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# The Identification of Individualized Eye Tracking Metrics in VR Using Data Driven Iterative- Adaptive Algorithm*

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***ABSTRACT***

*Eye tracking metrics provide information about cognitive function and basic oculomotor characteristics. There have been many studies analyzing eye tracking signals using different algorithms. However, these algorithms generally are based on the initial setting parameter. This might cause the subjective interpretation of eye tracking analysis. The main aim of this study was to develop a data-driven algorithm to detect fixations and saccades without any subjective settings. Five subjects were included in this study. Eye tracking signal was acquired with the VIVE Pro Eye in virtual reality (VR) environment while subjects were reading a paragraph. The algorithms based on the calculation of threshold were employed to calculate eye metrics including total fixation duration, total fixation number, total saccades number and average pupil diameter. The proposed algorithm, which is based on calculating the initial threshold, based on mean, and standard deviation of eye tracking signal within experiment duration, gave the same results obtained adaptive filtering reported in literature (average fixation duration for five subjects= 10634.6 ms ± 5117.9, average fixation count for five subjects= 21.8 ± 7.5). On the other hand, our proposed algorithm didn't use any certain objective parameter as like adaptive filtering. As a conclusion, VIVE Pro Eye may be utilized as an eye movement assessment device, and, the suggested approach might be utilized to analyze objective eye tracking metrics.*

***Keywords*** : Eye Tracking, Virtual Reality, Head Mounted Display, Saccade, Fixation

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# Veriye Dayalı Yinelemeli-Uyarlamalı Algoritma Kullanılarak VR'da Göz İzleme Metriklerinin Tanımlanması

**ÖZ**

*Göz izleme ölçümleri, bilişsel işlev ve temel okülomotor özellikler hakkında bilgi sağlar. Farklı algoritmalar kullanarak göz izleme sinyallerini analiz eden birçok çalışma yapılmıştır. Ancak bu algoritmalar genellikle ilk ayar parametresine dayalıdır. Bu, göz izleme analizinin öznel yorumuna neden olabilir. Bu çalışmanın temel amacı, herhangi bir öznel ayar olmaksızın fiksasyonları ve sakkadları tespit etmek için veriye dayalı bir algoritma geliştirmekti. Bu çalışmaya beş katılımcı dahil edilmiştir. Denekler VR'de bir paragraf okurken, sanal gerçeklik (VR) ortamında VIVE Pro Eye ile göz izleme sinyali alındı. Toplam sabitleme süresi, toplam sabitleme sayısı, toplam sakkad sayısı ve ortalama göz bebeği çapı dahil olmak üzere göz ölçümlerini hesaplamak için eşiğin hesaplanmasına dayalı algoritmalar kullanıldı. Deney süresi içinde göz izleme sinyalinin ortalama ve standart sapmasına bağlı olarak başlangıç eşiğini hesaplamaya dayanan önerilen algoritma, literatürde bildirilen uyarlamalı filtreleme ile elde edilen sonuçların aynısını vermiştir (beş denek için ortalama fiksasyon süresi= 10634.6 ms ± 5117.9, beş denek için ortalama fiksasyon sayısı= 21.8 ± 7.5). Öte yandan, önerilen algoritmamız uyarlamalı filtreleme gibi belirli bir nesnel parametre kullanmamıştır. Sonuç olarak, VIVE Pro Eye bir göz hareketi değerlendirme cihazı olarak kullanılabilir ve önerilen yaklaşım objektif göz izleme metriklerini analiz etmek için kullanılabilir.*

***Anahtar Kelimeler*** **:** *Göz İzleme, Sanal Gerçeklik, Başa Monte Ekran, Sakkad, Fiksasyon*

## INTRODUCTION

Eye tracking is an objective method to record and analyze visual behavior. This allows researchers to investigate cognitive function and basic oculomotor characteristics during a range of activities. In literature, many studies have used eye movement analysis in patients with neurological disorders, such as Amyotrophic lateral sclerosis, Alzheimer's disease, Parkinson's disease, multiple sclerosis and epilepsy, to assess cognitive function (Poletti et al., 2017; Noiret et al., 2018; Pavisic et al., 2017; de Boer et al., 2016; Fielding et al., 2009; Lunn et al., 2016).

