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RESEARCH ARTICLE

Simple Wearable Eye Tracker With Mini-Infrared Point Sensors

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ABSTRACT In this study, we developed a wearable eye tracker leveraging mini-infrared point sensors. The eye tracker utilized two inexpensive mini-infrared ray (IR) point sensors to measure the left-right eye movements of both eyes. These left-right eye movements, play a crucial role in monitoring and treating mental disorders such as post-traumatic stress disorder, and are also essential in eye movement desensitization and reprocessing therapy (EMDR). The proposed eye tracker can track a user's eye movements by detecting the left-right pupils. We developed a dual sensor positioning algorithm that measures the left-right movements of both eyes using only two sensors. The strategy of positioning the sensor symmetrically between or outside the eyes allows for the precise measurement of the movements of both eyes. To validate the proposed wearable eye tracker, we analyzed the left and right eye movements of 10 participants and found that there was no statistically significant difference. Further analysis demonstrated a high correlation between the measured eye-movement and the input eye-movement frequency (Spearman's correlation coefficient: 0.9619). The proposed device showed the feasibility of employing a wearable and inexpensive eye tracker with only two mini-IR point sensors to accurately measure the left-right movements of both eyes.

INDEX TERMS Eye tracker, eye-movement desensitization and reprocessing, infrared sensor, post-traumatic stress disorder.

I. INTRODUCTION

Eye Movement Desensitization and Reprocessing (EMDR) is a treatment developed by Francine Shapiro [1], [2]. Currently, it is regarded as one of the most effective psychological treatments for mitigating the aftereffects of trauma, such as Post-Traumatic Stress Disorder (PTSD) [3], [4]. EMDR serves to alleviate the mental and physical discomfort linked to early traumatic memories, fostering a positive self-perception, and thereby aiding in reducing cognitive processing changes and trauma-related pain associated with distressing memories. Consequently, treatment methods incorporating EMDR offer patients relief from mental anxiety and facilitate their return to their original life by fostering resilience within the brain itself. The method of Alternating Bilateral sensory Stimulation (ABS) using EMDR is employed in psychotherapy to treat mental disorders such as PTSD. ABS achieves this by stimulating the nervous system through left-right eye-movements, influencing the efficacy of EMDR treatment [5], [6]. Traditional EMDR treatment involves manual bilateral stimulation achieved through hand movements. However, this approach can lead to neck stiffness, shoulder pain, and wrist discomfort. One recent solution employed Light-Emitting Diode (LED) bars [7] that guided the patient's eye-movements. EMDR LED bar not only mitigate overall psychotherapist fatigue but also offer controllable conditions such as LED color, intensity, and speed to accommodate patient preferences. Here, a patient initiates left-right eye-movements facilitated by the EMDR LED bar. Consequently, the nervous system is stimulated by the left-right eye motion, thus positive affecting the EMDR treatment.

The patient receives ABS through an EMDR LED bar under the guidance of a psychotherapist. To ensure the reliability of EMDR treatments, EMDR LED bar were used

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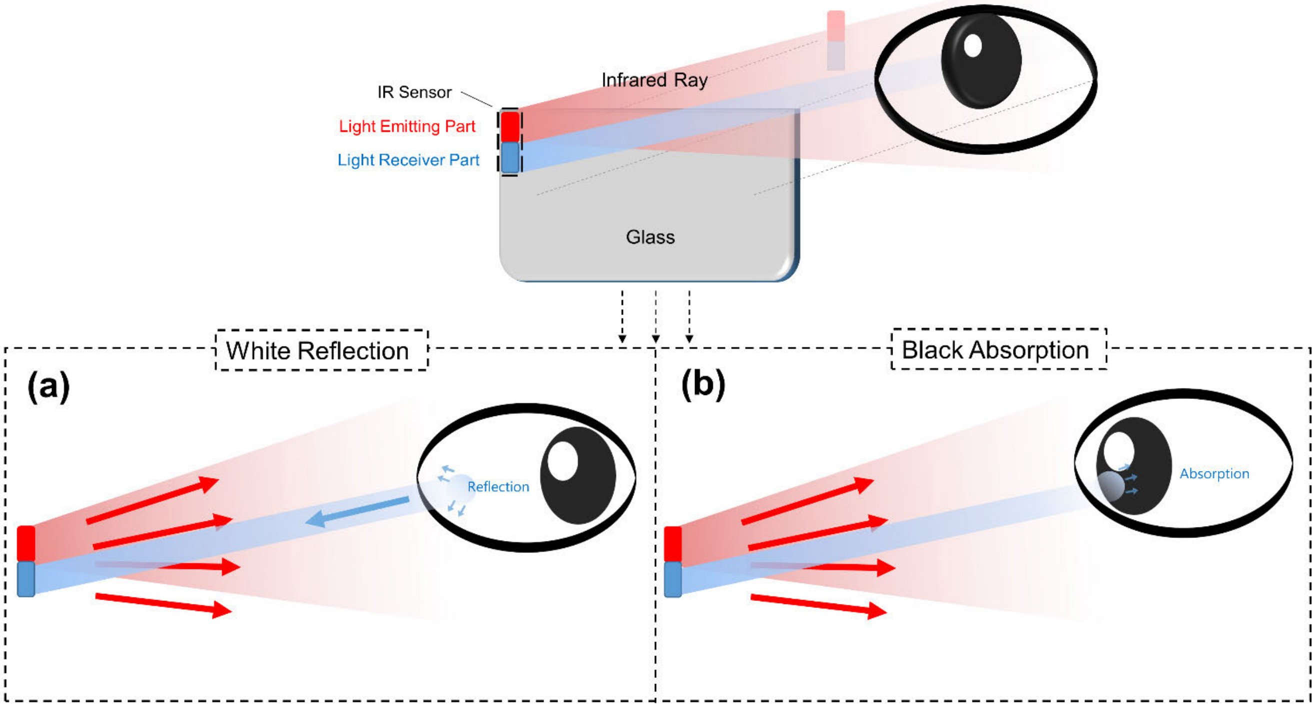

