Noncontact brain–computer interface based on steady-state pupil light reflex using independent bilateral eyes stimulation*

Ariki Sato and Shintaro Nakatani

Abstract— **Steady-state visual evoked potential (SSVEP), which uses blinking light stimulation to estimate the attending target, has been known as a communication technique with severe motor disabilities such as ALS and Locked-in-syndrome. Recently, it was reported that pupil diameter vibration based on pupillary light reflex has been observed in the attending target with a constant blinking frequency. This fact suggests the possibility of a noncontact BCI using pupillometers as alternatives to contacting scalp electrodes. In this study, we show an increment in the number of communication channels by stimulating both eyes alone or in combination with different frequencies. The number of selective targets becomes twice the number of frequencies using this method. Experiments are conducted by recruiting three healthy participants. We prepare six target patterns comprising three frequencies and detect the target using a coefficient of correlation of power spectrum between the pupil diameter and stimulus signal. Consequently, the average classification accuracy of the three participants of approximately 83.4% is achieved. The findings of this study demonstrate the feasibility of noncontact BCI systems.**

I. Introduction

In the field of brain-machine interfaces, many papers and products have kindled an enormous among not only the scientific community but also the lay public [1]. Noninvasive BMI systems primarily exploit electroencephalograms (EEGs) to control a wheelchair or other devices. Although the limited capacity of the communication channels provided using EEG-based techniques, this approach has approved to communicate with the people who suffer from severe motor disabilities such as amyotrophic lateral sclerosis (ALS), locked-in syndrome, and spinal cord injury [2], [3].

Steady-state visual evoked potential (SSVEP) is one of the major paradigms of noninvasive BCI [4]–[6]. In SSVEP-based BCI, several patterns modulated at different frequencies are simultaneously presented to the user. Each pattern of response is associated with an action of an output device, and the corresponding action performs by the appearance of the response obtained using electroencephalography. However, the measurement of brain activity causes physical discomfort to the user owing to the need for setting electrodes and probes on the scalp.

The pupil size oscillates according to the oscillation of a visual stimulus under luminance. This phenomenon is known as the pupillary light reflex [7]. The pupillary light reflex increases when a user is subjected to visual stimulus. This allows for decoding the attended target from the frequency of the pupil size oscillation [8], [9].

These results suggest that SSVEP-based BCI can replace the electrode-based contacted scalp potential measurements using electrodes with the noncontact vibration of pupil diameter measurements using a camera. We propose a noncontact BCI system based on a pupilometer (e.g., a remote camera). This system is expected to be a noncontact and calibration-free system that has the same functions as the SSVEP-based BCI system.

Pupillary oscillations caused by light reflex are limited to approximately 2.5 Hz because of biomechanical limitations. This value is lower than the limitation of SSVEP (16 Hz). Frequency limitations can be a disadvantage of the noncontact BCI system in terms of the quantity of information to be transmitted.

In this study, we propose an independent stimulation of both eyes for increasing the quantity of information to be transmitted. The pupillary light reflex causes a combination of the stimuli of both eyes [10]. By presenting the user with patterns modulated at single frequencies and those modulated with a combination of frequencies, more selections can be offered by generating a lesser number of frequencies.

Fig. 1 shows an overview of the proposed system. First, the pupil responses when the participant's eyes are gazing at the target are measured. Second, the obtained signal is compared with the stimulus signal using frequency analysis and the most similar pattern is estimated as the gazing target. Finally, external devices are controlled by following the command of the selected target, such as computers, electric wheelchairs, and robot arms.

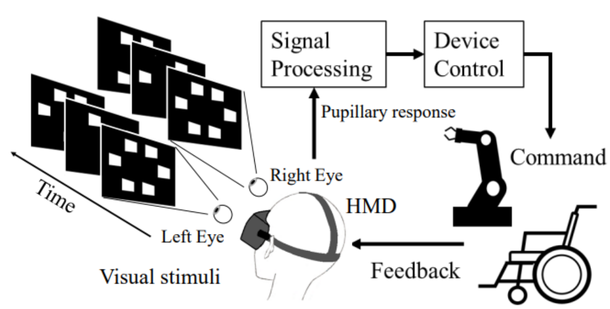

Figure 1. Overview of the proposed noncontact BCI system.

*Research supported by The MAZDA Foundation.

