ORIGINAL ARTICLE

Evaluating Objective Smooth Pursuit Eye Movements with Tobii Eye Tracker: Normative Data and Clinical Applications

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ABSTRACT

Background: Smooth pursuit eye movements (SPEMs) are essential for stabilizing vision during the tracking of moving objects, ensuring continuous alignment on the fovea. This study aims to establish normative data for SPEMs within a clinical context using the Tobii eye tracker, enhancing diagnostic assessments of eye movement abnormalities. **Methods:** Thirty participants, aged 20 to 24 years, from the International Islamic University Malaysia community, were selected according to strict inclusion criteria to minimize confounding factors that could affect eye movement performance. Participants' SPEM performance was assessed using key metrics: root mean square error (RMSE) and pursuit gain, which evaluate tracking accuracy and synchronization with target movement. The data generated served as a normative baseline for comparison with patient data. **Results:** The study generated normative data, revealing an average RMSE of 0.63 ± 0.10 and a pursuit gain of 0.99 ± 0.05, closely aligning with or surpassing existing normative benchmarks. Minor tracking deviations, particularly at peak target velocities, were observed, reflecting expected physiological limitations of smooth pursuit accuracy. **Discussion:** The findings demonstrate the effectiveness of the Tobii eye tracker in providing precise, objective measurements of SPEMs, establishing it as a reliable tool for clinical diagnostics. The normative data offer a valuable reference for clinicians to identify deviations that may indicate neurological or psychiatric disorders. This study highlights the role of eye-tracking technology in improving the diagnostic evaluation of oculomotor dysfunction, supporting its integration into clinical practice for early detection and intervention. **Conclusion:** The established benchmarks serve as a valid reference for clinicians to detect abnormalities in smooth pursuit patterns, aiding in the identification of potential disorders.

Keywords:
smooth pursuit; eye tracking; pursuit gain; root mean square error

INTRODUCTION

Smooth pursuit eye movements (SPEMs) are crucial components of the human oculomotor system, allowing the eyes to track and maintain the image of a moving object on the fovea, where visual acuity is highest. These movements are essential for daily activities, such as reading, driving, and sports, that require precise visual tracking of moving objects. Functionally, SPEMs serve to minimize retinal motion blur and maintain a stable image during dynamic visual tasks, supporting clearer and more accurate visual perception (Barnes, 2008; Leigh & Zee, 2015).

Role of SPEMs in Diagnostic Assessment

Abnormalities in SPEMs can be early indicators of various neurological and psychiatric conditions (Benson et al., 2012). For example, patients with Parkinson's disease often exhibit impaired smooth pursuit, characterized by reduced gain and increased position error relative to healthy controls (Lencer & Trillenberg, 2008). Schizophrenia and other psychiatric conditions are also associated with specific SPEM deficits, such as lower gain and more frequent saccadic intrusions (Benson et al., 2012; Hutton et al., 1998). SPEMs have similarly shown diagnostic value in developmental disorders, where children with ADHD, for instance, demonstrate reduced smooth pursuit gain and accuracy, which may serve as potential biomarkers for the condition (Caldani et al., 2020). These observations underscore the clinical importance of SPEM assessment as a non-invasive, accessible means of identifying early-stage or progressive impairments across diverse patient groups.

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Advances in Eye-Tracking Technology for SPEMs

In clinical practice, SPEMs is evaluated through tests such as the ocular motility test (OMT), in which a penlight is smoothly moved across various gaze positions to assess eye movement balance and detect any overshoot or undershoot. However, this method relies on patient cooperation and clinician expertise, and subtle eye movement abnormalities may go undetected, potentially delaying urgent referrals for serious underlying conditions (Shafee, 2021). However, recent advances in eye tracking technology have significantly enhanced the precision, accessibility, and versatility of SPEMs measurement. Modern eye trackers, such as the Tobii eye tracker used in this study, offer non-invasive tracking of eye movements and provide detailed, objective data that supports both research and clinical diagnostics across various fields. The Tobii eye tracker, specifically, has been extensively utilized in studies on cognitive function, neurology, and human-computer interaction, showcasing its versatility and value as a tool in both research and clinical settings (Brunyé et al., 2019).