FIGURE 1. Pupil-detection principles using a mini-IR sensor. (a) In the of the sclera, the IR emitted from the light-emitting part meet the white surface of the sclera, and the IR are reflected. The reflected IR were detected in the light-receiving area. (b) In the case of a pupil, when IR emitted from the emitter meet a black pupil, the black pupil absorbs the IR, which then do not enter the receiver.

to induce eye-movements in patients since stable and constant eye-movements aid in standardizing EMDR treatments. However, psychotherapists must verify whether the patient is performing the eye-movements correctly, underscoring the need for an eye tracker to streamline EMDR treatments.

An eye tracker is a device that measures the position and movement of the eye [8], [9]. It is widely used in psychology and marketing, especially in the fields of mental treatment, rehabilitation, and medical support [10], [11], [12]. An eye tracker tracks the user's gaze and measures eye-movement; it typically employs cameras and sensors to detect eye-movement and pinpoint the user's focal points. It improves user-interface experiences through eye tracking and assesses advertising campaign efficacy and product design testing [13]. In the medical field, this technology contributes to studying neurological diseases such as strokes, Parkinson's disease, and Alzheimer's disease, and aids in developing treatments [14], [15], [16], [17], [18], [19], [20]. Recently, eye trackers have been adopted in areas like virtual reality and augmented reality technologies to dynamically change the environment based on user gaze [21], [22]. These devices vary in types and sizes, selected according to their usage and environment. The range encompasses desktop-mounted, head-mounted, portable, remote, and wearable eye trackers. A wearable eye tracker, worn as glasses, goggles, and masks, tracks eye movements during daily activities. Here, IR camera [23], [24], [25], [26], [27], [28] is employed to identify the eye position and track eye movements. Wearable eye trackers are suitable for real-time monitoring due to their high integration and convenient portability. As a result, it can collect user gaze-tracking data more accurately, thereby enhancing the precision of eye-tracking analysis.

Thus, a simple and wearable eye-movement measurement device is necessary for standardizing EMDR treatments. Therefore, we developed a simple, wearable EMDR medical device using inexpensive mini-IR sensors, such as the wearable eye tracker. As shown in Fig. 1, inexpensive mini-IR sensors could distinguish pupil and sclera, offering the potential for wearable and inexpensive eye trackers.Fig. 1(a) shows most IR is reflected by sclera and Fig. 1(b) shows pupil absorb most IR and reflected IR is small. Unlike the expensive and heavy IR cameras currently used in eye movement monitoring systems, we proposed an algorithm that can measure the left and right movements of both eyes using two mini- IR sensors. The remainder of this paper is organized as follows. Section II describes the algorithm of the device. Section III presents the testing results of the prototype. Section IV explains statistical analysis methods. Section V introduces eye detection using mini-IR sensors. Section VI discusses the results of the eye measurement experiments, while Sections VII and VIII provide discussion and conclusions. The paper highlights are as follows.

[Highlight of Eye Tracker]

- The left-right eye-movement using dual mini-IR (Dual sensor positing algorithm)
- Cheap and wearable eye tracker

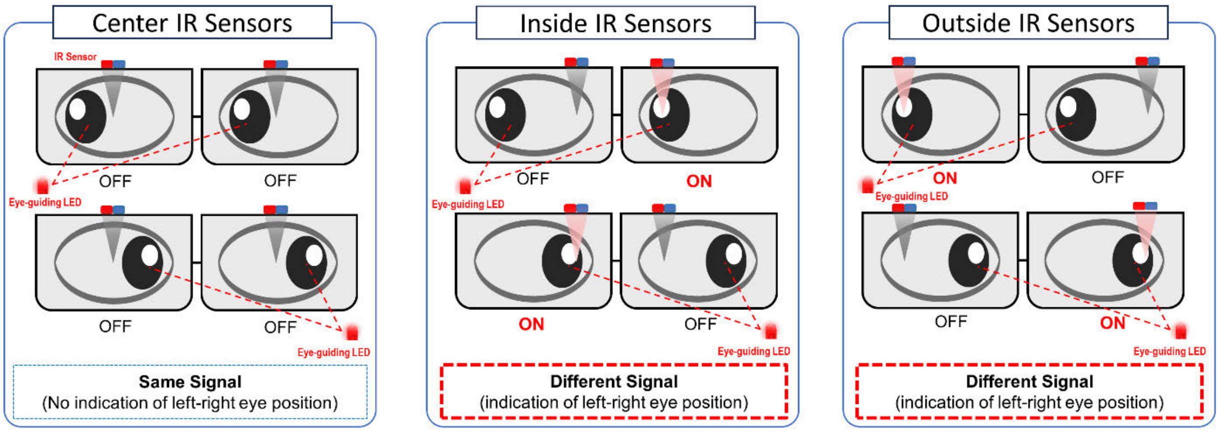

FIGURE 2. Dual sensor positioning algorithm for the left-right eye-movement. Left-right eye-movement cannot be distinguished when the sensor is centered. However, when the sensor is placed between or outside, the left-right eye-movement can be measured.

