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Estimation of Input Letter Based on Pupillary Responses and Optokinetic Nystagmus

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ABSTRACT

An information-input interface was developed in which pupillary responses and optokinetic nystagmus (OKN) are used to identify a visual stimulus targeted by a user's attention. The result suggests that pupillary responses and OKN can be used to identify which letter a user intends to select.

1 Introduction

Developing a method of communication for individuals with severe disabilities who cannot express their intentions through limb movements or speech is important. Brain-computer interfaces are one of the most common information-input methods [1]. This interface uses nerve signals from the brain as information input so that it can be used by individuals with severe disabilities to express their intentions. However, many of these methods are invasive and require surgical procedures and maintenance, such as electrode cleaning. In addition, many of the devices are expensive, limiting their practical application.

One common information-input method is gaze input based on eye movement measurements [2]. Gaze input uses infrared illumination to generate reflections from the cornea that are captured by a camera using the corneal reflection method to locate the position of the gaze. Therefore, gaze input is a noninvasive, inexpensive method for information input; however, it is not effective for users with limited eye movement.

A new interface that does not use eye movement has been developed using pupil response [3,4]. Visual attention can be directed to a different position than gaze [5]. These studies are based on the finding that the pupil changes with the brightness of not only the gaze position but also the position to which visual attention is directed [6-8]. For example, the pupil constricts (dilates) when attention is directed to a letter presented on a white (black) background. This change in pupil size is used to estimate the input letter. However, there is a problem that the input time becomes long because the only indicator for estimating the input letter is the pupil response. Therefore, this study examined an information-input method using two indicators: pupil response and optokinetic nystagmus (OKN).

OKN is an involuntary eye movement comprising slow (pursuit movements in the direction of the stimulus motion) and fast (saccadic return movements in the direction opposite to that of the stimulus motion) phases. As with pupillary response, OKN is induced by the stimulus motion at the eye position and that at the attention position [9]. In addition, the pupil and OKN change corresponding to the luminance and motion direction of the perceptually dominant object while observing transparent motion [10] or binocular rivalry stimuli [11]. Based on these findings, this study examined whether the timing of attention switching to the target letter could be estimated from OKN and pupil responses.

2 Experiment

In the experiment, random dots with different directions of motion and brightness were presented in superposition. When a target letter was presented, participants switched their attention to the dot pattern with the same direction of motion and brightness as the target letter.

2.1 Participants

Ten undergraduate and graduate students (5 females; age range: 18–24 years; mean age: 21.9) participated in this experiment. They had self-reported normal or corrected-to-normal visual acuity (20/20) and provided written informed consent before participating. The study was approved by the Ethical Review Committee on Research Involving Human Subjects of Utsunomiya University and conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2 Apparatus

The stimuli were presented on a 24.1 in. liquid crystal display (EIZO ColorEdge CS2420-Z, 1920 × 1200 pixels, 51.84 × 32.4 cm, 48.9 × 31.7°) with a refresh rate of 60 Hz. Each participant sat in a dark room and observed the stimulus with her or his head fixed on a chin rest. The viewing distance was 57 cm. Stimuli were produced and presented using a MacBook Pro (macOS Sierra, 10.12.6, Apple) and MATLAB (R2017b, MathWorks, Inc.) with the Psychophysics Toolbox [12,13]. The right eye position and pupil size were measured during the trials by using an infrared eye-tracker camera with a sampling rate of 500 Hz (iRecHS2 system) [14].

2.3 Stimuli

Stimuli comprised two random dot patterns with different motion directions (left/right) and brightness (black/white) within a red framed (RGB [255, 0, 0]) circle with a diameter of 26.05 deg (Figure 1). The target letters were Japanese Hiragana "a," "i," "u," "e," and "o" presented in that order. Letter sizes ranged from 5.37 to 5.71 deg in width and from 4.77 to 5.75 deg in height. The velocity of the letters was 12.21 deg/s, and the distance between the centers of the letters was

34.73 deg. A letter was presented only when the center coordinate of the letter was within the circle frame. The diameter of a dot was 0.68 deg; the dot density was 1.24 dot/deg^2; and the luminance of the white and black dots was 32.06 cd/m^2 and 0.04 cd/m^2, respectively. The velocity of the dots was 24.42 deg/s for the same brightness as the letters and 12.21 deg/s for different brightness. The luminance of the background was 6.86 cd/m^2.