A. Sato is with the Graduate School of Sustainability, Tottori University, 101 4-chome Koyama-cho Minami Tottori-city, Tottori 6808552 Japan.

S. Nakatani is with the Graduate School of Sustainability, Tottori University, 101 4-chome Koyama-cho Minami Tottori-city, Tottori 6808552 Japan (phone/fax: 0857-31-5835; e-mail: snakatani@tottori-u.ac.jp).

II. METHOD

A. Participants recruitment

Three healthy naive males in their twenties (referred to as P1–P3) from the community of Tottori University were enrolled in this study. Informed consent was obtained from all participants before the experiments. The experimental design details were approved by the ethics committee for non-medical research of Tottori University and conformed to the Declaration of Helsinki (7th rev.).

B. Experimental setup

The presentation of stimuli and monitoring of pupil diameter were conducted using a head-mounted display (HMD) (Vive Pro Eye, HTC Corp.). Within this device, each eye views an independent circular segment of a 1,440 × 1,600 pixels stimulus display that subtends a 55° diagonal field of view. The device has integral video-based eye-tracking, performed under continuous infrared illumination at a sampling rate of 120 Hz.

C. Stimulation patterns

As shown in Fig. 2, blinking frequencies were selected from three frequencies, i.e., $F_1 = 0.9$ Hz, $F_2 = 1.25$ Hz, and $F_3 = 1.5$ Hz. The six stimulus patterns ($F_1 : F_1, F_2 : F_2, F_3 : F_3, F_1 : F_2, F_2 : F_3$, and $F_1 : F_3$) were equally displayed in a circle with a radius of 14° of visual field angles from the center of the visual field. Each target was square, and the width and height were both 8° of visual field angles. In this paper, stimulation frequencies are described as (stimulation frequency for the left eye: stimulation frequency for the right eye) using ":". All stimuli were presented at a refresh rate of 90 Hz. Each target consisted of a black 0 $\mathrm{cd/m^2}$ and a white 122 $\mathrm{cd/m^2}$ repetitive blinking stimulus, with a black 0 $\mathrm{cd/m^2}$ background. The luminance of the stimuli was calibrated using a chromameter (ColorCAL II, Cambridge Research System, Kent, UK). Visual stimulation and pupil data acquisition was programmed using Unity (Unity Technologies, USA) with SRanipal SDK (Ver. 1.3.2.0, HTC Corp.).

D. Experimental procedure

We measured the pupil diameter for P1–P3 during an experiment. In one trial of the experiment, the first 10 s were dark, followed by 45 s of visual stimulation. Participants gazed at six targets in random order to eliminate the order effects. We executed three trials to derive the pupil diameter for 18 measurements per participant. Participants were allowed to take a break between trials.

E. Data analysis

To account for individual variability in pupil size, the pupil data were normalized to a 5 s baseline period before each stimulus onset (i.e., normalized pupil size = absolute pupil size/baseline pupil size) [11]. In all the participants, no differences in pupil diameters between the left and right eyes were observed. Given the well-established consensual response of the pupillary light reflex and symmetry in pupil responses between the two eyes in healthy participants, in this paper, we report only the left eye's pupil diameter [12]. Pupil size was interpolated with a cubic spline fit during blinks. The strength of the pupil oscillations was analyzed by performing a discrete Fourier transform, which produces a power spectrum between frequencies. The pupil response was divided into 20 s windows with a frequency resolution of 0.05 Hz, and the power spectral densities were additively averaged with a 50% overlap rate.

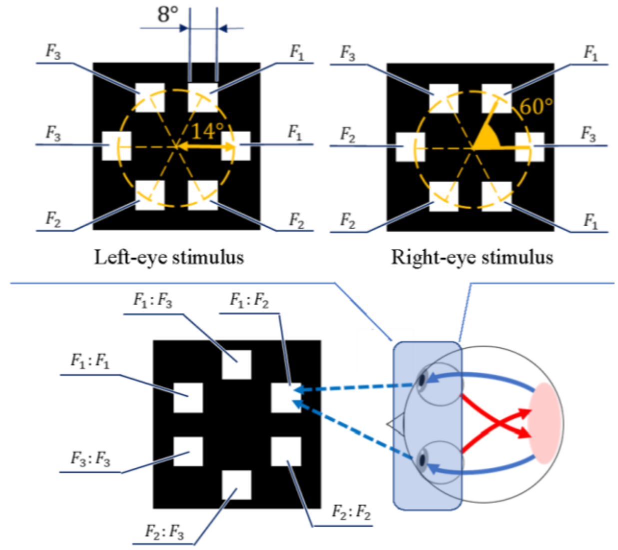

Figure 2. Stimulation patterns of the experiment.