Current Gaps and Objectives

While normative data for SPEMs exist, they often differ due to variations in testing paradigms. Although extensive research on age-related eye movement norms using video eye tracking has been conducted, these methods can yield inconsistent results (Liversedge, S. et al., 2011). Therefore, establishing normative data is essential before comparing eye movement anomalies across new eye movement recording paradigms.

This study aims to fill this gap by establishing normative data for SPEMs in young adults within the IIUM community, using the Tobii eye tracker. By providing reliable normative benchmarks, we seek to assist clinicians and researchers in accurately identifying SPEM abnormalities and enhancing the diagnostic utility of eye-tracking technology in detecting oculomotor dysfunctions.

MATERIALS AND METHODS

Study Design and Ethical Approval

This cross-sectional study was conducted in accordance with the principles of the Declaration of Helsinki and received ethical approval from the IIUM Research Ethics Committee (IREC 2023-KAHS/DOVS10). The study aims to establish normative data for SPEMs in a population of young adults at IIUM, using the Tobii eye tracker for accurate and objective measurement.

Participants

Thirty participants (six males and twenty-four females), aged between 20 and 24 years, were recruited for this study. All participants met the following inclusion criteria: (1) absence of any ocular or systemic disease, (2) not on any medication that could affect eye movements, (3) best-corrected distance visual acuity of 0.2 logMAR or better in each eye, and (4) ability to maintain focus on a moving target (Shafee, 2021). Exclusion criteria included individuals with high myopia, strabismus, nystagmus, or any ocular motility deficit, as these could confound smooth pursuit measurements.

All participants provided informed consent after receiving a detailed explanation of the study's purpose and procedures. They were assured of the right to withdraw at any stage without any consequences.

Participant and Display set-up

Figure 1 shows the setup for the experiment, where participants were positioned comfortably in a quiet, controlled environment with standard room lighting. A chin and forehead rest were used to minimize head movements, ensuring stable and consistent measurements during the test. The chin rest was disinfected with alcohol wipes between participants. Each participant was seated at a standardized distance of 60 cm from the computer screen. The study setup utilising two computers: one laptop dedicated to gathering data from the Tobii eye tracker, and a separate display monitor used to present stimuli to participants.

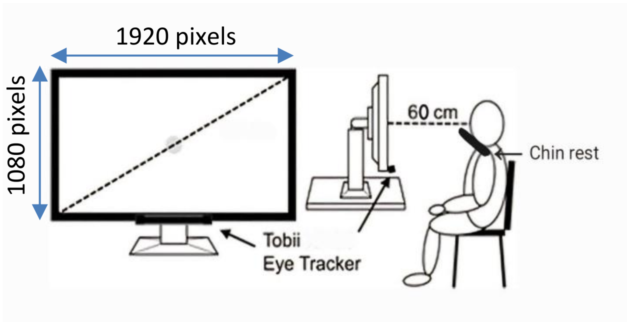

Figure 1: Participant positioning during eye tracking. The participant was seated with a chin rest, at a distance of 60 cm away from the display monitor. The Tobii Eye Tracker was mounted at the bottom edge of the monitor to record eye movements accurately.

Pre-Test Procedures and Participant Preparation

Upon arrival, each participant's visual acuity was verified, and a comprehensive history was taken to confirm adherence to inclusion criteria. Visual acuity testing was conducted to ensure that only those with 0.2 logMAR or better would proceed. A cover test and OMT were also performed to exclude participants with strabismus, nystagmus, or other motility disorders.

Eye Tracker Calibration and Validation

In this study, Tobii Pro Fusion eye tracker (Tobii Pro AB, Danderyd, Sweden) with 120 Hz sampling frequency was utilized to record the eye movements. The eye tracker was attached to the display monitor, AOC (Model: 22B2HN) with refresh rate of 75 Hz.

Prior to each test, the Tobii eye tracker was calibrated to enhance accuracy. The calibration process involved presenting a stationary target at five predetermined points on the monitor, which the participant fixated upon to set baseline eye position measurements. This calibration was immediately followed by a validation phase with the same five points to confirm the precision of calibration. Optimal calibration was achieved when the numerical feedback values met the tracker's accuracy threshold.

Stimulus of the SPEMs

The Tobii eye tracker was used to assess the smooth pursuit eye movements (SPEMs) of each participant. The stimulus presented was a black cross with a diameter of 2.5 mm. It moved horizontally across the monitor in a smooth, sinusoidal path, oscillating with a fixed amplitude of ±10°. The stimulus was designed using MATLAB (The MathWorks, Inc., Natick, Massachusetts, US).

