Effect on Prosthetic Vision Visual Acuity by Filtering Schemes, Filter Cut-off Frequency and Phosphene Matrix: A Virtual Reality Simulation

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Abstract—**Visual acuity of prosthetic vision was examined under virtual reality simulation. Prosthetic vision was simulated by first filtering an image using circular mean filters or Gaussian smoothing filters of different cut-off frequencies. Pixel values at 100 fixed sites of the filtered image were taken, sampling either with a regular rectangular or hexagonal matrix. Each pixel value was transformed into a Gaussian intensity profile centered at the corresponding position at which the sample was taken to simulate the evoked visual effect of an electric stimulation. Visual acuity scores of three subjects, each completing two sets of results, were recorded across different filtering schemes, cut-off frequencies and sampling matrices. The best mean score recorded was 1.55 logMAR, with the worst being 1.70 logMAR. The difference was mostly attributed to filter cut-off frequency. Differences between filtering schemes were insignificant. Results also showed emerging trends demonstrating differences between rectangular and square sampling matrices.**

Keywords— **prosthetic vision, vision prosthesis, visual acuity, virtual reality**

I. INTRODUCTION

Guide dogs and walking canes may soon no longer be the depending navigational aids for the vision-impaired. Human trials by Dobelle [1], Humayun [2, 3] and Veraart [4] have shown stimulating unimpaired sections of the human visual pathway with suitable electrical current waveforms is able to elicit perceptions of generally rounded spots of light in the visual field called *phosphenes*. Multiple electrodes directing current to multiple sites would be able to compose an image in this "virtual visual field" with phosphenes of different intensity levels and/or different sizes being used to render the underlying visual scene (Fig. 1).

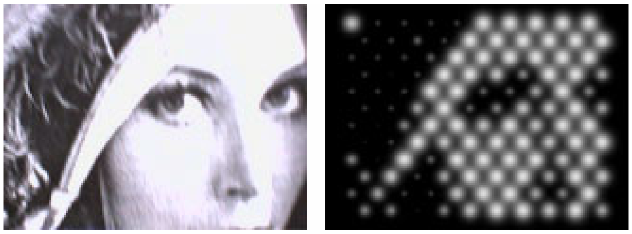

Fig. 1. "Lenna" and viewing her under simulated prosthetic vision.

Several investigators have simulated and studied the quality of prosthetic vision using various techniques. Cha *et al.* [5-7] in their papers employed visual acuity, reading speed, and maze navigation as assessments of quality of vision. Hayes *et al.* [8] also examined similar exercises; in addition they added object recognition and some simple hand-eye coordination tasks into assessment. Thompson *et al.* [9] otherwise focused on facial recognition.

However, these studies have been centered on the number and density of phosphenes, i.e. the number and density of electrodes. These are factors determined by the available manufacturing techniques of the physical device. In technological reality, advances in implant manufacturing and electronics are often slow, limited and costly.

Though the number and density of phosphenes may seemingly give a theoretical bound to quality of prosthetic vision, the quality of prosthetic vision is also intimately affected by image processing techniques. As a precursor to vision implants, advancement of cochlear implants in recent years is a good indicator to future trends in vision prosthesis research. The number of electrodes of cochlear implants has scarcely increased. The spearhead of hearing quality improvements has been investments in researching into better speech processing and electrode stimulus combinations. With respect to a vision implant, this corresponds to:

i) The algorithm condensing the information from each camera frame into the limited number of phosphenes.

ii) The rendering of the intensity, size and perhaps color of the phosphenes so they best represent the original image through triggering the appropriate stimulus waveforms.

Hallum *et al.* [10] conducted a study in area (i) above. They described an object-tracking task whereby the performance difference was assessed under original image sampling conditions of no filtering, mean filtering and Gaussian smoothing. Improved performance was reported after an initial period of learning in favor of the Gaussian smoothing, warranting further investigation in improving image-processing techniques. Result from no filtering was in orders of magnitude worse than either mean filtering or Gaussian smoothing.

This paper extends this investigation. The primary aim is to investigate the effect on visual acuity (VA) across the range of filter cut-off frequencies. The secondary aim is to compare VA between the traditional rectangular phosphene matrix and the more compact hexagonal matrix. VA was chosen as the index of quality of prosthetic vision in this investigation as it has long been the foremost clinical screening test for visual quality and health.

II. METHODOLOGY

Three subjects were given VA tests under simulated prosthetic vision. 20 different schemes (2 matrices × 2 filters × 5 cut-off frequencies) were examined. Each subject partook tests for each scheme twice. VA scores are given in logarithm of minimum angular resolution (logMAR).