Fixations and saccades are two common metrics of gaze information captured by eye tracking. Fixations are periods when the user's eyes stop scanning a point in space over time by taking in detailed information about what is being looked at. Saccades are described as the rapid eye movement between two consecutive fixations. Another metric captured by eye tracker is pupil diameter. There is a relationship between mental effort and pupil diameter because it has been reported that pupil responses had an association with mental effort during cognitive load (Beatty, 1982; van der Wel et al., 2018).

Several devices have been developed to measure eye tracking. One of which is Electrooculography (EOG) known as a traditional technique (Young and Sheena, 1975). This technique measures the changes in electrical potential between the two electrodes placed on the skin around the eyes. Although it is a low-cost device and has a good temporal resolution, it suffers from artifacts triggering a dramatic increase in the potential above the eyes (Chang, 2019).

The other technique is the use of Frenzel goggles which disables the user's ability to visually fixate on an object while allowing the examiner to investigate her / his eyes. However, this technique has some drawbacks including its heavy, large size and the need for electrical power (Strupp et al., 2014).

Optical methods are also used in eye tracking. The combination of an infrared video camera and the infrared light source is used to monitor where the user is looking at. The light source emits infrared light through the cornea of the eyes. Although it provides high spatial resolution, it needs more calibration (Pantanowitz et al., 2021).

In recent years, video-based eye tracking has been more popular. With the advancement in technology, developers have succeeded to merge video-based eye tracking into a virtual reality (VR) headset. This system is a useful tool to measure eye movements in VR experience. Therefore, this enables users to obtain real-time feedback on the performance of participants with disability or neurodegenerative disease without forcing them to take risks (Ma and Zheng, 2011) .

On the other hand, several algorithms have been developed to calculate eye tracking metrics by classifying the gaze coordinates produced by the eye tracker. These algorithms are categorized in accordance with the velocity, dispersion and area criteria. The most popular algorithm is the Velocity-threshold fixation identification (I-VT) because of its easy implementation (Munn et al., 2008; Salvucci and Goldberg, 2000).

The problem with this algorithm is to set a peak velocity threshold. Also, the other algorithms, including I-VT, velocity-based algorithms of the hidden Markov model identification, dispersion-threshold, position-based algorithms of the minimum spanning tree identification and identification area of interest have some problems such as difficult implementations and setting parameters (Salvucci and Goldberg, 2000). Also, one study developed an adaptive filtering to identify fixations, saccades and glissades (Nyström, M, and Holmqvist, K., 2010). The shortcoming of this algorithm is the use range for initial threshold for data-driven algorithm. Moreover, one study collected gaze information from VR headset with HTC VIVE Pro Eye and normalized velocity and used 0.5 threshold peak detection in accordance with the design of the experiments (Imaoka et al., 2020). However, in that study, it was reported that the algorithm they used required a high sampling frequency to detect saccades.

This study aimed to develop a data-driven algorithm to detect fixations and saccades without subjective setting and any certain threshold and to compare the results of the several algorithms.

## 1. MATERIALS AND METHODS

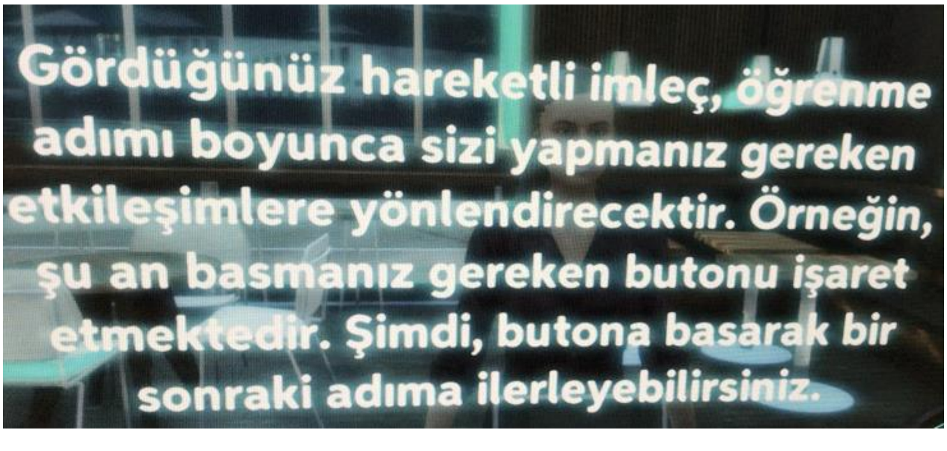
### 1.1. Subjects

Five subjects without any neurological disease and visual deficit were included in this study. The mean age of the group was 18.80 (standard deviation (SD) = 6.50). The Institutional Review Board approved the study protocol, and participants provided written informed consent after explaining the examination's nature. At the end of the experiment, all subjects underwent a virtual reality sickness questionnaire (Kim et al., 2018) to test whether participants have unpleasant experiences because of the VR system.

