis modeling.

The estimate of phosphene position variability in the blind subject is given in Table 4. The data show only a small difference between bright and dim stimuli (approximately 1.5° or less). However, precision was observed to be an average of 3.3° worse in peripheral versus central phosphenes. Earlier work has shown that central phosphenes in the blind subject tended to be larger than peripheral ones (27). In using her visual prosthesis to recognize and detect objects, the blind subject would therefore have to develop a scene-scanning strategy that minimizes the loss of spatial acuity caused by the larger central phosphenes, with the decreased precision of the smaller peripheral phosphenes. This hypothesis is consistent with the observation that the phosphenes most frequently used by the volunteer during a typical localize-and-identify experiment are in the intermediate deviation angle range of ω = 10–20° (28).

The assumption that pointing errors in the blind subject are similar to those of the sighted subjects is supported by the literature. Gaunet and Rossetti compared both accuracy (i.e., distance from target) and precision (i.e., spread of responses about the mean) in early-blind, late-blind, and blindfolded-sighted subjects who pointed to proprioceptive targets (29). Although it was found that both blind groups pointed more accurately than the sighted subjects, there was no significant difference in pointing precision between the three groups. Gaunet and Rossetti further concluded that for tasks in which there is no delay between target presentation and the subsequent pointing movement, subjects in all three groups used egocentric (i.e., body centered) coding. Therefore, in both precision and frame of reference,

blind and sighted subjects perform equivalently in pointing toward zero-latency targets. Furthermore, there is evidence to indicate that the frame of reference itself may not necessarily affect pointing precision. In investigating sighted subjects pointing to a recalled target after a delay of 8 s, Lemay et al. found no difference in pointing precision between tasks that forced subjects to use allocentric (i.e., relative to external points) versus egocentric frames of reference (30). Therefore, even if the sighted subjects in the present study used a different position coding mechanism than that of the blind subject, their pointing precision would still be a reasonable approximation of that of the blind subject.

One potential advantage that the sighted subjects may have had over the blind subject is the ability to exploit visual landmarks such as the pointing hemisphere and its registration marks. However, Obhi and Goodale demonstrated that, in trials in which volunteers immediately pointed at briefly lit LEDs on a tabletop, the presence of illuminated landmarks did not significantly improve pointing precision, neither in the *x* nor the *y* dimensions (i.e., parallel and perpendicular to the subject, respectively) (31). The blind subject began every trial by placing her finger on a small point at the center of the hemisphere surface (which may be construed as a tactile landmark) and by training her right eye to that same point (as monitored by camera). The sighted subjects in the present study were instructed to keep their eyes trained on this same point.

CONCLUSION

This work has presented data on phosphene variability in an optic nerve visual prosthesis subject and has adjusted those data by removing that portion of observed variability that can be attributed to normal human-pointing inaccuracies. This information can be used to enhance the reality and utility of VR simulations of visual prosthesis systems, as well as to help explain part of the variability in reported phosphene locations from visual prosthesis subjects.

Acknowledgments: This work was supported by the Commission of the European Union "Esprit" Grant # 22 527 (MiViP) and IST-2000-25145 (OPTIVIP). The authors gratefully acknowledge the contributions of Drs. O. Collignon and M. Brelèn.

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