VA was examined using Landolt rings. The gap of the ring was either in one of the eight orientations, or completely missing (i.e. a true ring). Subjects were shown one ring at a time. Ring sizes varied in the range of 2.0 logMAR to 1.3 logMAR with intervals of 0.1 logMAR.

VA scores were calculated by fitting a cumulative normal psychometric function over the percentage correct versus logMAR plot. The procedure of maximum likelihood fitting as described by Wichmann and Hill [11] was used. The 50% mark of the psychometric function (55.56% on the percentage correct axis) was taken as the VA score.

Subjects were required to wear a head-mounted display (HMD) and interact with the virtual visual field via a head-tracker. The HMD used was the i-Glasses (i-O Display Systems, Sacramento, CA, USA), having 640x480 resolution, covering a visual field approximated to 25.6° × 19.2°, i.e. 1 pixel width is approximated to 2.4 arcmin. The head-tracker employed was the InertiaCube2 (InterSense Inc., Burlington, MA, USA), with the ability to measure the angular positions (yaw, pitch and roll) of the head. Samples from the head-tracker were taken at 20Hz, synchronous with the simulation frame rate. Subjects were to indicate the orientation of the gap in the Landolt ring via corresponding joystick positions (joystick centred for no gap).

Prosthetic vision was simulated by first passing the original image through a filter before sampling at the fixed locations dictated by the phosphene matrix. This is equivalent to employing a filter kernel over the area of interest in the original image at corresponding positions for each phosphene. Fig. 2 shows the overlay of phosphene kernels.

Two phosphene matrices were investigated: the traditional rectangular matrix (Fig. 2 A and B) and the hexagonal matrix (Fig. 2 C and D). To make a fair comparison, the number of phosphenes for both matrix was 100, and the minimum phosphene centre-to-centre spacing (PS) for both matrix was 42 pixels on the HMD, corresponding to 1.68° of separation in the visual field.

Two filtering schemes were investigated: mean filtering with a circular aperture (CMF) (Fig. 2 B and D) and Gaussian smoothing filter (GSF) (Fig. 2 A and C). The cut-off frequency was varied by adjusting the filter aperture (FA). For CMF, this was the radius of the circular kernel; for the GSF, this was the sigma of the Gaussian. These values are expressed as a percentage of the phosphene centre-to-centre separation (%PS) (42 pixels) in the results.

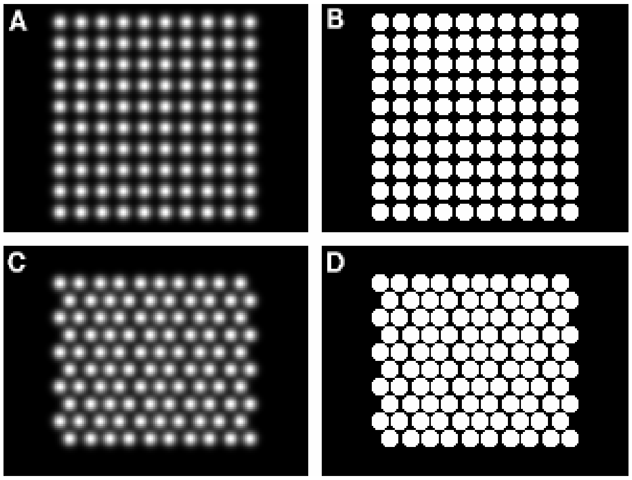

Fig. 2. Rectangular and hexagonal matrix of phosphene filter kernels. A and C illustrate Gaussian Smoothing Filter. B and D illustrate Circular Mean Filter. Each dot represents the filter kernel for a phosphene. These images are overlays of kernels as they apply on the original image.

Visually, each phosphene was rendered as a spot of light with a two-dimensional Gaussian grayscale intensity profile. An implant which can elicit eight distinguishable profiles was assumed currently possible [3], and simulated. Therefore, the intensity value of the centre pixel of the Gaussian profile took one of the eight discrete values linearly distributed in the range {0, 255}. The sigma of the Gaussian intensity profile also varied, and took one of the eight corresponding levels distributed linearly in the range {0, 16} pixels, i.e. {0, 38}%PS.

III. RESULTS

At the time of writing, three subjects have participated in a pilot study under the aforementioned methodology. Each subject has completed four visits: two under the traditional rectangular matrix, two under the hexagonal matrix. For each visit, all ten filter settings were examined. In total, six complete result sets were available for each setting investigated.