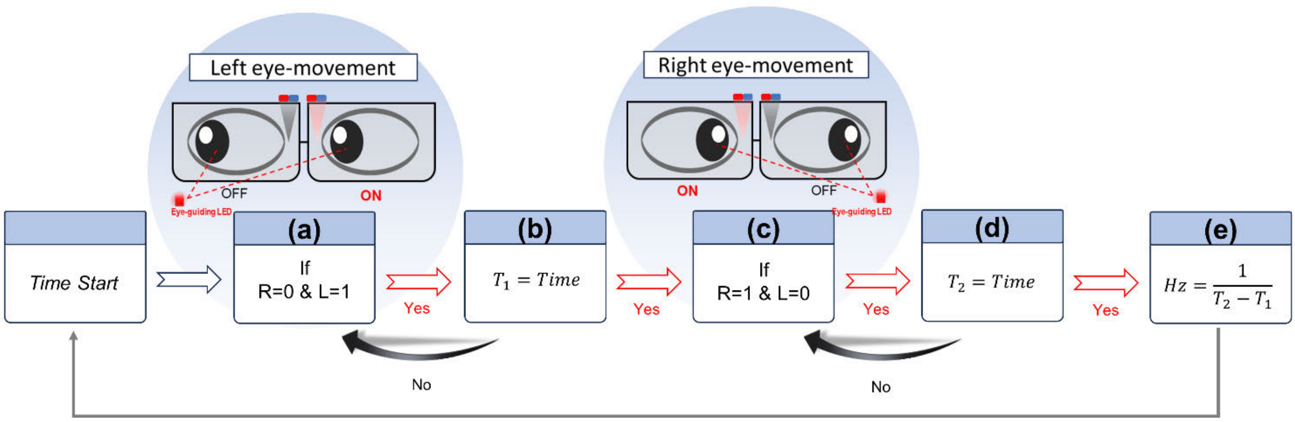

FIGURE 3. Flow chart of the dual sensor positing algorithm for measuring the left-right eye-movement frequency. The time measurement is obtained when the right signal is 0 and the left signal is 1, the T1 time measurement is obtained. Conversely, when the left signal is 1 and the right signal is 0, the T2 time measurement is obtained. The time T1 and T2 acquired is used to measure the patient's frequency. If the T1 and T2 time measurements do not align with the specified criteria, a re-measurement is performed. (a) Determine the time when Right = 0 and Left = 1. (b) The time when Right = 0 and Left = 1 is stored as T1. If the conditions are not met, measure again. (c) Determine the time when Right = 1 and Left = 0. (d) The time when Right = 1 and Left = 0 is stored as T1. If the conditions are not met, measure again. (e) When T1 and T2 are obtained under the applicable conditions, Hz is measured using the above formula.

- Integrated eye tracker with eye-guiding LED for EMDR (eye movement desensitization and reprocessing therapy)

II. EYE-MOVEMENT FREQUENCY MEASURING ALGORITHM

The optimal sensor position was determined by comparing the sensor location with that of the eye. Fig. 2 illustrates the activation and deactivation of the sensor based on its position and that of the eye. When the sensor is placed at the center and the pupil is also centered, it detects the pupil's position, thus resulting in an activated state. However, if the pupil is located on the left or right side, the sensor does not detect its movement and is deactivated. Conversely, if the pupil is centered when the sensor is placed between or outside, it falls outside the detection range of the sensor and remains deactivated. However, if the pupil moves from left to right, each sensor on either side detects the movement that results in an activated state. In this case, the accurate measurement of left-right eye-movements is possible, thus making the sensor position favorable. Through this analysis, we established the optimal sensor position, thus enabling the precise detection and measurement of eye-movements. Fig. 3 presents an algorithm for measuring and a method for calculating the left- right eye-movement frequencies (in Hz) in detail. The algorithm primarily involves time measurements obtained from signals received by sensors. As shown in Fig. 3(a), we measured the time at which the right signal was 0 (OFF) and the left signal was 1 (ON). This situation indicates the left eye-movement. If the signals did not match, the measurement process was restarted to ensure precise data collection. In Fig. 3(b), the time at which the right and left signals were 0 (OFF) and 1 (ON) is denoted as T1. Similarly, in Fig. 3(c), we measured the time at which the right signal