During testing, participants were instructed to maintain precise fixation at the center of the black cross and to follow its movement while ensuring their gaze always remained fixed on the stimulus's center. To ensure data consistency and reliability, each participant completed four trials.

SPEMs Testing Protocol

The testing room was maintained at a quiet and consistent ambient light level to prevent distractions. Participants were instructed to maintain focus on the moving target with minimal head movement and were given brief breaks between trials to prevent fatigue.

Data Collection and Analysis

The primary SPEMs parameters measured were root mean square error (RMSE) and pursuit gain. RMSE indicates the average error between the target and the actual gaze position, providing a measure of tracking accuracy. Pursuit gain represents the ratio of eye velocity to target velocity, with an ideal gain value close to 1.0 indicating accurate tracking of the target's movement.

Data from all four trials were recorded for each participant, and the average values of RMSE and pursuit gain were calculated. Data analysis was conducted using Statistical Package for Social Sciences (SPSS, version 12 for Windows, SPSS Inc., Chicago, IL, USA). Normality of the data was tested to determine the appropriate statistical tests. One-sample t-tests were used to compare the average pursuit gain and RMSE against established benchmarks from previous studies. Statistical significance was set at $p < 0.05$.

RESULTS

A total of 30 participants aged between 21 and 24 years (mean age = 22.3 ± 1.1) met the inclusion criteria and successfully completed the study. The main parameters analyzed were pursuit gain and RMSE, both of which provide key insights into SPEMs accuracy and stability.

SPEMs Outcomes

The mean SPEMs gain for the sample was 0.99 ± 0.05, which indicates a high degree of synchronization between the eye and target velocities, aligning with the ideal gain of 1.0. The RMSE, averaging 0.63 ± 0.10, indicated minimal deviation between gaze and target positions.

Comparison with Prior Normative Data

To assess the validity of our findings, we compared our pursuit gain and RMSE values with those reported in previous studies (Shafee, 2021). The t-test for pursuit gain and RMSE showed statistically significant differences, suggesting that our sample had slightly higher pursuit gain and RMSE compared to previously documented values, as summarized in Table 1. These findings may reflect specific demographic or methodological factors and underscore the need for establishing population-specific norms.

Table 1: Table shows the result on SPEMs

SPEMs Parameters	Test value	Mean ± SD	p-value
Gain	0.89	0.99 ± 0.05	0.03
RMSE	0.56	0.63 ± 0.10	0.04

Graphical Analysis of SPEMs in Relation to Stimulus

Figure 2 illustrates a time-series comparison of the stimulus and the actual pursuit eye movement of the right eye and the left eye. The x-axis represents timestamps in seconds, while the y-axis displays the normalized eye position ranging from 0 to 1.

The eye trajectories closely match the sinusoidal stimulus, with minor deviations observed at the peak positions. These deviations, although subtle, are expected due to the increased difficulty in maintaining smooth pursuit at the extreme edges and during directional changes of the target. At these points, small catch-up saccades may occur as the eye adjusts to realign with the moving target.

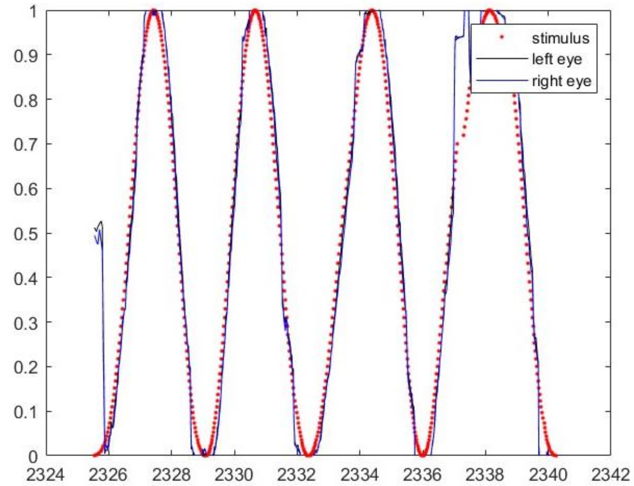

Figure 2: Graph shows comparison of stimulus trajectory and SPEMs. Stimulus trajectory = sinusoidal red dotted line, left eye = blue line and right eye = black line.

