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Psychophysics of reading with a limited number of pixels: Towards the rehabilitation of reading ability with visual prosthesis

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Abstract

Psychophysics of reading with limited numbers of pixels has received increasing attention as the envisioned visual prosthesis offers a possibility to restore some useful reading ability to the blind through the pixelized vision it generates. This paper systematically studied how several important parameters of pixelized vision affect reading performance. A closed-circuit television reading platform with digital image processing capacities was developed to convert images of printed text into pixelized patterns made up of discrete dots. Reading rates in six normally sighted subjects were measured under different combinations of pixel number, window width, and angular subtense of pixel array. The results showed that reading is possible with as few as 6×6 binary pixels, at 15 words/min. It was also found that for a given array of pixels, maximum reading rates occur at a specific medium window width, due to a tradeoff between window width and character sampling resolution. It was also observed that pixelized reading exhibits more significant scale dependence than normal vision. Reading rates were decreased by increasing the angular subtense of the pixel array while keeping other parameters fixed. We hope these results will be helpful to the design of visual prosthesis for the rehabilitation of reading abilities.

Keywords: Psychophysics; Reading; Pixelized vision; Window width; Angular subtense of pixel array size; Visual prosthesis

1. Introduction

Electronic visual prosthesis has been proposed to restore functional vision to the profoundly blind (Brelen, Duret, Gerard, Delbeke, & Veraart, 2005; Chow & Chow, 1997; Delbeke, Oozeer, & Veraart, 2003; Dobelle, 2000; Humayun & de Juan, 1998; Humayun et al., 2003; Normann, Maynard, Rousche, & Warren, 1999; Rizzo & Wyatt, 1997; Rizzo, Wyatt, Loewenstein, Kelly, & Shire, 2003; Veraart et al., 1998; Zrenner et al., 1999; Zrenner, 2002). By punctate electrical stimulation of certain sites along the visual pathway, phosphenes can be induced and serve to convey limited but useful visual information to the blind.

Rehabilitation of reading ability is regarded as one of the major functions of the envisioned visual prosthesis. It has been proposed that phosphenes could be utilized to produce pixelized spatial patterns to depict characters or geometric symbols that are recognizable to visual prosthesis recipients. In a few preliminary clinical trials, researchers have attempted to convey phosphene-formed letters or Brail characters to blind patients and achieved encouraging results (Dobelle & Mladejovsky, 1974; Dobelle, Mladejovsky, & Evans, 1976; Humayun et al., 1999; Veraart, Wanet-Defalque, Gerard, Vanlierde, & Delbeke, 2003).

Sufficient knowledge on psychophysics of pixelized reading will be necessary for a successful visual prosthesis for reading ability rehabilitation. Previously, Legge and his colleagues have made prominent contributions to the psychophysics of pixelized reading. They discovered that when text is subject to hexagonal matrix sampling, reading speed dropped only if sampling density is below some critical

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value. The critical value, depending on font size, ranges from about 4 × 4 samples/character for characters near the resolution limit of the eye, to about 20 × 20 samples/character for very large characters, suggesting that pixelized reading is dependent on the angular subtense of characters (Legge, Pelli, Rubin, & Schleske, 1985).

The work of Legge and his colleagues emphasized the critical character resolution with no restrictions on the total number of pixels, while in visual prosthesis, the number of stimulation electrodes given beforehand are strictly limited by various complicated factors. Faced with a severely restricted number of pixels, researchers are interested in obtaining the maximum reading speed with a given set of pixels, to exploit the most utility from a visual prosthesis.

Cha, Horch, Normann, and Boman (1992) originally designed a head-mounted phosphene simulator, which optically produced pixelized text by a perforated film mask, to estimate the design specifications such as electrode number, electrode density, etc., for cortical visual implants. They estimated that 625 electrodes implanted in a 1cm area near the foveal representation of the visual cortex are sufficient to provide reading rates near 100 words/min. The optimum window width for 16 × 16, 25 × 25, and 32 × 32 arrays was found to be four letters, which was identical to the critical window width for normal vision (Legge, Ross, Luebker, & LaMay, 1989). Dagnelie, Thompson, Barnett, and Zhang (2000) incorporated a wider range of parameters into their simulation studies of prosthetic vision, including dot size, phosphene gap size, dropout percentage, and gray levels. Recently, Sommerhalder et al. (2003) designed a simulation system to present stimuli at fixed degree of eccentricities to mimic retinal prosthesis implanted at extrafoveal locations. Pixelized four-letter words were used as stimuli. Result showed that 90% correctness was possible with 300 pixels, but performance dropped severely at eccentricities beyond 10°. Their latest experiment on full-page text reading showed that with 600 pixels, subjects' final performance reached 86% to 98% correctness with a window width of six letters (Sommerhalder et al., 2004).

Despite the efforts devoted to the simulation studies of pixelized reading, two major questions remain unexplored. First, most previous experiments were based on arrays of more than 10 × 10 pixels, and the minimum number of pixels necessary for useful reading remains unknown. Second, window width, defined as the number of simultaneously visible characters in the width of a pixel field, has not received enough attention. In pixelized reading, window width counteracts with character sampling density. Therefore, we propose that window width is a key factor affecting reading speeds in pixelized vision. However, except Cha and his colleagues, window width in most previous studies of pixelized reading was either uncontrolled or fixed at a constant value. This would lead to underestimation of potentials of pixel arrays and compromise the comparability of the measured reading rates. As a result, systematical knowledge about the effects of window width on pixelized reading, and its implications for the design of visual prostheses remain to be explored.

In this study, a wider range of parameters were studied, and window width was carefully controlled in all tests. The experimental variables included pixel number, window width and angular subtense of the pixel array. The tested pixel numbers were 6 × 6, 8 × 8, 10 × 10, 15 × 15, 20 × 20, and 32 × 32, respectively. The range of window width was 1–10 letters, and three different angular subtenses of pixel arrays, 1.2°, 5.7°, and 13.7°, were involved. The effect of monocular and binocular viewing on pixelized reading was also investigated.

The results showed that under carefully chosen window width, reading is possible even for as few as 6 × 6 binary pixels, at a speed of about 15 words/min (wpm). We found that optimum reading rates were achieved with a specific medium window width, which struck a balance between the two contradicting factors of window width and sampling resolution. It was also observed that under some viewing conditions, pixelized reading exhibited notable scale dependence properties, i.e., reading speeds went up rapidly as the angular subtense of pixel array decreased while pixel number and window width remained unchanged.

2. Methods

2.1. Experimental set-up

A close-circuit television (CCTV) reading platform with digital image processing capacities was developed to generate pixelized textual stimuli (see Fig. 1). The platform consisted of a moveable paper tray, a video camera, a computer for image processing, and a head-mounted display (HMD). The moveable paper tray, mounted on well-lubricated sliding tracks, bore the printed reading materials. The video camera (Panasonic WV-BP330, PAL, 25 fps) shot the reading material through a reflection mirror. (The mirror was introduced to allow convenient installation of the camera. The upside down image cause by the mirror was inverted by real-time image processing software installed on the computer.) The camera's

Fig. 1. Setup of the pixelized reading task. Through the reflection mirror, the video camera captured images of the reading materials placed on a moveable paper tray. The captured images were degraded into low resolution and transformed into simulated phosphenes patterns in real time. A head-mounted display presented pixelized images to the subject. This picture shows a subject reading with manual page navigation with this simulation system.