### 1.2. Virtual Environment and Data Collection

Experiments have been employed at Neo Auvra® Digital Health and Bionic Technologies and Services Inc., Istanbul, Turkey. Eye-tracking data was acquired in a virtual environment displayed through the HTC Vive Pro Eye (Woltering et al., 2013) with Unreal Engine. A field of view of is 110°, resolution is 1400 × 1600 pixels per eye in total with a refresh rate of 90 Hz. VIVE Eye SDK 1.3.0.9 was used. Also, HTC base station covers a 2.5 m X 2.5 m area. Nora VRx™ (Neo Auvra® Inc.) was utilized as the VR experience. Calibration was done using the embedded head-mounted display (HMD)'s calibration mechanism for each subject.

Subjects stood in a quiet room and were free to move the head and the torso. Figure 1 shows an example paragraph showing in the VR environment. The paragraph consisted of six rows, 26 words and six punctuation marks. Subjects were instructed to read each word loudly through paragraph from left to right and row by row and complete the reading part. The video was recorded through a computer scene, that enabled to match gaze information of eye tracking and real-time data.



Gördüğünüz hareketli imleç, öğrenme
adımı boyunca sizi yapmanız gereken
etkileşimlere yönlendirecektir. Örneğin,
şu an basmanız gereken butonu işaret
etmektedir. Şimdi, butona basarak bir
sonraki adıma ilerleyebilirsiniz.

**Figure 1**: Illustration of a Paragraph in the Virtual Reality Environment

Time information was recorded with timestamp in SRanipal SDK and FDateTime.Now\Millisecond on Unreal system because timestamp resolution corresponds to one millisecond. Moreover, the other recorded parameters using in this analysis were followed as: normalized x, y and z directions, pupil diameter, origin x, y, z directions and timestamp.

### 1.3. Post-processing

An in-house software was written in MATLAB Statistics and Machine Learning Toolbox R2021a (The MathWorks Inc., Natick, MA). Figure 2 shows all steps of eye tracking signal analysis and calculation of the metrics for the proposed algorithm.

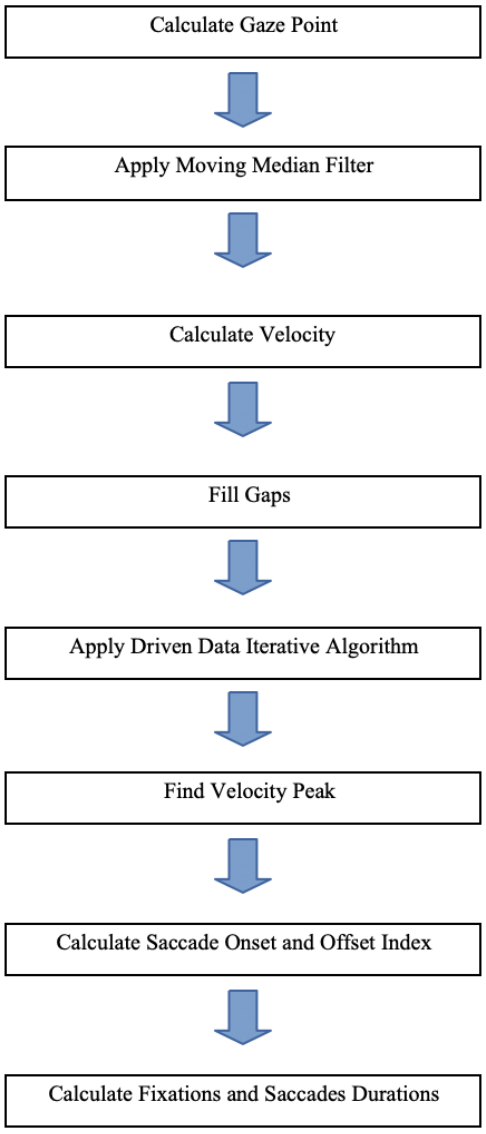


**Figure 2:** Flow Chart of the Post-Processing Steps

In the post-processing step, gaze point was calculated in degrees with the following formula:

$$GD = \frac{arctan\left(\frac{GDx}{GDz}\right)}{pi} 180°, \quad [1]$$

where GD is the gaze point, Gdx is the normalized gaze direction on the X axis and Gdz is the normalized gaze direction on the Z axis. Then, a moving median filter was applied in calculated gaze points with an order of 10. Gaze velocity was calculated by dividing the difference as between two consecutive gaze points by time difference.