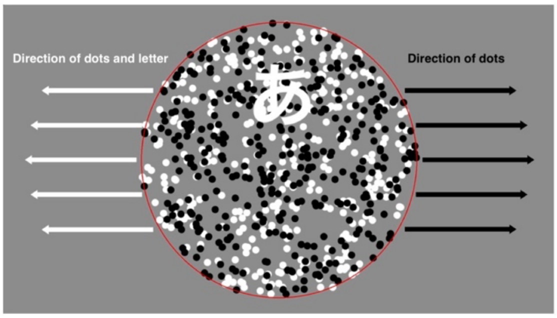

Fig. 1 Stimulus example

2.4 Procedure

Each trial began with the participant pressing a button. Immediately afterward, the participant was instructed on the brightness of the dots to which attention was directed and the target letter. The participant was also instructed to attend to the dots with the same brightness as the target letter when the target letter was presented in the circle. Next, by pressing the button, the fixation point and the target letter were presented for 6 s. Next, the stimulus was presented for 25 s. Twenty conditions were presented in random order: two conditions for the direction of dot motion, two conditions for the brightness of the letter and dots, and five conditions for the target letter. The number of repetitions was one, and the participant performed 20 trials.

2.5 Analysis

Periods of blinking were detected using iRecHS2's default algorithm and were treated as missing data. In addition, trials with more than 35% missing data during the 25 s of the stimulus presentation were excluded from the analysis. Otherwise, outliers were defined as elements more than three times the standard deviation away from the mean, and their missing data were replaced by the nearest nonoutlier using the "filloutliers" function in MATLAB. After replacement, pupil size was smoothed using a Gaussian-weighted moving average filter with a window length of 200 ms, using the "smoothdata" function in MATLAB. Pupil size was measured as arbitrary units (an area of scaled image pixels). Furthermore, default pupil size and pupil response varied among participants. Therefore, pupil size during the stationary and motion stimuli presentation (25 s) for each trial (x_i) was subtracted by its mean (u_i) and divided by its standard deviation (σ_i) to normalize to z scores (zi) so that the mean was 0 and the standard deviation was 1 ($z_i = (x_i – u_i)/\sigma_i$) [11,15,16].

The study identified the slow phase of OKN by referring to the literature [10,11,16]. Horizontal eye velocity as a function of time was calculated by the derivative of the horizontal eye position. For obtaining the slow phase of OKN, the fast phase of OKN and saccade components were excluded from the eye velocity trace, based on the velocity criterion (>12.21 deg/s). After exclusion, data were smoothed using a Gaussian-weighted moving average filter with a time window of 1,000 ms, using the "smoothdata" function in MATLAB. These processed pupils and OKN data were averaged within conditions for each participant.

3 Results

Figure 2 presents pupil size averaged across participants around the timing of the target presentation. The ordinate represents the normalized pupil size. The abscissa represents the time when the target letter was presented as zero. The target letter exited the circle at approximately 2 s. The solid red line shows the mean data under the condition of switching attention from the white dots to the black dots, and the solid blue line shows the mean data under the condition of switching attention from the black dots to the white dots. The color-filled areas show the range within the standard error among the participants' mean values.

The red line in Fig. 2 shows that the pupil began to dilate before the target letter was presented and that the pupil began to constrict after the target letter left the circle. The blue line in Fig. 2 shows that the pupil began to constrict approximately 0.68 s after the target letter was presented and that the pupil began to dilate after the target letter left the circle.