A psychometric function was fitted to each result set and VA calculated as described in the methodology. The average score was taken of the six scores available for each setting. These are graphed with their standard errors in Fig. 3. Fig. 3A is the VA scores for CMF versus FA. Fig. 3B is the VA scores for GSF versus FA. Circular markers identify the scores for the traditional rectangular matrix. Square markers identify the scores for the hexagonal matrix.

Both Fig. 3A and 3B show a “U” shape trend in the VA scores, more pronounced in A than B. The scores were approximately 1.65-1.70 logMAR where the FA is small relative PS. Scores reach a minima of 1.55-1.60 logMAR at around 50%PS for CMF, and 33%PS for GSF. Then, they increase again as FA increases, returning to approximately 1.65-1.70 logMAR. The size of this change means one can read at least one more complete line on the standard log-

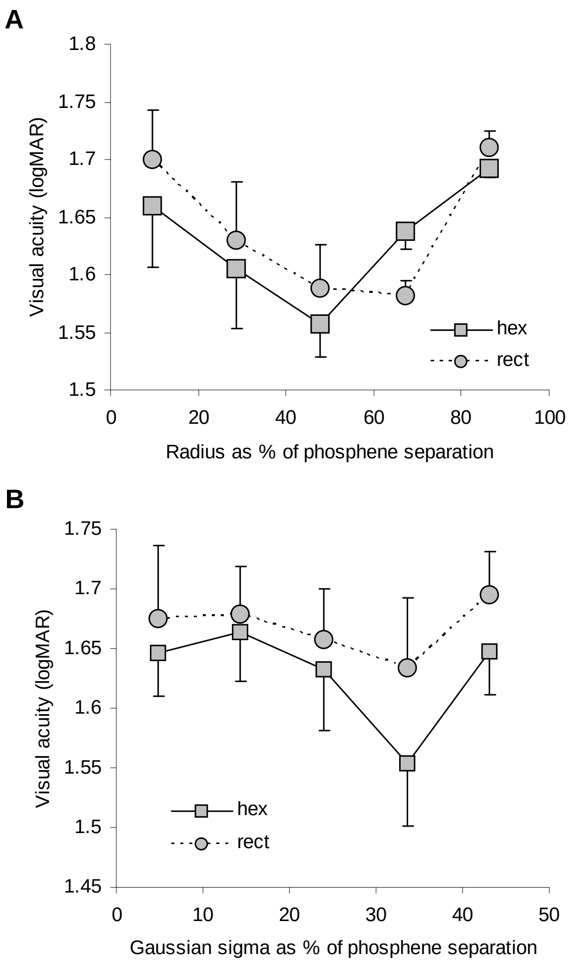

Fig. 3. Visual acuity scores (logMAR) plotted against filter size expressed as percentage of phosphene centre-to-centre separation. A is the result for the mean filtering. B is the result from the Gaussian smoothing. Results are averages of six scores. Error bars indicate standard error. The smaller the logMAR score, the sharper the visual acuity.

MAR based VA chart.

At the minima of both graphs, the VA score for both CMF and GSF are approximately equal. On the hexagonal matrix, both minimum values are approximately 1.55 logMAR. The scores differ by only 0.05 logMAR on the rectangular matrix.

Comparing results between the traditional rectangular matrix and the hexagonal matrix, for CMF, there is a suspicion that the minimum of the rectangular matrix scores might occur at a higher %PS, i.e. closer to 70% rather than 50%. For GSF, it appears that the minimums occur at similar positions, but the rectangular matrix scores might be higher than hexagonal matrix scores (by approximately 0.08 logMAR in the results).

IV. DISCUSSION

A. Visual acuity compared to previous investigations

Other investigators have reported similar VA scores under simulated prosthetic vision. In the work of Cha *et al.* [6], they simulated prosthetic vision by setting up subjects to view through pinhole matrices. Their rectangular matrix of 10x10 pinholes spans a visual field of 1.7° × 1.7° (pinhole spacing of 0.19°). The VA they measured for this setting was approximately 20/110 or 0.74 logMAR. If Cha *et al.*'s 10×10 matrix was extrapolated so that its pinhole spacing was similar to the PS used in this study (1.68°), and assuming linear worsening in the VA denominator, the result is approximately 20/978 or 1.69 logMAR.

Hayes *et al.* [8] also simulated prosthetic vision using a HMD. They measured VA under mean filtering with a 6 × 10 rectangular matrix of 2° PS was 20/1330 or 1.82 logMAR. If the same exercise is performed on this result to make PS 1.68°, the VA is 20/1117 or 1.75 logMAR.