F. Statistical analysis and Classifications

Power spectrum densities of each stimulus frequency ($F_1 - F_3$) were statistically compared with a two-factor analysis of variance (ANOVA), conducted with a gazed target as factor 1, stimulation frequency as factor 2, and Welch's t-test with Bonferroni correction for multiple comparisons. All significance levels were set as $p < 0.05$.

The coefficients of correlation between the power spectrum of the transmitted blinking stimulations and the measured pupil responses were obtained for classifying the gazing target. The one with the highest correlation coefficient was estimated as the gazing target.

III. RESULTS

A. Temporal response

Fig. 3 shows the temporal variation of the pupil diameter during gazing at one of the six visual stimuli. The observer looked at six stimuli that flickered at different frequencies. Before and during the stimulus onset, the pupil was relatively enlarged during the rest period. After stimulus onset, the pupils constricted for about 1 s, after which the pupils oscillated steadily. The pupil dilates before the start of light stimulation, and upon blink stimulus input, the pupil oscillates in synchrony with the blink stimulus. In all participants, pupil oscillation was elicited by the blink stimulus.

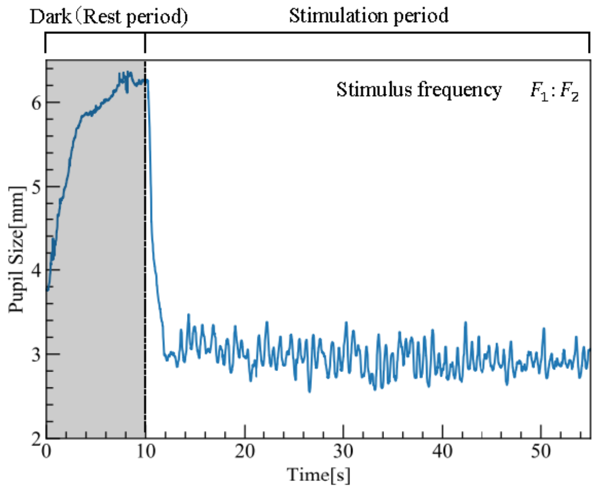

Figure 3. An example of the pupillary light reflex when participant P2 gazes at the F1:F2 (left eye 0.9 Hz: right eye 1.25 Hz) stimulation target. The stimulus was initiated 10 s after the start of the experiment; however, the pupil vibration began after approximately 1 s.

B. Frequency analysis

Fig. 4 shows an example of the frequency analysis of participant P2. The figure shows the power spectrum densities of the light reflex obtained when gazing at each visual stimulus ($F_1: F_1, F_2: F_2, F_3: F_3, F_1: F_2, F_2: F_3, F_1: F_3$). When both eyes stimulated by the same frequency (ex. $F_1: F_1, F_2: F_2, F_3: F_3$), the higher amplitude of the peaks were generated than that of different frequencies (ex. $F_1: F_2, F_2: F_3, F_1: F_3$) were into each eye. The same stimulus given to the left and right retina increases the amount of coincident signal compared with the same stimulus given to one eye.

Fig. 5 shows the mean and standard deviation of the spectral peaks generated when gazing at the visual stimuli blinking at each stimulus frequency. Two-way repeated measures of ANOVA of the gazed target ($F_1: F_1, F_2: F_2, F_3: F_3, F_1: F_2, F_2: F_3, F_1: F_3$) × the stimulation frequency (F_1, F_2, F_3) identified a significant interaction between gazed target and stimulation frequency ($F(10,144) = 1.897$, $p < 0.001$). Under each gaze condition, the power of the gazed stimulus frequency was significantly greater than that of the nongazed stimulus frequency ($t(8) >= 2.8$, $p < 0.05$). In other words, the power of the gazed stimulus frequency was greater than that of the frequency excluded from the gazed stimulus in both the condition in which the same frequency stimulus was gazed and the condition in which the left and right pupils gazed at different frequencies. The power spectrum selectively enhanced the frequency of the gazed patterns.