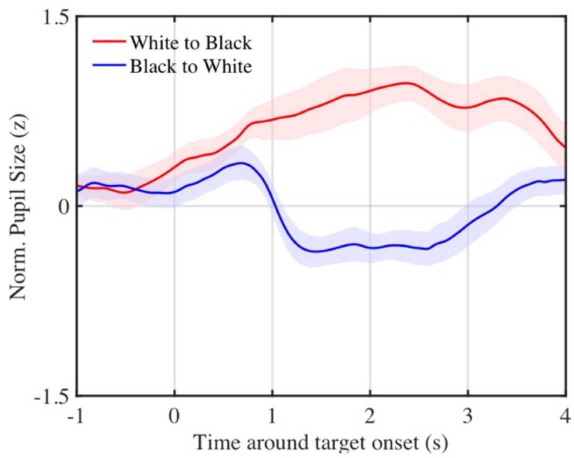

Fig. 2 Time course of average pupil size across participants

Figure 3 presents the slow-phase velocity of OKN averaged across participants around the timing of the target presentation. The ordinate represents the slow-phase velocity of OKN (deg/s). A positive value on the ordinate indicates that an eye velocity is directed to the right side of the display. The solid red line shows the mean data under the condition of switching attention from the dots moving to the right to that moving to the left, and the solid blue line shows the mean data under the condition of switching attention from the dots moving to the left to that moving to the right. The abscissa and each color-filled area represent the same as those in Fig. 2.

The red line in Fig. 3 shows that the slow-phase velocity of OKN changed from positive to negative approximately 0.21 s after the target letter was presented. In addition, the slow-phase velocity of OKN changed from negative to positive approximately 1 s (approximately 3 s) after the target letter left the circle. The blue and red lines in Fig. 3 are similar.

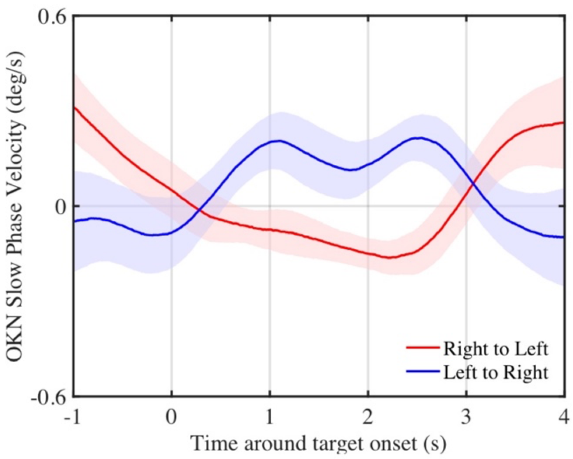

Fig. 3 Time course of average slow-phase velocity of OKN across participants

4 Discussion

This study examined whether the OKN and pupillary responses to the direction and brightness of target motion occur when attention was switched to dots when the target letter was presented. The results showed that the slow-phase velocity of OKN corresponded to the motion direction of the target approximately 0.2–0.3 s after the target was presented. In the pupil response, pupil contraction corresponding to the white target was observed approximately 0.68 s after the target was presented. However, pupil dilations corresponding to the target could not be discriminated; the reason for that limitation was that the pupils dilated before the target was presented when attention was switched from the white dots to the black dots. This study suggests that the two indicators, OKN and pupil response, can be used to estimate the letter to be input.

The result that the changes in the pupil corresponded with the brightness of the attended object when attention was switched to an object with different brightness is consistent with results in the literature [6-8]. However, determining when attention was switched to the black dots was not possible. The reason for this limitation was that the pupil had dilated before the target was presented when the brightness of the target to which attention was switched was from the white dots to the black dots. The reason for pupil dilation before the target presentation is presumed to be that the pupil had returned to its resting state after being fully constricted by the white dots before the target presentation. Thus, restoring pupil size to the resting state is necessary before the attention switch in estimating the timing of the attention switch from pupil size.

The result that the slow-phase velocity of OKN changed corresponding to the motion direction of the attended object is consistent with results in the literature [10]. Unlike the pupil results, OKN corresponded to the motion direction of the attended target, regardless of the motion direction of the target to which attention was switched. The slow-phase velocity of OKN corresponding to the motion direction of the target occurred approximately 0.2–0.3 s after the target was presented, indicating that the response of OKN to the attentional target was faster than the pupil response. This rapid response of the OKN may be related to eye movements involving the OKN and attentional shifts sharing some neural mechanisms [17-19].

5 Conclusions

This study revealed that the input letter can be estimated from the OKN and pupil responses by switching attention to the object at the gaze position. In this study, five letters were presented as input letter candidates. Therefore, it would be possible to increase the number of candidate input letters by simultaneously presenting the letters from various directions (e.g., left, right, up, down, diagonal) and analyzing the directional component of the slow-phase velocity of OKN at that time.

The findings of this study contribute to the development of communication tools for individuals with physical disabilities and elderly individuals. In addition, this technology has high potential for use in the shift from touch-panel input tools to noncontact input tools in various aspects of daily life as a countermeasure against coronavirus disease 2019.

