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Psychophysics of Prosthetic Vision: I. Visual Scanning and Visual Acuity

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***Abstract*—Recipients of vision prosthesis prototypes have reported electrically elicited visual perceptions as discrete dots of light (phosphenes). Phosphenes construct the scenery in discontinuous small isolated patches, resulting in visual information deficit to a large portion of the visual field. Visual scanning therefore plays an important role in the utility of prosthetic vision. In a psychophysical study, normally sighted subjects undertook a visual acuity task in a simulation of prosthetic vision with scanning facilitated by head movements. Subjects who adopted the circular scanning technique (4/12) correctly identified >60% of the test items, compared to subjects with no particular scanning patterns (3/12) with <50%. Increased head movement velocity was correlated to increased performance; at optimal scanning velocities, we estimated a 50% increase in identification rate or a two-fold improvement in visual acuity threshold compared to otherwise complete lack of scanning movement. Improved performance likely resulted from positive interactions with the temporal processes of the human visual system, which may as much as double the spatial information of that originally afforded by the phosphene lattice.**

***Keywords*—vision prosthesis, visual scanning, visual acuity.**

I. Introduction

In recent years, there have been clinical human trials of vision prosthesis prototypes targeted at restoring vision to the blind. Subjects commonly report electrically elicited restored vision as spots of light in the visual field, known as "phosphenes" [1-4]. Fig. 1 illustrates a simple simulation of such restored vision. Each phosphene is brought about by electrical stimulation activating a population of neurons which code visual perception in a small localized area of the visual field. Presently known neural interface and electrical stimulation technology are unable to afford spatial visual continuity remotely close to that of normal vision; that is, in restored vision, there are prevailing areas of the visual field between discrete and isolated phosphenes where no visual information is provided to the recipients (refer to right-hand image of Fig. 1). Scene scanning is therefore an important skill for filling in this lack of information and learning the most effective scanning method may significantly aid in the post-implantation rehabilitation process.

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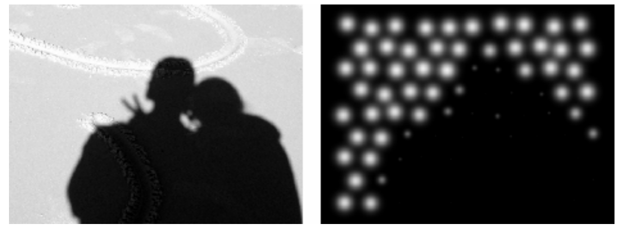

Fig. 1. Simulation of prosthetic vision illustrating the lack of visual information in the "gaps" between phosphenes. Left: Original image of the shadow of two people on sand. Right: Simulation of prosthetic vision of the original image. It is much harder to separate sections of the shadow belonging to each individual.

Scanning techniques have been identified as an important factor contributing to the utility of prosthetic vision in human clinical trials. Dobelle [3] noted that scanning assisted his cortical implant recipient's ability to recognize letters and various symbols. Further, the implant recipient believed that his performance in other tasks would improve with additional experience in scanning. Veraart *et al*. [4], [5] reported a scanning routine deemed by their optic nerve implant recipient as the most efficient method for utilizing phosphenes for identifying symbols. This routine was based on scanning in the horizontal direction followed by the vertical.

In studies based on simulation of prosthetic vision (SPV) with normally sighted human subjects, the importance of visual scanning techniques has also been reported. Cha *et al.* [6] suggested that visual scanning may have assisted in task performance by allowing their subjects self-directed visual information maximization. In addition, though a static image of phosphenes may simply appear like discrete dots, when movement is induced via scanning or object motion, a more coherent structure of the scenery emerges, allowing better identification of object contour and silhouette. This phenomenon is believed to involve temporal processes of the human visual system, such as "mental image" [7], visual memory [8], or temporal integration [9]. It is also believed to be the mechanism behind identifying spatial details beyond the Nyquist limit of the phosphene sampling lattice [8-10]. For example, studies in our laboratory have demonstrated up to 3.5 fold improvement in visual acuity [9].

Existing discussions in the literature have been limited to qualitative observation and deductions. In this paper, we present data illustrating head-directed scanning preferences exhibited by normally sighted subjects undergoing an assessment of visual acuity in a SPV. We correlated these scanning preferences to the visual acuity performances of individual subjects and discuss the mechanisms likely to underlie these correlations. These results may serve to further our understanding of head movement, scanning and related performance gains pertaining to prosthetic vision.