The power of the stimulation frequency was greater in the condition in which participants gazed at the same frequency stimulus than in the condition in which participants gazed at different frequencies on the left and right sides ($t(8) >= 2.8$, $p < 0.05$), although no significant difference between $F_2: F_2$ and $F_1: F_2$ for F_2 ($t(8) = 0.84$, $p = 0.8$) was observed. This indicates that the participants responded strongly to the gazed stimuli and equally reflected the effects of visual stimuli on the left and right pupils without erasing them.

C. Classification

TABLE I indicates the estimated accuracy (in %) for each target. The correlation coefficient between the power spectrum of the transmitted blink stimulus and the measured pupil response was calculated, and the one with the highest correlation coefficient was estimated as the gazing target. The results for the conditions in which the subjects gazed at the same frequency stimuli ($F_1: F_1, F_2: F_2, F_3: F_3$) were 100 %,

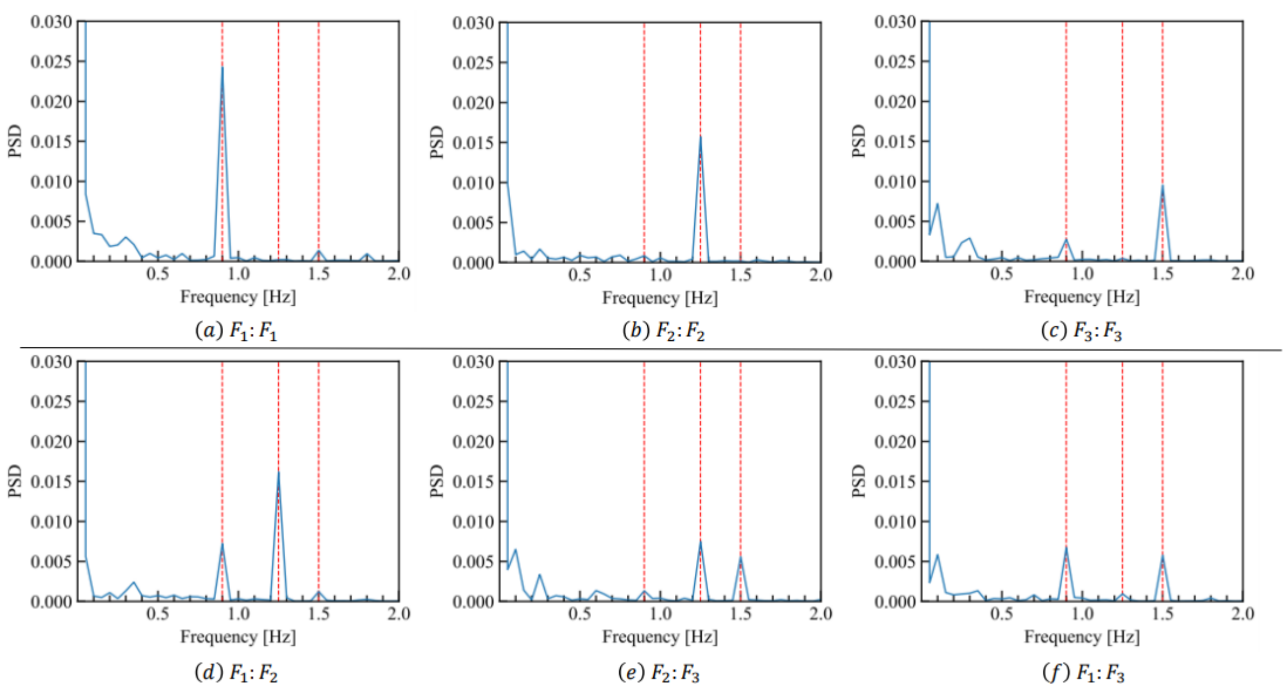

Figure 4. Frequency analyses during the participants P2 were looking each stimulation pattern.