It must be noted, however, since the methodologies of arriving at a VA score were different, a fair comparison cannot be made. Nevertheless, the higher VA scores obtained from the present study (1.70 logMAR) do not differ significantly from previous reports. Result from this study may indicate that the previous reported values might be conducted with FA that is too small or too large; a better chosen FA might possibly improve the VA outcome to 1.55 logMAR or better.

B. Seeing beyond the Nyquist limit

Nyquist limit of sampling theoretically puts a limit on the best VA score given PS; for this study, it was 2.0 logMAR. It is clear that all VA scores recorded in the study exceed the theoretical limit. Cha *et al.*'s results [6] and those of Hayes *et al.* [8] also exceed the Nyquist limit.

The mechanism that allows VA to exceed the Nyquist limit may be due to 1) judgment based on lower frequency components, and 2) motion integration in the visual system.

Bondarko and Danilova [12] presented a paper on the spatial frequency components of the Landolt ring and Tumbling E optotypes. Both optotypes have a significant lower frequency component at approximately half of the highest frequency component. This component may be used effectively in judging the orientation of the character, resulting in higher VA scores. Observers may be able to discern characters at as much as half of the Nyquist size limit, i.e. approximately 0.3 logMAR drop or halving the Snellen denominator. This also justifies Hayes *et al.*'s claim [8] that grayscaling the phosphenes is the source of this hyper-acuity, since grayscale grading (as oppose to black/white) would greatly assist in bringing out the lower frequency components.

Short-term visual memory and motion integration would assist the visual system to "fill-in" the gaps between the phosphenes by repeated scanning of the image. The extent this contributes to VA under prosthetic vision would be related to the image refresh rate (20Hz in this study) and speed of the head movement while scanning the image, both warranting future investigation. Short-term visual memory and motion integration may be exploited to further improve quality of prosthetic vision through image processing and devising an optimal electrical stimulation protocol.

C. Low-pass filtering and aliasing

The “U” shape trend observed in the results may be interpreted in terms of image filtering. As the FA increases, the cut-off frequency of the filter decreases, i.e. the filter becomes increasingly low-pass. Under such conditions, the expectation is that less higher frequency content would be available to the subjects. This is reflected in higher VA scores for larger FA.

On the other hand, when FA decreases, higher frequency content was included in the output spectrum. However, due to the sampling resolution determined by PS, higher frequency contents were aliased into the low-frequency content. The effect of this is reflected in worsening in VA scores in the results.

The study shows that a “best configuration” can be sought which balances between the availability of high frequency content and the detrimental effects of aliasing. This configuration for FA is at 50%PS for CMF and 33%PS for GSF. The interesting correlation between these two configurations is that these are approximately where the FA of filter kernels for each phosphene is maximal with minimal overlap.

D. Filtering schemes and learning

Subjects in this study have yet to be given the opportunity to progress along a learning curve. At present, the results show statistically equal performance under both filtering schemes. This is consistent with the initial observation made by Hallum *et al.* [10]. In Hallum *et al.*’s study, the results from object-tracking initially favored mean filtering. After a period of learning, the Gaussian smoothing became the better-performing filter. Prolonged study is therefore required to confirm whether Hallum *et al.*’s observation with object-tracking also holds true for VA.

E. Phosphene matrix

A hexagonal matrix offers the most compact structure in two-dimensional space. This properly allows for the highest density of phosphene organization within the available visual field. As previous investigators have reported [5-9], phosphene density seems to be the single most important factor pertaining to quality of prosthetic vision.

Results from this preliminary study are inconclusive with regards to the benefits of a hexagonal arrangement over the traditional rectangular one. However, there is a slight trend that indicates that the hexagonal grid may provide superior VA scores.

Another benefit of the hexagonal matrix through its isotropic and optimal adjacency properties may be its superiority in discerning oblique orientations over the cardinal directions. More data is needed to confirm this difference.

V. CONCLUSION

This paper investigated several parameters that may effect the quality of prosthetic vision. These are the filtering scheme, filter aperture and the phosphene matrix. With regard to filter aperture, the results demonstrate that clinically significant improvement can be achieved merely by adopting an optimized configuration. The generality of this optimal configuration requires further investigation under different phosphene centre-to-centre separations. With regards to filtering scheme and phosphene matrix, prolonged study is required to confirm emerging trends in the pilot data.

The measured visual acuity scores all exceed the theoretical expectation based on the Nyquist limit. It is evident that the mechanisms behind this needs to be studied and optimized to the advantage of prosthetic vision.

Finally, the limited scope of the study has not allowed for any significant learning to take place with regard to prosthetic vision. Learning would improve visual acuity scores, but for which settings, and by how much?

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