II. Methods

Twelve naïve subjects participated in the study, each attending ten sessions of 400 test items per session. Subjects wore a head-mounted display (HMD) viewing computer-generated test items in a SPV whilst undergoing an examination of visual acuity. The SPV phosphene lattice theoretically offered subjects an equivalent of 2.0 logMAR (logarithm of Minimum Angle of Resolution) acuity of vision based on the Nyquist sampling limit [9], [10]. Landolt C optotype test items of randomized sizes and gap orientation were displayed at random positions in the subjects' visual field. Optotype sizes ranged from 1.3 to 2.0 logMAR. Subjects' responses were self-paced without time restrictions. (Most sessions were completed between 20 to 40 minutes.)

A head-tracker (InertiaCube2, InterSense Inc., Burlington, MA, USA) was used to reposition the display at 20 frames per second (fps) using the angular orientation (yaw and pitch) of the head so that the test items were made to remain stationary in space whilst subjects executed visual scanning over the test items with the phosphene lattice. Subjects were not given prior instructions or encouraged to any visual scanning techniques to aid in item identification. Subjects were asked to restrict eye movements during the test.

All experimental procedures were conducted under UNSW Human Ethics Committee approval HREA#08/05/30.

Please, refer to [9], [11] for more detailed description of the experimentation protocol and apparatus.

A. Polar Histogram

Polar domain histograms (equi-spaced radial and angular bins) were used to show head velocity patterns of each subject (Fig. 2). A logarithm scale was used on the radial axis; the center of the histogram corresponded to 0 log°/s (1°/s) and the periphery of the histogram corresponded to 2 log°/s (100°/s). Velocities less than 1°/s were discarded, though this caused minimal loss of information.

Velocity vectors were derived from the head angular orientation vectors by taking the difference between consecutive data frames. This gave an estimate of the instantaneous velocity between each data frame.

B. Visual Acuity

Visual acuity is the measure of one's ability to resolve detail. In this study, visual acuity was assessed by overall percentage correct identification of test items and by calculating the logMAR threshold. For the latter, the psychometric fitting method was used. An extended description of the psychometric method can be found in [9]. In the Snellen fraction measure, 20/20 vision is 0 logMAR, and 20/200 is 1 logMAR.

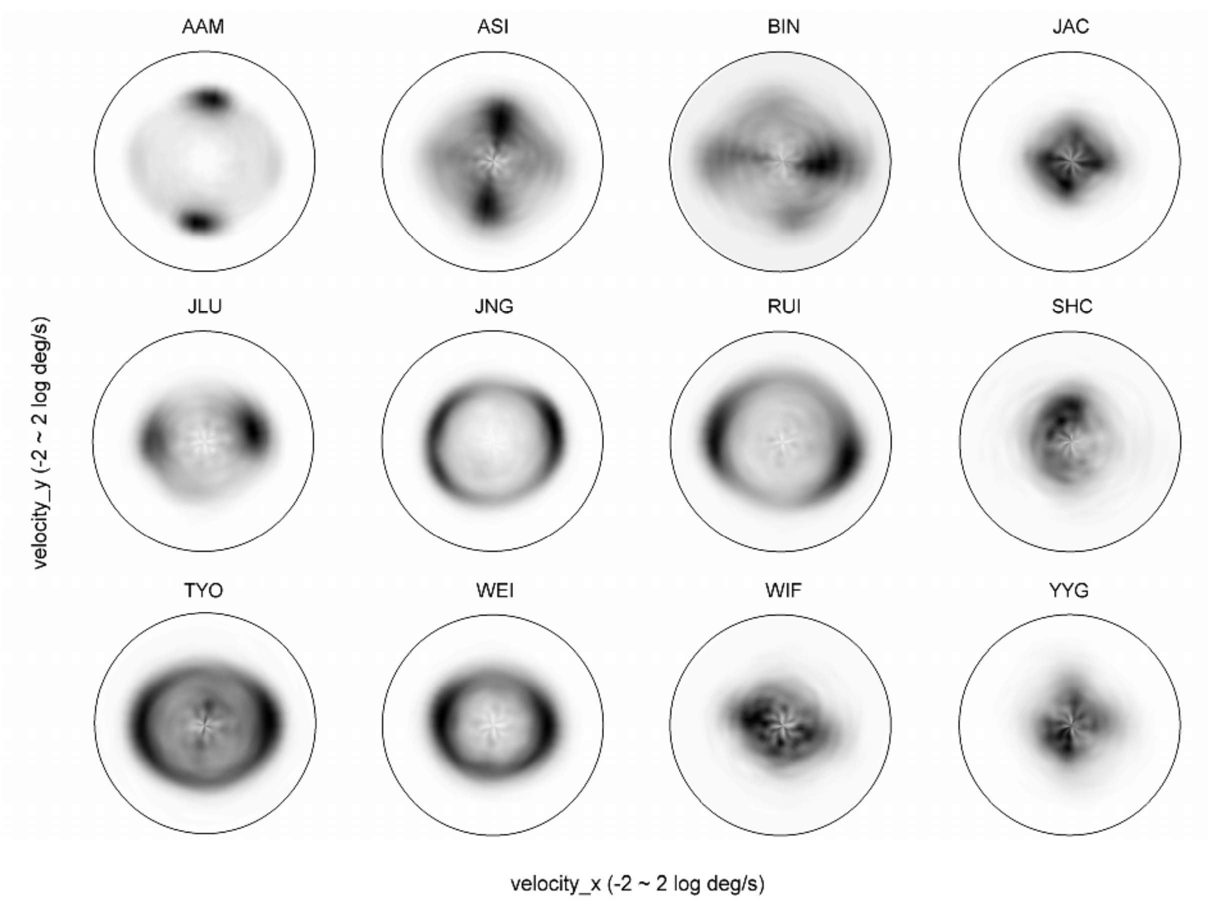

Fig. 2. Individual subjects' head velocity histograms. Bins were equi-spaced in the polar domain and gray-scale from light to dark representing increasing counts. The radial axis is on a logarithmic scale; the origin of the radial axis for all plots is 0 log°/s (1°/s) and is 2 log°/s (100°/s) at the circumference. The angular axis was arranged so that the horizontal orientation represents horizontal head movements, and vertical likewise.

IV. Results

A. Head Scanning Patterns

Fig. 2 depicts the head velocity polar histograms for each subject. Grayscale from light to dark represented increasing counts. The vectors were accumulated from sessions six to ten with the first second of data discarded to remove patterns relating to the centering of the item rather than the scanning action. These plots showed circular scanning preferences by four of the twelve subjects (Subjects JNG, RUI, TYO and WEI), all with a stronger preference towards the horizontal direction. Peak histogram counts were in the range between 10 and 20°/s.

Subjects ASI, BIN, AAM and JLU demonstrated a stronger preference to either the horizontal or the vertical directions, with peak histogram counts reaching 10°/s and higher. Subjects AAM and JLU had particularly highly accentuated velocities in the vertical and horizontal directions respectively (AAM: nodding action, JLU: shaking action). Subject JAC adopted a slower technique, scanning both horizontal and vertical directions with maximum velocity less than 10°/s.

Subjects SHC, WIF and YYG did not show any discernible scanning techniques. Their scanning velocities were well within 10°/s.

B. Head Movement and Performance

Table I lists each subject's scanning preference and acuity score. Subjects who adopted the circular scanning routine (top four) all scored over 60%, and subjects with no particular scanning preference (bottom three) all scored less than 50%. Similar ranking was also apparent in the logMAR visual acuity thresholds. The difference in visual acuity threshold between the top and the bottom of the table was 0.2 logMAR, which was a 1.6-fold difference in physical size. Classifying scanning patterns into "circular", "axial" (horizontal, vertical and both) and "none" categories for the Kruskal-Wallis nonparametric ANOVA demonstrated significant differences between the means of each category ($p < 0.01$).

In Fig. 3, the visual acuity performance per session is plotted against the average session velocity. Exponential decay functions were fitted against the data to model the correlation between visual acuity performance and average session velocity. The standard error about the fitted line was 0.01 logMAR (top graph) and 1% (bottom graph). These equations modeled exponential decay in performance improvements reaching a constant performance value at high session velocities (the asymptotic performance). This asymptotic performance was 1.58 logMAR or 62% correct.

At 0°/s, the model predicts the performance levels of static stimuli, that is, the performance when there is no head movement. The prediction for correct identification was 34%, almost a 50% reduction in performance compared to the asymptotic performance. In terms of visual acuity threshold, the static stimuli prediction was 1.87 logMAR; compared to the asymptotic performance, this was an increase of almost 0.3 logMAR, which means that one can only identify gaps at half the physical size with static stimuli compared to high velocity scanning.

Table I
Subjects' Head Scanning Preference and Visual Acuity Performance (5 Sessions x 400 Items)

Subject	Scanning Type	% Correct ±StdErr	logMAR ±StdErr
WEI	Circular	68.55±1.04	1.516±.007
RUI	Circular	65.20±1.07	1.544±.007
JNG	Circular	63.25±1.08	1.566±.007
TYO	Circular	62.95±1.08	1.572±.006
AAM	Vertical	58.00±1.10	1.620±.006
BIN	Horizontal	55.30±1.11	1.642±.006
JLU	Horizontal	54.95±1.11	1.641±.006
ASI	Vertical	52.90±1.12	1.661±.007
JAC	Both Axial	52.40±1.12	1.666±.006
YYG	None in particular	48.50±1.12	1.706±.007
SHC	None in particular	47.35±1.12	1.715±.006
WIF	None in particular	46.65±1.12	1.720±.006