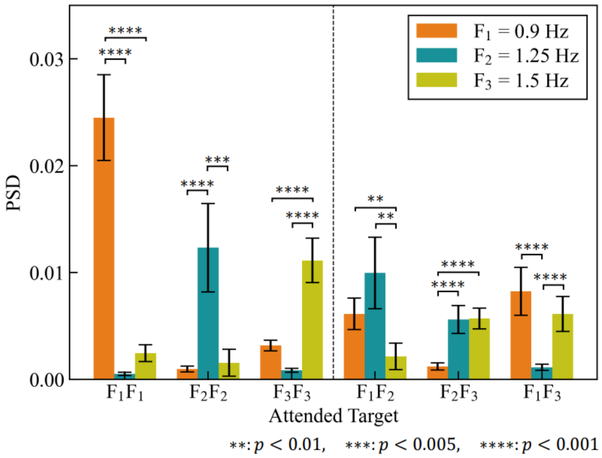

Figure 5. Means of the power spectrum. Error bars show standard deviation.

TABLE I. Normalized confusion matrix classifying the six patterns. the accuracy of F2:F3 is the lowest because the amplitude decreases as the frequency increases, resulting in a poor signal-to-noise ratio.

(%)		Estimated label					
		F_1: F_1	F_2: F_2	F_3: F_3	F_1: F_2	F_2: F_3	F_1: F_3
True label	F_1: F_1	100	0	0	0	0	0
	F_2: F_2	0	100	0	0	0	0
	F_3: F_3	0	0	88.9	0	0	11.1
	F_1: F_2	0	22.2	0	66.7	11.1	0
	F_2: F_3	0	11.1	22.2	0	66.7	0
	F_1: F_3	22.2	0	0	0	0	77.8

100%, and 88.9%, respectively. Additionally, for the condition in which the subjects gazed at stimuli of different frequencies (F_1: F_2, F_2: F_3, F_1: F_3) on the left and right sides, the 66.7%, 66.7%, and 77.8% values were obtained. False positives, due to the influence of nearby stimuli were found to be significantly higher than all chance levels. These results show that six patterns created from three frequencies could be separable.

IV. Discussion

In this study, we investigated the response of the pupil when the stimulation frequency of each eye was different. We used an HMD to measure the temporal changes in the pupil diameter when the gaze stimuli were changed in each trial. As a result, the spectrum of the frequency equivalent to the gazed stimulus became larger. When both eyes gazed at a single frequency stimulus, a single peak appeared, and when both eyes gazed at different frequencies, two peaks appeared. The amplitudes of the peak were high when the stimuli frequency of both eyes were the same (e.g., F_1: F_1, F_2: F_2, F_3: F_3), and it was low when the stimuli frequency of each eye was different (e.g., F_1: F_2, F_2: F_3, F_1: F_3).

The discrimination rate was 96.3% for the condition in which participants gazed at the same frequency stimuli and 70.4% for the condition in which participants gazed at different frequencies on the left and right sides. The discrimination rate of the condition in which the left and right eyes gazed at different frequencies of stimuli was smaller than that of the condition in which the participant gazed at the same frequency. The power of the stimulus frequency increased in the condition where the stimulus frequency was the same. However, in the condition where the stimulus frequency was different between the left and right eyes, the power of each stimulus frequency decreased because the power of each frequency was distributed to the two stimulus frequencies.

The discrimination rate was higher than the chance level (16.7%), suggesting that it is possible to discriminate the target of attention. In a recent report, an SSVEP-based BCI achieved an average discrimination rate of 90.9% against the chance level of 20% [13]. Our result is not so bad compared with the recent SSVEP-based BCI. Eye tracking by camera or electro-oculography (EOG) is also useful in gaze estimation, but eye tracking requires accurate calibration and has the misclassification of selecting unattended (but looking) targets. However, eye tracking requires accurate calibration and has the misclassification of selecting unattended (but looking) targets. Therefore, by combining eye movement measurement by eye tracking and SSVEP measurement by blinking stimuli, we can discriminate truly gazing objects [14], [15]. In this system, pupil measurement is also expected to be combined with eye tracking in a simple system using only a camera.

In addition, by providing simple stimuli modulated only by ON-OFF to the left and right eyes independently, we can easily predict responses and reduce the consideration of luminance characteristics of monitors.

By providing different visual stimuli to the left and right, nonlinear responses are expected to be obtained in both SSVEP and pupillary responses. However, there are many theories about the integration of the signals transmitted from the left and right retina [16], and the mechanism of this nonlinearity is still unclear. It is expected that the nonlinearity of the pupil diameter change caused by multiple frequency stimuli will be clarified in the future.