$$Velocity = \frac{GD_{(i+1)} - GD_{(i)}}{Time_{(i+1)} - Time_{(i)}} \quad [2]$$

Gap occurs due to an eye blink. In proposed algorithm, gaps were found by checking whether the difference time between samples is lower than 410 ms (Woltering et al., 2013). Then, gaps were filled by calculating break time and subtracting it from timestamps of following samples.

To find the optimal threshold, an iterative algorithm was employed. Initial threshold based on mean and SD of the samples within experiment were taken for the algorithm instead of a certain value as a threshold. For each iteration, threshold was estimated as the sum of the mean and six times SD of the samples with velocities lower than threshold. The algorithm kept working until the absolute difference value of the consecutive thresholds was lower than 10/second.

After detection of the threshold, velocity peaks that were higher than the last threshold were found. The first sample which is lower than threshold and Velocity(i)>=Velocity (i+1) while going back from velocity peak is defined as saccade onset. On the other hand, the first sample which is lower than threshold and Velocity(i+1)>=Velocity (I) is defined as saccade offset. Samples which are not either between saccade onset and offset and shorter than 150 ms (Galley et al., 2015) are defined as fixations. Several metrics including the duration of fixation, total number of fixation and saccade, and the average of pupil diameter were calculated.

To compare the other algorithms with our proposed algorithm, all steps except the step of the threshold determination were repeated. After that, the fixation and saccade of different thresholds calculated by Z-score, setting to 0.5 °/second after normalization, setting the initial threshold to 100-300 °/second were calculated and reported.

The location and average of fixation and saccade durations were detected and calculated by analyzing the video recorded during the experiment. These were compared with results by estimating using the different thresholds.

Additionally, heat maps were calculated by finding the coordinates of target point. The gaze vectors consisting of origin x, y and z directions were created using the below formula for both left and right eye.

$$GazeVector = [x_{origin}, Y_{origin}, Z_{origin}] \qquad [3]$$

Intersection point of left and right gaze vectors was defined as target point. Figure 3 show two gaze vectors from eye origin points and coordinate of target point within the 3D coordinate system of HTC VIVE Pro Eye. A heat map was built from fixation values.

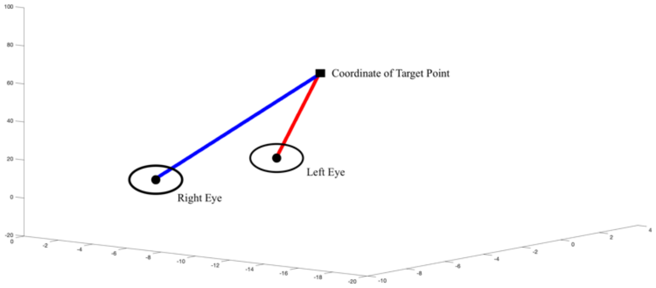


**Figure 3.** Coordinate system of eyes, gaze vectors, target point within HTC VIVE Pro Eye.

To compare results of the other algorithms with that of the proposed algorithm in this study, analysis was repeated. Firstly, all steps except the step of the threshold determination were repeated for the adaptive algorithm reported in the literature (Nyström and Holmqvist, 2010). Also, without applying data-driven algorithm, threshold was defined separately as the Z-score based on velocity and 0.5 °/second (Imaoka et al., 2020) based on normalized velocity in order to label as fixations and saccades. After, the eye metrics, described previously, were calculated for each algorithm.

## 2. RESULTS

The average time for the subjects to complete reading during the VR experience was 19.40 seconds (SD: 7.73). As a result of VRSQ, side effect associated with immersion in VR has been not seen for any subjects. Table 1 shows that the eye metrics including total fixation duration (TFD), total fixation number (TF), total saccade number (TS) and pupil diameter (PD), calculated from five subjects by employing four algorithms based on different threshold in order to calculate fixations and saccades.