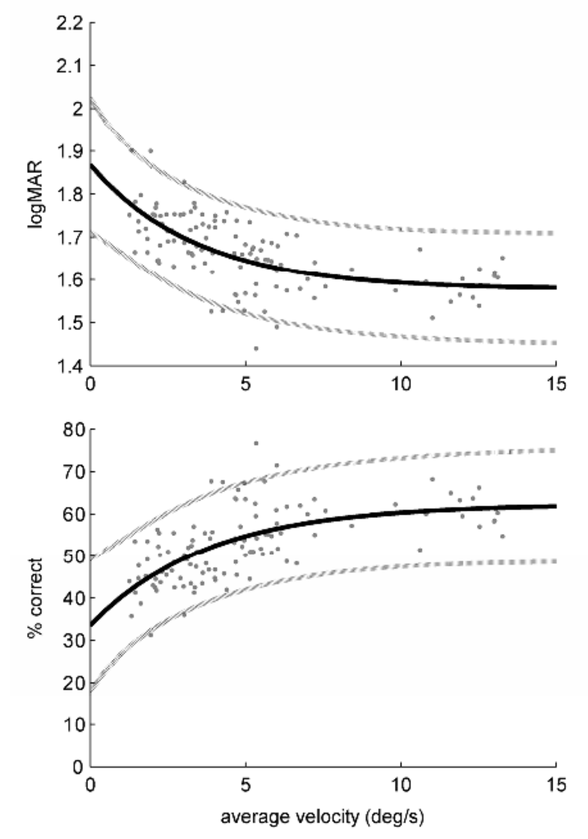

Fig. 3. Performance versus average session velocity magnitude for all 120 sessions. Solid black lines illustrate exponential curves fitted against the data. Dotted gray lines mark the 95% prediction interval for new data. Top: Performance measured in terms of visual acuity threshold in logMAR units. Bottom: Performance as measured in terms of percentage correct per session.

V. Discussion

A. Visual Scanning and Visual Acuity Performance

In this study, the development of a regular scanning pattern assisted in improving the ability to correctly identify the test items. Most developed preferences involved high velocity magnitudes (~10°/s and higher), although low-velocity horizontal and vertical patterns (Subject JAC) were also beneficial to performance compared to those who did not develop any scanning patterns in particular.

The circular scanning pattern was the best from the 12 subjects studied. It is likely that scanning in a circular locus more effectively revealed new visual information as compared to separate horizontal and vertical scans. There is currently no comparison in the literature known to the authors to show the benefits of the circular scanning technique in other tasks such as object identification, face recognition, reading, navigation, etc. The most appropriate technique may depend on prosthesis design and intended task. (The circular shape of the test items, the Landolt C optotype, might have favored those who adopted the circular technique.) Further investigations are planned, particularly using the modeling method based on mutual information suggested by Hallum *et al.* [12] with modifications to reflect the subjects' scanning preferences.

Despite instructions to subjects to restrict eye movements, in the HMD experiment setting, involuntary eye movements could not be completely eliminated. Thompson *et al.* [7] suspected that eye scanning movements may have elevated performance in facial recognition. Cha *et al.* [13] also noted that eye-directed scanning with stabilized retinal actually produced poorer reading results than head-directed scanning. In future studies, an eye movement monitor will be incorporated into the experimental set up in order to gain a more complete understanding of the combined head-eye scanning patterns and related performance outcomes.

B. Temporal Properties of Human Visual System

In Fig. 3, we extrapolated the exponential decay model to 0°/s to represent static stimuli – stimuli that will not trigger any temporal processes of the visual system. The predicted visual acuity for static stimuli was two-fold larger than the size of the asymptotic performance. In effect, the temporal processes of the human visual system can as much as double the spatial frequency information afforded by the sampling rate of the phosphene lattice. If this suggests that the information from two frames of data at 20 fps can be effectively retained in memory, to achieve the best sampling result, the scanning movement would need to traverse half the phosphene separation between each frame – given the phosphene separation in this study was 1.6°, this would be 0.8°/frame, or 16°/s at 20 fps. In the light of this, it is not surprising to find peak velocity histogram counts of subjects with circular scanning preferences in the range between 10 and 20°/s, and correspondingly in subjects adopting other high velocity patterns.

In the light of our results, we postulate that the temporal dynamic content can be optimized to improve the quality of prosthetic vision. For example, the pre-filtering schemes may be tuned to retain more spatial frequency information, and may be adapted to the scanning velocity effected by the subject; such was the suggestion of adaptive image processing techniques by Hallum *et al.* [12, 14].

VI. Conclusion

We have shown the impact of visual scanning techniques to the visual acuity performance under prosthetic vision in virtual reality simulation. Our results showed that circular scanning is the best technique developed independently by our subjects without specific guidance or training. Maximizing visual information with respect to the temporal processes of the human visual system is likely to be the mechanism behind adaptation to such scanning routines and the associated performance improvements.

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