DICUSSION

This study aimed to establish normative data for SPEMs in a young adult population using the Tobii eye tracker, a device suitable for objective eye movement assessments. Our findings provide valuable normative benchmarks that can serve as a reference in clinical settings, enhancing diagnostic capabilities for conditions associated with abnormal eye movements.

Comparison with Prior Studies

The mean pursuit gain and RMSE observed in our sample were comparable to previously reported values in similar populations, with our mean pursuit gain of 0.99 closely aligning with prior studies that reported a gain of approximately 0.96 (Shafee, 2021). Minor discrepancies between studies may be attributed to variations in instrument used, testing strategies, sample size, or specific characteristics of the population. Such consistency across studies underscores the reliability and clinical utility of Tobii eye tracker measurements for SPEMs, validating our findings as robust and suitable for clinical application.

Graphical Analysis of Eye Movements

The graphical analysis of eye movements confirmed that participants' smooth pursuit motions closely followed the sinusoidal stimulus trajectory, with minimal deviations observed at the peaks and troughs. These minor deviations likely reflect physiological constraints of the smooth pursuit system or inherent limitations in the response time of the eye-tracking technology. The high degree of synchronization between the eye movements and the stimulus supports the Tobii eye tracker's capacity for precise measurement, further affirming its utility in clinical and research settings.

Clinical Implications

The normative data generated from this study holds significant potential for enhancing clinical assessments of eye movement disorders. Clinicians can utilize this reference to determine if a patient's SPEM performance falls within the typical range or exhibits deviations indicative of underlying neurological, psychiatric, or developmental conditions. For instance, abnormalities in pursuit gain or increased RMSE have been observed in patients with conditions like Parkinson's disease, schizophrenia, and attention-deficit/hyperactivity disorder (ADHD), where decreased gain and higher tracking errors often serve as early indicators of dysfunction (Caldani et al., 2020; Hutton et al., 1998). By providing a normative baseline, this study enables early detection of these anomalies, facilitating timely intervention and potentially improving patient outcomes.

Methodological Considerations

Although the normality test indicated a slight skew in the average gain distribution, we employed parametric tests based on the Central Limit Theorem, as the sample size (N = 30) is sufficient for such analyses. This approach is consistent with established statistical guidelines and ensures that our findings remain statistically valid. Additionally, the high level of consistency in pursuit gain across trials underscores the reliability of the Tobii Eye Tracker for repeated measures in smooth pursuit assessment, supporting its adoption in clinical environments.

Limitations and Recommendations for Future Research

While our study provides foundational normative data, the sample size and focus on young adults aged 20-24 limit the generalizability of these findings. Future studies should expand the sample to include diverse age groups to better capture age-related variations in SPEMs, which would enhance the applicability of these norms across a broader demographic spectrum. Furthermore, our study did not account for potential confounding factors, such as cognitive load or attention, both of which are known to influence smooth pursuit performance. Previous studies have shown that higher attentional demands, such as working memory tasks, can disrupt smooth pursuit by increasing phase lag and positional errors, highlighting the need to control for these factors in future research (Stubbs et al., 2019).

To strengthen the clinical applicability of these findings, future research should aim to (1) expand normative datasets across age groups, as previous studies have reported a decrease in smooth pursuit gain with aging (Moschner & Baloh, 1994), (2) examine the impact of cognitive and attentional factors on SPEMs performance, and (3) explore the use of Tobii and similar technologies in longitudinal studies to assess changes in SPEMs over time.

Technological Advancements in Eye Tracking

This study highlights the capabilities of modern eye-tracking technology, particularly the Tobii eye tracker, in facilitating precise, non-invasive assessments of SPEMs. The device's ease of use, coupled with its high accuracy, offers significant advantages for clinical adoption, particularly in settings requiring reliable and efficient diagnostics. By enabling objective and reproducible measurement of eye movements, the Tobii eye tracker bridges a critical gap in clinical practice, offering optometrists and other eye care professionals a practical tool for detecting and managing eye movement disorders. As eye tracking technology continues to advance, its applications may expand to include more sophisticated analyses, such as differentiating between subtle neurocognitive conditions based on unique SPEM patterns.

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