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UNIVERSITY OF CALIFORNIA SAN DIEGO

Free-Moving Gaze-Related Electroencephalography for P300 Detection in Immersive Virtual Reality

A thesis submitted in partial satisfaction of the requirements for the degree Master of Science

in

Bioengineering

by

Nathaniel Minh Green

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Shankar Subramaniam
Ying Choon Wu

2026

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University of California San Diego

2026

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LIST OF ABBREVIATIONS

Abbreviation	Definition
3D	Three-dimensional
BCI	Brain-Computer Interface
Cz	Central midline EEG electrode
EEG	Electroencephalography
ERP	Event-Related Potential
FRP	Fixation-Related Potential
FWER	Family-Wise Error Rate
GIP	Gaze-Intersection Point
GRP	Gaze-Related Potential
ICA	Independent Component Analysis
KS	Kolmogorov-Smirnov distance, the maximum absolute difference between cumulative distribution functions; lower values indicate higher similarity
LSL	Lab Streaming Layer
P300	Positive ERP component occurring approximately 300 ms after a task-relevant stimulus
Pz	Parietal midline EEG electrode
SNR	Signal-to-Noise Ratio
SSVEP	Steady-State Visual Evoked Potential
VR	Virtual Reality
VOR	Vestibulo-Ocular Reflex

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Chapter 2, in part, includes material from collaborative work conducted with Tzyy-Ping Jung, Ying Choon Wu, Enrique Carrillosulub, and Cory Stevenson. The thesis author was the primary author of this chapter.

Chapter 3, in part, includes preliminary material from ongoing collaborative work conducted with Tzyy-Ping Jung, