SIMULATION OF A PHOSPHENE FIELD BASED VISUAL PROSTHESIS

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Abstract

A visual prosthesis for the blind based upon electrical stimulation of the visual cortex requires the development of an array of electrodes. To establish design specifications for such an electrode array, we have conducted psychophysical experiments with normally sighted subjects wearing a portable 'phosphene' simulator. The simulator consists of a small video camera, a monitor masked by an opaque perforated film, and optical lenses. The visual angle subtended by the masked monitor is 1.7° or less. We measured visual acuity and reading rate as a function of the number of pixels and their spacing. Our results indicate that a phosphene image produced by 600 electrodes implanted in a 1 cm^2 area near the foveal projection on the visual cortex should provide a limited but useful visual sense for the profoundly blind.

Introduction

Punctate electrical stimulation of the visual cortex evokes the sensation of a spot of light (a phosphene). An array of electrodes implanted in the visual cortex could be used, in principle, to create a visual image consisting of an array of phosphenes (pixels), resembling the type of image produced by the scoreboard at a football field [2,5]. In such a system, the number of phosphenes and their spacing determine the quality of the image. In order to establish design specifications for a visual prosthesis based on cortical stimulation, we have studied the psychophysics of vision mediated by pixelized images.

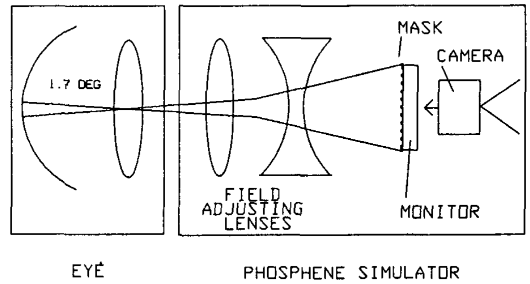
This was done by using a phosphene simulator which created a pixelized visual field. Normally sighted subjects using the simulator were tested with two measures of visual function: visual acuity and reading rate. The extent of visual task perfromance was determined as a function of the number of pixels and their spacing.

Methods

Phosphene Simulator

The phosphene simulator was designed to simulate a pixelized visual field similar to that expected to be produced by an array of intracortical electrodes. The simulator consisted of a small video camera, a video monitor and optical lenses, as shown below.

The monitor was masked with a perforated metal film to create the pixelized image. Because the image on the monitor could be seen only through the pinholes, the image seen by the subject was composed of a number of dots (pixels). Optical lenses placed between the monitor and the subject's eye adjusted the image size so that it subtended 1.7° or less. The acceptance angle of the camera was set by external lenses. All components of the device were mounted on opaque ski goggles so the subject was only able to see the pixelized image with his or her right eye, but had complete mobility and could scan objects with head movements.



The two parameters tested in these experiments were the number of pixels and their spacing. The number of pixels varied from 1024 (a 32x32 mask) to 100 (a 10x10 mask). One set of masks maintained a fixed field size (1.7°), and the other set maintained a fixed spacing between pixels (corresponding to the spacing of the 32x32 mask).

Psychophysical Tests

The subjects for these tests were undergraduate students at the University of Utah.

Visual acuity was tested by presenting the letter 'E' on a computer monitor as a white target on a black background. The orientation of the 'E' was randomly chosen from among four orthogonal directions for each presentation. The subjects identified the orientation of the 'E' using a keypad. A staircase procedure was used to determine threshold size for detecting target orientation.

Reading speed was measured by having the subjects read text displayed on a computer monitor while wearing the simulator. In one set of tests, the acceptance angle of the camera was fixed so that it encompassed four letters at one time. Text was selected from materials ranging in difficulty from grades 4 to 8.

Two types of displays were used: a window display and a screen display. In the window display, text was scrolled across a window, 10 letters wide, and the scroll speed was varied. In the screen mode, the text was displayed on an entire screen and subjects scanned the text with head movements. The fastest rate at which the subjects could read aloud without error was determined.

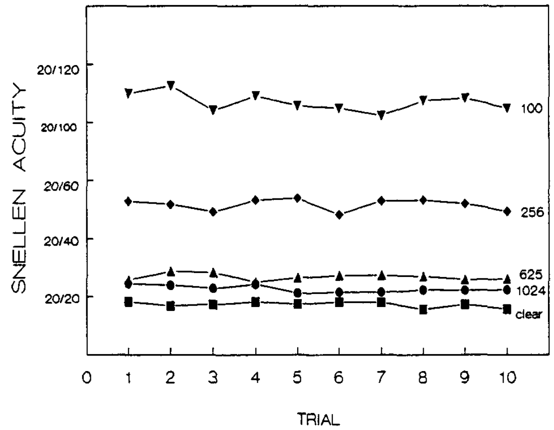
Results

Visual Acuity

For subjects wearing the simulator, the angular size of the stimulus to the eye depends on not only the size of the target but also the acceptance angle of the camera. To provide a standardized reference, the acuity data presented here are expressed as Snellen acuity estimated from the angular size of the letter 'E' as presented to the subject's eye.