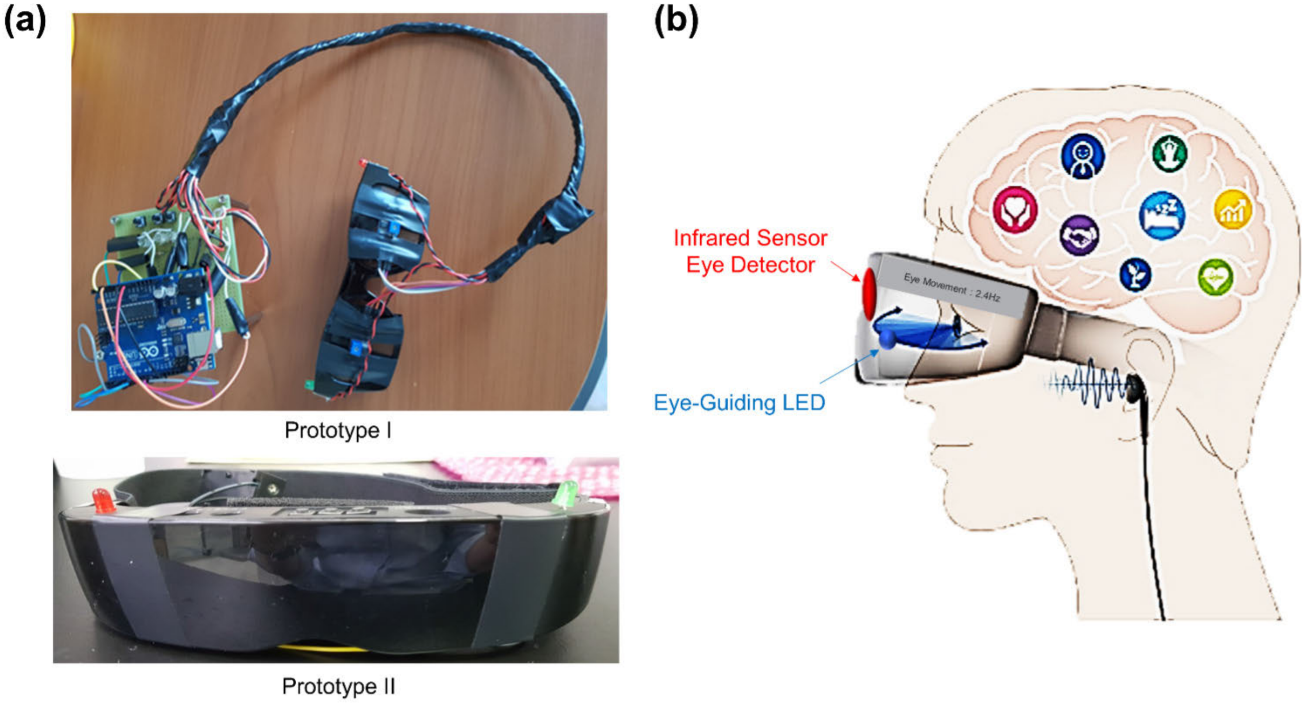

FIGURE 4. Measured frequency (Hz) according to different frequencies of eye-movement. (a) Sample of prototypes I and II worn and used by humans. Prototype I was an early model, and prototype II was an improved model with an eye-guiding LED. (b) Illustration in which a mini-IR sensor detects and measures the frequency when the user is wearing an eye tracker and performing eye-movements.

was 1 and the left signal was 0. This situation indicates the right eye-movement. In Fig. 3(d), the measurement time was T2, wherein the right and left signals were 1 (ON) and 0 (Off), respectively. In Fig. 3(e), the frequency of movement (Hz) of the left-right eyes was calculated using the following formula:

$$Frequency[Hz] = \frac{1}{T_2 - T_1} \tag{1}$$

III. EYE-MOVEMENT FREQUENCY MEASURING ALGORITHM

Fig. 4(a) presents photographs of the prototypes I and II of the eye trackers. In Prototype I, only mini-IR sensors are used to measure the movement of the user's eyes. Prototype II included an eye-guiding LED eye-movement for the EMDR treatment in patients. The eye-guiding LED the patient to move their eyes during the EMDR treatment, and the mini-IR sensors monitor the eye-movements while the patient performs eye-movements as part of the treatment. In the existing EMDR treatment, the therapist monitors the patient's eyes to see if they are receiving treatment by moving their eyes according to the LED guide. Prototype II supports simultaneous eye-movement guidance and eye-movement, thus allowing therapists to focus on intensive care. Fig. 4(b) presents an illustrative image of prototype II. Fig. 5 presents each prototype during operational testing. In Prototypes I and II, we created indication LEDs over the eye trackers. It was confirmed that the eye-indicating LED lights on the left-right over the eye tracker were turned on when the eyeball moved left-right.

IV. STATISTICAL ANALYSIS

All statistical analyses were performed using the GraphPad Prism software 10 (version 10.0.1; Los Angeles, CA, USA). We conducted tests to compare the frequencies of the eye-guiding LED (control) and the ten participants under the same conditions. The p value was calculated using the mean value for each participant. The p value was set at a 95% confidence interval with a two-tailed approach, and a p value of less than 0.05 was considered statistically significant.

V. DETECTION OF PUPIL USING MINI-INFRARED POINT SENSOR

The pupil detection tests were conducted using general-purpose mini-IR sensors (IR transmission and reception; TCRT5000, VISHAY, USA). The sensor is widely known for its versatility and ease of implementation in various applications, facilitating the production of inexpensive eye trackers. As shown in Fig. 1, the mini-IR sensor emits IR directed toward the subject's eyes. These IR interact with the eye surface and are reflected, eventually entering the light-receiving part of the sensor. To quantify the reflected IR and analyze their behavior, we carefully measured IR intensity reflected from the eye into the light-receiving portion of the sensor. The collected data was graphically displayed to visualize and interpret IR intensity patterns. Fig. 6(a) presents a photograph