The proposed algorithm and adaptive algorithm provided the shortest TFD in line with the expected results. Moreover, the calculated TF, TS, and PD of these two algorithms were similar. The algorithm using 0.5 °/second threshold after normalization gave the longest TFD and the least TF and TS. Interestingly, for subject #3, subject #4 and subject #5, the algorithm using 0.5 °/second threshold after normalization didn’t find any saccades. The last algorithm based on Z- Score gave a longer TFD than both of the proposed algorithm and the adaptive algorithm.

In Figure 4, the distribution of fixations was shown as a heat map during experiment. In this figure, each fixation added a value to the color map at the location of the target point regardless of the fixation duration. Moreover, this heat map provides information about the subject performance over the paragraph shown in VR system.

Figure 5 shows the graph of the eye tracking signal with marks of the threshold peaks, saccade onset and offset calculated by the proposed algorithm for one subject.

**Table 1:** The Eye Metrics That Were Calculated from Five Subjects by Employing Four Different Algorithms

| Algorithms | Metrics | Subjects | | | | |
|---|---|---|---|---|---|---|
| | | SBJ #1 | SBJ #2 | SBJ #3 | SBJ #4 | SBJ #5 |
| Proposed Algorithm | TFD (ms) | 5343 | 19045 | 10157 | 10391 | 8237 |
| | TF | 16 | 14 | 22 | 33 | 24 |
| | TS | 16 | 13 | 23 | 46 | 37 |
| | PD | 4.14 | 4.86 | 3.63 | 4.95 | 3.74 |
| Z- Score | TFD (ms) | 11980 | 19486 | 15589 | 14507 | 10933 |
| | TF | 17 | 26 | 22 | 27 | 26 |
| | TS | 5 | 7 | 8 | 2 | 3 |
| | PD | 4.13 | 4.85 | 3.73 | 4.97 | 3.76 |
| $0.5^0$/second Threshold<br>(Imaoka, 2020) | TFD (ms) | 13046 | 21252 | 17381 | 15648 | 12022 |
| | TF | 4 | 6 | 5 | 2 | 3 |
| | TS | 1 | 2 | 0 | 0 | 0 |
| | PD | 4.16 | 4.88 | 3.68 | 4.98 | 3.70 |
| Adaptive Algorithm (Nyström and Holmqvist, 2010) | TFD (ms) | 5343 | 19045 | 10157 | 10391 | 8237 |
| | TF | 16 | 14 | 22 | 33 | 24 |
| | TS | 16 | 13 | 23 | 46 | 37 |
| | PD | 4.14 | 4.86 | 3.63 | 4.95 | 3.74 |

*TFD: Total Fixations Duration, TF: Total Fixations Number, TS: Total Saccades Number, PD: Pupil Diameter during Fixations.