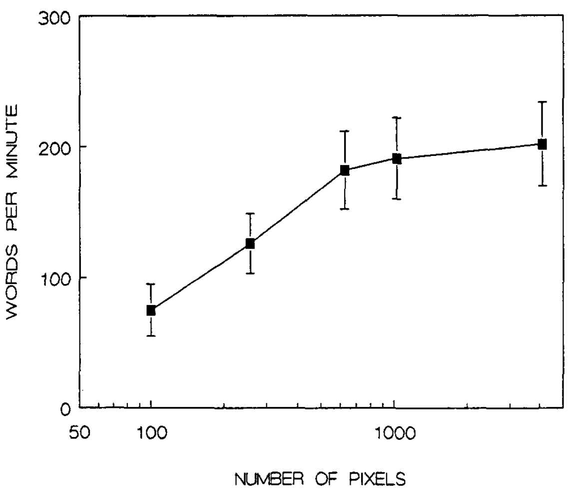
For the visual acuity tests, six subjects were trained until their performances stabilized. Then 10 trials were conducted for each mask. The data from these sets of 10 trials with fixed field masks are shown below.

VISUAL ACUITY



Visual acuity with a "clear mask" (i.e., a mask in which the entire image within the 1.7° field was visible) was about 20/20, and depended on the subjects' own acuity. Visual acuity with fixed field masks, in which the pixel spacing varied, was proportional to pixel density (the number after each curve shows the total number of pixels in the 1.7° field). Visual acuity with fixed spacing masks (data not shown), did not change with pixel number over the range tested. We conclude that pixel density is the key component in determining visual acuity.

READING RATE



Reading rate

In the reading tests, normal reading rate, in which the subjects viewed the text presented on the computer monitor without the simulator, was measured as a control. The normal reading rate was about 270 wpm both in the window and screen display modes. The six subjects were then trained for two weeks with a 32x32 mask until individual reading rates were stabilized. During training, the average reading rate improved from 100 words/minute (wpm) to 180 wpm. Five test trials were then conducted for each mask. The results showed that, unlike the acuity tests, pixel spacing, over the range tested, had little effect on reading speed. However, the number of pixels did have strong effect. The results from the window tests with fixed spacing masks are shown in the last figure. The full screen tests produced comparable data.

Average reading rates from the six subjects with masks consisting of more than 625 pixels were relatively constant, between 170 and 200 wpm in the window display. As the number of pixels was reduced below this limit, reading speed fell off significantly. We conclude that when the number of pixels is limited, reading rates are a function of the number of pixels.

Discussion

Visual acuity, as measured by the ability to determine the direction of the letter 'E', was a linear function of pixel density over the range tested. Calculation of the letter size at threshold versus the pixel spacing showed that a grid containg about 4.5 pixels on average was required to identify the orientation of the 'E'. Less formal tests with the letter 'C' as a target showed the same results. This finding is in keeping with Brindley's suggestion that five pixels per letter should suffice to read ideally designed letters [3].

It has been observed that reading rates increase with field size, but only up to 4 letters [6]. Our observations confirmed this finding, so we used a camera acceptance angle which encompassed 4 letters in the tests reported here. Further increases in acceptance angle decreased reading speeds due to the concomitant loss in acuity imposed by having a fixed image size on the masked monitor. However, given a fixed acceptance angle, reading speed depended not on pixel density itself, but on the number of pixels constituting the image. This effect saturated between the 25x25 and 32x32 masks.

Head movements seem to be important for performing visual tasks with the low density masks. For example, performance in both the visual acuity and reading tests improved dramatically with the 10x10 masks once the subjects learned to use head movememts during the tests.

Our data indicate that a pixelized visual sense consisting of about 600 phosphenes evenly distributed in the foveal projection of the visual field should produce a visual acuity of about 20/30. This would provide useful pattern recognition abilities such as the reading tasks used in this study.

Once the dimensions of an array of cortical electrodes are given, the size of the corresponding phosphene field can be calculated. The cortical magnification factor, the distance on the cortex corresponding to one degree of visual field, is about 6mm/° at the fovea in primates [4,7]. An array of 600 electrodes implanted in $1cm_2$ near the foveal projection of the visual cortex, would produce a image similar to the fixed field 25x25 mask used in this simulation study. Such an array can be developed using current electrode design techniques [1,8].

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