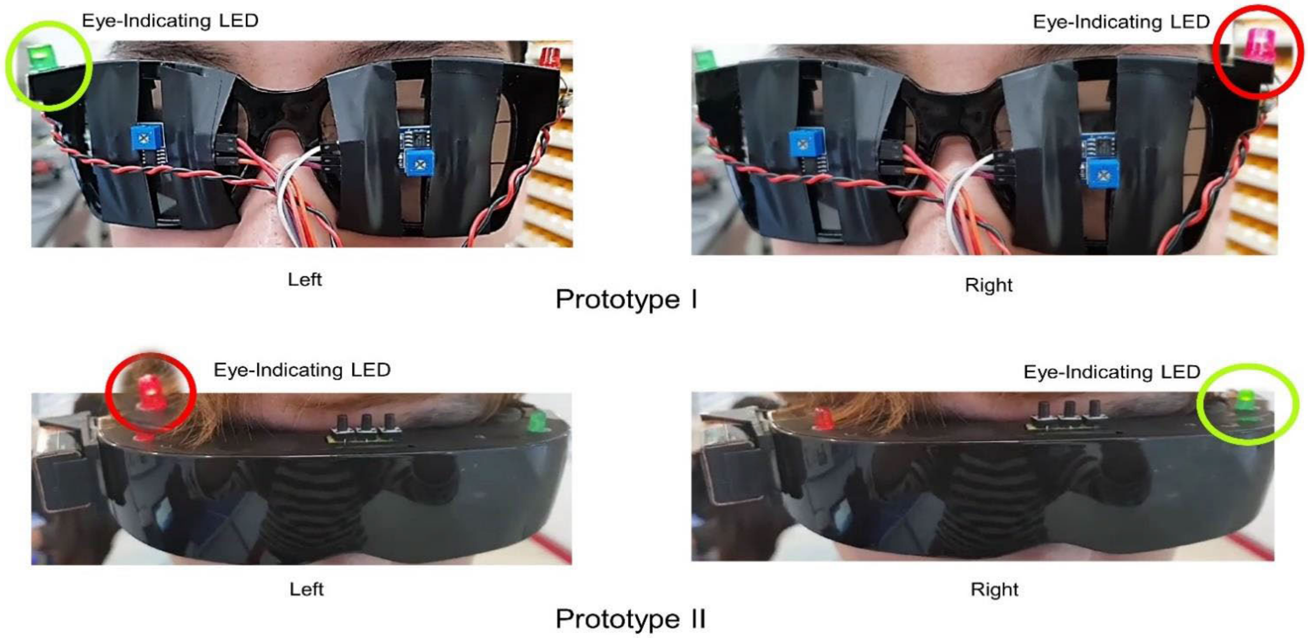

FIGURE 5. **Measured frequency (Hz) according to different frequencies of eye-movement. (a) Sample of prototypes I and II worn and used by humans. Prototype I was an early model, and prototype II was an improved model with an eye-guiding LED. (b) Illustration in which a mini-IR sensor detects and measures the frequency when the user is wearing an eye tracker and performing eye-movements.**

of the position of the mini-IR sensor associated with the subject's eyes. The resulting graph in Fig. 6(b) presents the inverted signals of IR intensity reflected from the eye. This unique pupil behavior in response to IR light facilitates its differentiation from other parts of the eye. When we examined the sclera, that is, the white part of the eye, we noted that the inverted IR intensity value remained at approximately 50 AU, indicating the effective reflection of the incident IR. In contrast, the pupils exhibited a significantly higher inverted IR intensity level above 150 AU. The black color of the pupil absorbed all the IR radiation and exhibited a high intensity of the inverted IR radiation.

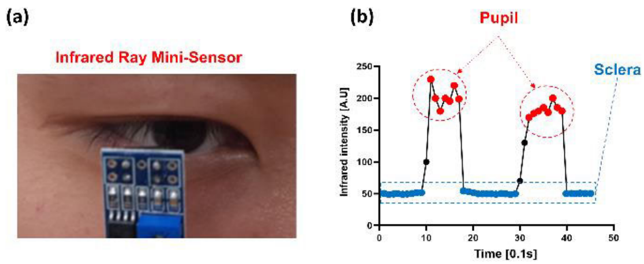

FIGURE 6. **Mini-IR sensor data according to pupil and sclera. (a) Sample of prototypes I and II worn and used by humans. Prototype I was an early model, and prototype II was an improved model with an eye-guiding LED. (b) Illustration in which a mini-IR sensor detects and measures the frequency when the user is wearing an eye tracker and performing eye-movements.**

VI. MEASUREMENT OF LEFT-RIGHT EYE-MOVEMENT

The left-right eye-movement detection algorithms depend on the positions of the two sensors (Fig. 2). The measurement results are influenced by the locations of the two sensors. For example, accurately measuring the left-right movements of the pupil is challenging when the sensor is placed in the middle position since the sensor signals of the left-right eye positions are identical. This makes it difficult to distinguish the left-right movements. However, if the sensor is placed in a left-right location, it is easier to differentiate the left-right eye-movements. Fig. 3 provides a detailed illustration of the eye-movement frequency-measuring algorithm. Using this algorithm, we measured the interval times of the eye-movements based on the signals from the left-right eyes. The frequencies (Hz) of the eye-movements were calculated using these interval times.

Eye-movement frequency measurements were performed on the ten participants to thoroughly evaluate the effectiveness of the eye tracker. During this trial, the participants were instructed to move their eyes along an eye-guiding LED on a prototype IR eye tracker. The eye-guiding LED moved at a frequency of 0.33 Hz. Notably, the measured eye-movement frequencies of all the ten participants closely matched the frequency of the eye-guiding LED, thus indicating the precise tracking capability of the proposed eye tracker (Fig. 7). To statistically validate our findings, we calculated the p values for each dataset, and the results showed no significant difference compared with the eye-guiding LED. In addition, the frequency of the eye-guiding LED was changed in seven steps within the eye-movement frequency range to provide a comprehensive evaluation. Subsequently, the measured frequencies of the eye tracker and eye-guiding LED were compared to determine whether they were similar.