V. Conclusion

In this study, we investigated the possibility of replacing the SSVEP generated in the visual cortex with a change in pupil diameter due to light reflex in BCI, which detects whether a person has gazed at a flickering target. We also proposed a method to increase the number of patterns by changing the stimulus input to the left and right eyes to resolve the problem that the number of available stimulus frequencies is smaller than that of SSVEP-based BCI.

We measured the temporal changes in the pupil diameter when flickering stimuli at different frequencies were presented to the left and right pupils using an HMD. As a result, the frequencies corresponding to the stimuli attended by the left and right pupils were observed mixed from the monocular. Therefore, it shows that we can provide many patterns for selections by combining a few numbers of frequencies for stimulation in light reflex-based noncontact BCI.

Acknowledgment

This research is supported by the MAZDA foundation.

REFERENCES

[1] J. R. Wolpaw, N. Birbaumer, D. J. McFarland, G. Pfurtscheller, and T. M. Vaughan, “Brain–computer interfaces for communication and control,” Clin. Neurophysiol., vol. 113, no. 6, pp. 767–791, 2002.

[2] J. P. Donoghue, “Bridging the Brain to the World: A Perspective on Neural Interface Systems,” Neuron, vol. 60, no. 3, pp. 511–521, 2008.

[3] L. F. Nicolas-Alonso and J. Gomez-Gil, “Brain computer interfaces, a review,” Sensors, vol. 12, no. 2, pp. 1211–1279, 2012.

[4] D. Regan, Human brain electrophysiology: evoked potentials and evoked magnetic fields in science and medicine. Elsevier C Publisher, 1989, pp. 413-414.

[5] M. M. Müller, T. W. Picton, P. Valdes-Sosa, J. Riera, W. A. Teder-Sälejärvi, and S. A. Hillyard, “Effects of spatial selective attention on the steady-state visual evoked potential in the 20-28 Hz range,” Cogn. Brain Res., vol. 6, no. 4, pp. 249–261, 1998.

[6] S. T. Morgan, J. C. Hansen, S. A. Hillyard, and M. Posner, “Selective attention to stimulus location modulates the steady-state visual evoked potential,” Neurobiology, vol. 93, no. May, pp. 4770–4774, 1996.

[7] P. M. Sherman and L. Stark, “A servoanalytic study of consensual pupil reflex to light,” J. Neurophysiol., vol. 20, no. 1, pp. 17–26, 1957.

[8] P. Binda, M. Pereverzeva, and S. O. Murray, “Attention to bright surfaces enhances the pupillary light reflex,” J. Neurosci., vol. 33, no. 5, pp. 2199–2204, 2013.

[9] M. Naber, G. A. Alvarez, and K. Nakayama, “Tracking the allocation of attention using human pupillary oscillations,” Front. Psychol., vol. 4, no. DEC, pp. 1–12, 2013.

[10] D. Varju, Human pupil dynamics. New York: Academic Press, 1969, pp. 442-464.

[11] M. Zivcevska, A. Blakeman, S. Lei, H. C. Goltz, and A. M. F. Wong, “Binocular summation in postillumination pupil response driven by melanopsin-containing retinal ganglion cells,” Investig. Ophthalmol. Vis. Sci., vol. 59, no. 12, pp. 4968–4977, 2018.

[12] I. E. Loewenfeld, The Pupil: Anatomy, Physiology, and Clinical Applications., vol. 1. Ames, IA: Iowa State University Press, 1993, pp.17-25.

[13] C. T. Lin et al., “A Wireless Multifunctional SSVEP-Based Brain-Computer Interface Assistive System,” IEEE Trans. Cogn. Dev. Syst., vol. 11, no. 3, pp. 375–383, 2019.

[14] A. N. Belkacem et al., “Real-Time Control of a Video Game Using Eye Movements and Two Temporal EEG Sensors,” Comput. Intell. Neurosci., vol. 2015, 2015.

[15] A. N. Belkacem, D. Shin, H. Kambara, N. Yoshimura, and Y. Koike, “Online classification algorithm for eye-movement-based communication systems using two temporal EEG sensors,” Biomed. Signal Process. Control, vol. 16, pp. 40–47, 2015.

[16] F. H. Baker, “Pupillary Response to Double-Pulse Stimulation; a Study of Nonlinearity in the Human Pupil System,” J. Opt. Soc. Am., vol. 53, no. 12, pp. 1430–1436, 1963.