References

[1] N. Birbaumer, “Breaking the silence: Brain–computer interfaces (BCI) for communication and motor control,” Psychophysiology, Vol. 43, No. 6, pp. 517-532 (2006).

[2] T. E. Hutchinson, K. P. White, W. N. Martin, K. C. Reichert, and L. A. Frey, “Human-computer interaction using eye-gaze input,” IEEE Transactions on Systems, Man, and Cybernetics, Vol. 19, No. 6, pp. 1527-1534 (1989).

[3] S. Mathôt, J. B. Melmi, L. Van Der Linden, and S. Van der Stigchel, “The mind-writing pupil: A human-computer interface based on decoding of covert attention through pupillometry,” PloS ONE, Vol. 11, No. 2, e0148805 (2016).

[4] Y. Muto, H. Miyoshi, and H. Kaneko, “Eye-gaze information input based on pupillary response to visual stimulus with luminance modulation,” PloS ONE, Vol. 15, No. 1, e0226991 (2020).

[5] M. I. Posner, “Orienting of attention,” Quarterly journal of experimental psychology, Vol. 32, No. 1, pp. 3-25 (1980).

[6] P. Binda, M. Pereverzeva, and S. O. Murray, “Attention to bright surfaces enhances the pupillary light reflex,” Journal of neuroscience, Vol. 33, No.5, pp. 2199-2204 (2013).

[7] S. Mathôt, L. Van der Linden, J. Grainger, and F. Vitu, “The pupillary light response reveals the focus of covert visual attention,” PloS ONE, Vol. 8, No. 10, e78168 (2013).

[8] M. Naber, G. A. Alvarez, and K. Nakayama, "Tracking the allocation of attention using human pupillary oscillations," Frontiers in psychology, Vol. 4, 919 (2013).
[9] K. Kanari, K. Sakamoto, and H. Kaneko, "Effect of visual attention on the properties of optokinetic nystagmus," PloS ONE, Vol. 12, No. 4, e0175453 (2017).
[10] K. Kanari and H. Kaneko, "Pupil response is modulated with optokinetic nystagmus in transparent motion," Journal of the Optical Society of America A, Vol. 38, No. 2, pp. 149-156 (2021).
[11] M. Naber, S. Frässle, and W. Einhäuser, "Perceptual rivalry: Reflexes reveal the gradual nature of visual awareness," PLoS ONE, Vol. 6, No. 6, e20910 (2011).
[12]D. H. Brainard and S. Vision, "The psychophysics toolbox," Spatial vision, Vol. 10, No. 4, pp. 433-436 (1997).
[13] D. G. Pelli and S. Vision, "The VideoToolbox software for visual psychophysics: Transforming numbers into movies," Spatial vision, Vol. 10, No. 4, pp. 437-442 (1997).
[14] K. Matsuda, T. Nagami, Y. Sugase, A. Takemura, and K. Kawano, "A widely applicable real-time mono/binocular eye tracking system using a high frame-rate digital camera," Lecture Notes in Computer Science, Vol. 10271, pp. 593-608 (2017).
[15] W. Einhäuser, J. Stout, C. Koch, and O. Carter, "Pupil dilation reflects perceptual selection and predicts subsequent stability in perceptual rivalry," Proceedings of the National Academy of Sciences of the United SAtates of America, Vol. 105, No. 5, pp. 1704-1709 (2008).
[16] S. Frässle, J. Sommer, A. Jansen, M. Naber, and W. Einhäuser, "Binocular rivalry: Frontal activity relates to introspection and action but not to perception," Journal of neuroscience, Vol. 34, No. 5, pp. 1738-1747 (2014).
[17] C. Wardak, E. Olivier, and J. R. Duhamel, "A deficit in covert attention after parietal cortex inactivation in the monkey," Neuron, Vol. 42, No. 3, pp. 501-508 (2004).
[18] K. G. Thompson and N. P. Bichot, "A visual salience map in the primate frontal eye field," Progress in brain research, Vol. 147, pp. 251-262 (2005).
[19] J. W. Bisley and M. E. Goldberg, "Attention, intention, and priority in the parietal lobe," Annual review of neuroscience, Vol. 33, pp. 1-21 (2010).