As shown in Fig. 7, the frequencies obtained from the eye tracker closely matched those of the eye-guiding LED at all

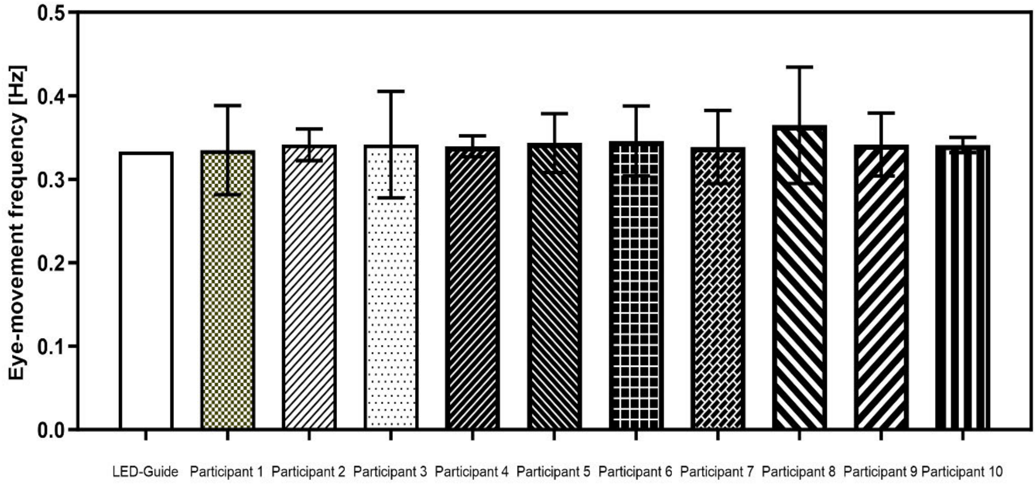

FIGURE 7. Measured frequency (Hz) of left-right eye-movement with eye-guiding LED (control) and ten participants. We compared the measurements of ten different people and controls in Hz, with a measured value of 0.33 Hz. As a result, the measured values were like those of the control Through the results in the graph above, it was confirmed that there was no statistically significant difference.

stages. To confirm that there were no differences between users, an experiment was conducted on ten participants, and it was confirmed that there were no statistically significant differences according to users. The *p* values are higher than 0.05, which means there is no significant difference. Fig. 8(a) resents the frequencies of the eye-guiding LED and the measured frequencies of the eye tracker. As the frequency of the eye-guiding LED increased, the measurement frequency also increased. Fig. 8(b) resents the relationship between the frequencies of the eye-guiding LED and eye tracker, thus confirming a high correlation between the two datasets ($R^2 =$ 0.9619). This result validates the accuracy and reliability of our eye-movement frequency measuring algorithm and its ability to track and analyze eye-movements precisely.

In conclusion, our eye-movement detection algorithm based on two inexpensive mini-IR point sensors proved an effective and accurate method for tracking eye-movements. The successful correlation between our eye tracker and eye-guiding LED demonstrates its potential for various applications, such as eye-tracking systems, medical diagnostics, and human–computer interaction, thus introducing new avenues for advancing eye-movement analysis and research. With its promising abilities and inexpensive mini-IR point sensors, our eye-movement detection algorithm has great potential for contributing to the fields of human behavior analysis, health monitoring, and cognitive research, which would usher in a new era of precise and reliable eye-tracking technology.

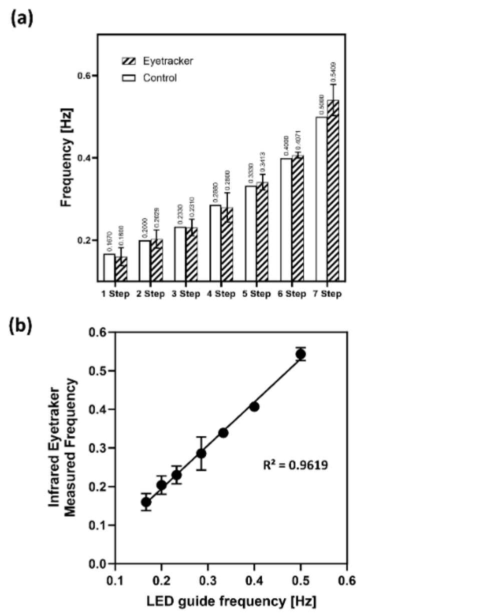

FIGURE 8. Measured frequency (Hz) according to different frequencies of eye-movement. The frequency obtained from the eye tracker worn by the user was compared with the control values at different stages. The frequencies measured using the eye tracker demonstrated a significant similarity to those recorded under the actual control conditions. The linearity of this graph was verified by the R^2 value (0.9619). This high R^2 value indicates a strong linearity between the eye tracker's measurement and control, which suggests a high accuracy in the tracking of the eye-movement frequencies over multiple steps. (a) The control frequency and measured frequency of eye tracker in a total of 7 steps (0.167~0.5Hz). (b) Comparison of the control frequency and measured frequency.

VII. DISCUSSION

EMDR therapy is an essential method for treating conditions such as PTSD and other trauma-related disorders. The EMDR LED bar helps patients move their eyes to the left-right using an eye-guiding LED. The EMDR LED bar not only alleviates the fatigue and discomfort of psychotherapists but also allows for diverse control conditions tailored to patients. Moreover, for sustained EMDR treatment, the LED bar induces eye-movements in patients, facilitating consistent and stable eye-movements that contribute to the effectiveness of EMDR therapy. However, the LED bar did not monitor the eye-movements, so Psychotherapists must monitor a patient's eye-movements for a long time. Therefore, in this study, we propose a new device that is easy to use and portable, which can induce eye-movement using a LED and monitor a patient's continuous eye-movement in real-time. This device employs two inexpensive mini-IR sensors to measure a user's eye-movements. Using inexpensive mini-IR sensors, it distinguishes between the pupil and sclera, with eye-indicating LEDs detecting the movement of the eye according to the signals from the mini-IR sensors. The dual-sensor positioning algorithm can detect left-right eye-movements when two sensors are positioned between or outside the eyes. The users wore an eye tracker and moved their eyes based on the eye-guiding LED. The mini-IR sensor detected eye-movements and the corresponding eye-indicating LEDs were illuminated. When the sensors were positioned at the center, it became difficult to accurately detect left-right eye-movements along the eye-guiding LED. However, when the sensors were placed between or outside the eyes, the eye-indicating LEDs on the respective side were illuminated as the eye moved left or right, thus allowing for the accurate detection of the eye's movement. Moreover, even if both the eyes blinked simultaneously, both the sensors were deactivated simultaneously to ensure that the device does not interfere with the detection of left-right eye-movements. The proposed eye tracker has seven frequency steps (0.167–0.5 Hz). Therefore, it is recommended that users adjust the frequency of the device as desired when receiving EMDR treatment. The proposed eye tracker combines a LED bar with an inexpensive mini-IR sensor-based eye tracker to create a prototype. In the future, we plan to improve the prototype by using various components and employ an enhanced product to measure the eye-movements in patients requiring EMDR therapy. This will provide a clear assessment of the effectiveness of psychological treatment based on eye-movement data.