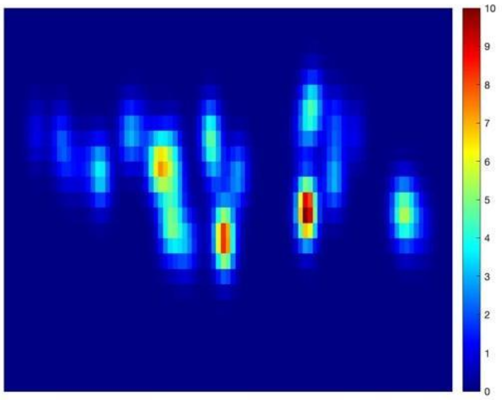


**Figure 4**: Heat Map Based on The Fixation Count During Experiment

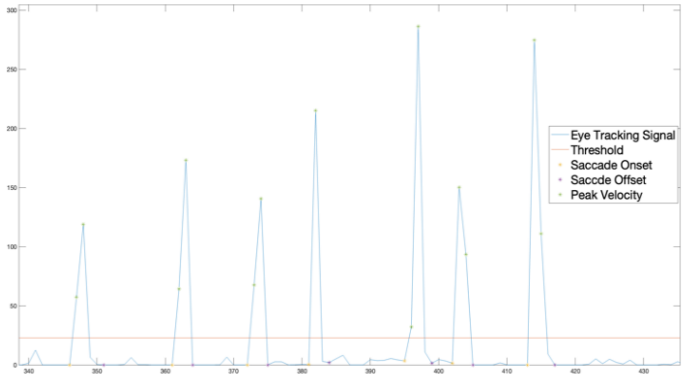


**Figure 5:** Eye Tracking Signal of One Subject Example During Reading

## 3. DISCUSSION

In this study, the eye tracking signal that was acquired from five healthy subjects by HMD eye tracking during reading in a VR environment was analyzed. When the results were compared, it was found that the proposed algorithm and algorithm used 100-300°/second initial threshold gave the eye metrics similar to the expected results found video record during the experiment. Therefore, we validated our proposed algorithm by getting the same results obtained from the adaptive algorithm.

Adaptive algorithm has been a well-established and widely used technique to analyze eye movements in literature. (Brescia-Zapata et al, 2022; Selaskowski B et al, 2023). Nyström, M et al. reported that the choice of initial peak velocity was not critical as long as there are saccades with peak velocities reaching this threshold (Nyström and Holmqvist, 2010) . However, it was observed that no peak velocity was found when the initial threshold was selected as higher than all the peaks. Therefore, it can be said that the proposed algorithm in this study provides realistic results for eye tracking analysis.

Pupil diameters were similar during reading in the experiments using different thresholds. This result is expected because pupil diameter is about the cognitive load and not related to fixation numbers calculated by employing different algorithms. If the average of pupil diameter is not be taken during fixations instead of experiment duration, pupil diameter size is the same for all different algorithms.

Algorithm based on the 0.5 °/second threshold (Imaoka, 2020) caused the loss of saccades, which may result in wrong interpretation of the results. On the other hand, it is known that eye tracking signals don't always have a normal distribution. But, Z-score filter assumes a normal distribution and calculates the probability of a score occurring within a standard normal distribution. In this study results, it can be seen that the algorithm based on Z-score didn't have a certain pattern for the eye tracking metrics collected from different subjects and different experiments.

There have been several studies to analyze eye movements (Andersson et al., 2017; Komogortsev et al., 2010; Nyström & Holmqvist, 2010; Imaoka, 2020). The performance of current algorithm techniques was evaluated and compared with each other using large sample sizes with different experiment designs. They found a different number of fixations and saccades between techniques (Andersson et al., 2017; Komogortsev et al., 2010). Because the algorithm structures of these studies depend on the chosen parameters for the eye tracker data analysis, results can be different even if the datasets are the same (Andersson et al., 2017; Komogortsev et al., 2010; Nyström & Holmqvist, 2010; Imaoka, 2020). The algorithm chosen in accordance with the experiment is significant to calculate correct fixations and saccades because the simulation of real-life experiences in VR supported cognitive sciences and educational technology (Shadiev et al., 2022). Our proposed algorithm aimed to analyze the characteristic of eye movements obtained from the eye tracker in HMD without setting any specified parameters and any assumptions for the analysis.

This study had some limitations. Head movement could provide information about the reading strategy by being suppressed to reduce the fixation instability because of the head movement (Ferman et al., 1987; Skavenski et al., 1979). The limitation of the study is not to collect the head movements of the subjects during reading and analyze whether there are any correlations between head movement and eye movements or not. In this study, the number of subjects was limited. In the future, the population may increase and the eye metrics results could be compared statistically. Also, machine learning algorithms could be applied to validate results if there are any statistically significant differences between different algorithms in the same subjects (Koç et al., 2020). The VR environment in this study was disruptive because this environment was similar to the real world.

## CONCLUSION

The purpose of this study was to evaluate different algorithms setting thresholds to calculate fixation and saccades of eye tracking signal acquired with the VIVE Pro Eye in a VR environment. The proposed algorithm could be used as an assessment tool for eye movement metrics. Eye movements of five healthy young adults were measured during reading a paragraph using Nora VRx™ that evaluates specific cognitive functions. The results of this study suggest that VIVE Pro Eye can be used as an assessment device of eye movements and the proposed algorithm based on the calculation of the initial threshold the mean and SD could provide more accurate eye metrics. Therefore, the proposed algorithm might serve as an objective alternative metric for the eye tracking analysis. To conclude, the use of dynamically computed threshold values enables us to investigate gaze parameters more reliably than the ones that have been proposed previously.

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