VIII. CONCLUSION

We have developed an eye tracker device using a Mini-Infrared Point Sensors that can distinguish between the whites and pupils of the eyes. This IR eye tracker overcomes the limitations of traditional expensive IR cameras to monitoring eye movements. We were able to confirm that the proposed device can accurately distinguish between sclera and pupils and track left-right eye-movements. In the case of distinguishing between whites and pupils, we utilized the intensity values from the inverted IR sensor, where high intensity represents the sclera and low intensity represents the pupils. For tracking left-right eye-movements, we observed the position of the pupils in response to LED light, and our results showed similarity to the control values. To demonstrate the feasibility of the proposed eye tracker device, we tested it with ten participants. The measured left-right eye-movement frequencies matched well with the frequencies of the eye-guiding LED under 7 frequency conditions. Compared to existing camera-based eye trackers, our device is not only significantly more cost-effective but also more portable due to its compact size. Patients can easily wear the device and monitor EMDR therapy through the eye-guiding LED lights on the eye tracker. This convenience can also benefit psychotherapists. Through our research, we have demonstrated that even with miniature IR sensors, it is possible to accurately distinguish between sclera and pupils. The proposed device offers a more efficient and practical alternative in EMDR therapy.

AUTHOR CONTRIBUTIONS STATEMENT

Sung Jae Chang, Soo-Il Kim, and Dong Woo Lee designed the study. Sung Jae Chang, Ji-Yeon Lee, Soo-Il Kim, Sang-Yun Lee, and Dong Woo Lee performed the research. Dong Woo Lee provided support and advice on overall study planning, data analysis, and study direction. Sung Jae Chang and Soo-Il Kim designed and manufactured the product themselves. Soo-Il Kim and Ji-Yeon Lee coded and tested the algorithms needed for the product. Sung Jae Chang, Sang-Yun Lee, and Dong Woo Lee analyzed the data. Sung Jae Chang and Dong Woo Lee wrote the manuscript. All authors reviewed and approved the final manuscript.

REFERENCES

[1] F. Shapiro, "The role of eye movement desensitization and reprocessing (EMDR) therapy in medicine: Addressing the psychological and physical symptoms stemming from adverse life experiences," *Permanente J.*, vol. 18, no. 1, pp. 71–77, Mar. 2014.

[2] F. Shapiro, *Eye Movement Desensitization and Reprocessing (EMDR) Therapy: Basic Principles, Protocols, and Procedures*, 3rd ed. New York, NY, USA: The Guilford Press, 2018.

[3] I. Mavranezouli, O. Megnin-Viggars, C. Daly, S. Dias, N. J. Welton, S. Stockton, G. Bhutani, N. Grey, J. Leach, N. Greenberg, C. Katona, S. El-Leithy, and S. Pilling, "Psychological treatments for post-traumatic stress disorder in adults: A network meta-analysis," *Psychol. Med.*, vol. 50, no. 4, pp. 542–555, Mar. 2020.

[4] C. Lewis, N. P. Roberts, M. Andrew, E. Starling, and J. I. Bisson, "Psychological therapies for post-traumatic stress disorder in adults: Systematic review and meta-analysis," *Eur. J. Psychotraumatology*, vol. 11, no. 1, Dec. 2020, Art. no. 1729633.

[5] J. Baek, S. Lee, T. Cho, S.-W. Kim, M. Kim, Y. Yoon, K. K. Kim, J. Byun, S. J. Kim, J. Jeong, and H.-S. Shin, "Neural circuits underlying a psychotherapeutic regimen for fear disorders," *Nature*, vol. 566, no. 7744, pp. 339–343, Feb. 2019.

[6] H. Wurtz, M. El-Khoury-Malhame, F. H. Wilhelm, T. Michael, E. M. Beetz, J. Roques, E. Reynaud, J. Courtin, S. Khalfa, and C. Herry, "Preventing long-lasting fear recovery using bilateral alternating sensory stimulation: A translational study," *Neuroscience*, vol. 321, pp. 222–235, May 2016.

[7] Y. van Pelt, P. Fokkema, C. de Roos, and A. de Jongh, "Effectiveness of an intensive treatment programme combining prolonged exposure and EMDR therapy for adolescents suffering from severe post-traumatic stress disorder," *Eur. J. Psychotraumatol.*, vol. 12, no. 1, May 2021, Art. no. 1917876.

[8] B. T. Carter and S. G. Luke, "Best practices in eye tracking research," *Int. J. Psychophysiol.*, vol. 155, pp. 49–62, Sep. 2020.

[9] K. Krafka, A. Khosla, P. Kellnhofer, H. Kannan, S. Bhandarkar, W. Matusik, and A. Torralba, "Eye tracking for everyone," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit. (CVPR)*, Jun. 2016, pp. 2176–2184.

[10] A. S. Chan, T.-L. Lee, S. L. Sze, N. S. Yang, and Y. M. Y. Han, "Eye-tracking training improves the learning and memory of children with learning difficulty," *Sci. Rep.*, vol. 12, no. 1, p. 13974, Aug. 2022.

[11] S. Fletcher-Watson and S. Hampton, "The potential of eye-tracking as a sensitive measure of behavioural change in response to intervention," *Sci. Rep.*, vol. 8, no. 1, p. 14715, Oct. 2018.

[12] D. Y. Lee, Y. Shin, R. W. Park, S.-M. Cho, S. Han, C. Yoon, J. Choo, J. M. Shim, K. Kim, S.-W. Jeon, and S.-J. Kim, "Use of eye tracking to improve the identification of attention-deficit/hyperactivity disorder in children," *Sci. Rep.*, vol. 13, no. 1, p. 14469, Sep. 2023.

[13] F. Muñoz-Leiva, J. Hernández-Méndez, and D. Gómez-Carmona, "Measuring advertising effectiveness in travel 2.0 websites through eye-tracking technology," *Physiol. Behav.*, vol. 200, pp. 83–95, Mar. 2019.

[14] L. Carelli, F. Solca, S. Tagini, S. Torre, F. Verde, N. Ticozzi, R. Ferrucci, G. Pravettoni, E. N. Aiello, V. Silani, and B. Poletti, "Gaze-contingent eye-tracking training in brain disorders: A systematic review," *Brain Sci.*, vol. 12, no. 7, p. 931, Jul. 2022.

[15] I. M. Pavisic, Y. Pertzov, J. M. Nicholas, A. O'Connor, K. Lu, K. X. X. Yong, M. Husain, N. C. Fox, and S. J. Crutch, "Eye-tracking indices of impaired encoding of visual short-term memory in familial Alzheimer's disease," *Sci. Rep.*, vol. 11, no. 1, p. 8696, Apr. 2021.

[16] J. Bek, E. Poliakoff, and K. Lander, "Measuring emotion recognition by people with Parkinson's disease using eye-tracking with dynamic facial expressions," *J. Neurosci. Methods*, vol. 331, Feb. 2020, Art. no. 108524.

[17] E. Duymaz, A. Durmuş, B. Isık, and F. Ciylan, "Early diagnosis of autistic children with eye tracker and artificial intelligence approach," in *Proc. Med. Technol. Congr.*, Oct. 2022, pp. 1–4.

[18] D. Greco, F. Masulli, S. Rovetta, A. Cabri, and D. Daffonchio, "A cost-effective eye-tracker for early detection of mild cognitive impairment," in *Proc. EEE 21st Medit. Electrotechnical Conf.*, Jun. 2022, pp. 1141–1146.

[19] M. A. Hassan, C. M. Aldridge, Y. Zhuang, X. Yin, T. McMurry, G. K. Rohde, and A. M. Southerland, "Approach to quantify eye movements to augment stroke diagnosis with a non-calibrated eye-tracker," *IEEE Trans. Biomed. Eng.*, pp. 1–9, 2022.

[20] I. Kobayashi, K. Sato, T. Uchida, and H. Nunokawa, "Compact calibration-free eye-tracking system for students with severe physical and intellectual disabilities," in *Proc. 7th Int. Conf. ICT Accessibility*, Dec. 2019, pp. 1–3.

[21] K. Qian, T. Arichi, A. Price, S. Dall'Orso, J. Eden, Y. Noh, K. Rhode, E. Burdet, M. Neil, A. D. Edwards, and J. V. Hajnal, "An eye tracking based virtual reality system for use inside magnetic resonance imaging systems," *Sci. Rep.*, vol. 11, no. 1, p. 16301, Aug. 2021.

[22] P. Drakopoulos, G. A. Koulieris, and K. Mania, "Front camera eye tracking for mobile VR," in *Proc. IEEE Conf. Virtual Reality 3D User Interfaces*, Mar. 2022, pp. 642–643.

[23] A. Khaldi, E. Daniel, L. Massin, C. Kärnfelt, F. Ferranti, C. Lahuec, F. Seguin, V. Nourrit, and J.-L. de Bougrenet de la Tocnaye, "A laser emitting contact lens for eye tracking," *Sci. Rep.*, vol. 10, no. 1, p. 14804, Sep. 2020.

[24] Y. Lee, S. Lee, J. Han, Y. J. Seo, and S. Yang, "A nystagmus extraction system using artificial intelligence for video-nystagmography," *Sci. Rep.*, vol. 13, no. 1, p. 11975, Jul. 2023.

[25] C. Falls, "Videonystagmography and Posturography," *Adv. Otorhinolaryngol.*, vol. 82, pp. 32–38, Jan. 2019.

[26] H. Zhou, Y. Sun, L. Wei, X. Wang, Y. Jiang, F. Li, J. Chen, W. Sun, L. Zhang, G. Zhao, and Z. Wang, "Quantitative assessment of oculomotor function by videonystagmography in multiple system atrophy," *Clin. Neurophysiol.*, vol. 141, pp. 15–23, Sep. 2022.

[27] V. Pawar, H. Ashraf, S. Dorsala, P. Mary, N. Hameed, H. D. Nair, S. P. Adatia, L. Raj, V. R. Ananthu, and M. Shouka, "Motorist's vestibular disorientation syndrome (MVDS)—Proposed diagnostic criteria," *J. Personalized Med.*, vol. 13, no. 5, p. 732, Apr. 2023.

[28] L. Bin and W. Jian, "Human eye characteristics in IR-based eye detection," in *Proc. IEEE Int. Conf. Consum. Electron.*, Apr. 2013, pp. 43–44.

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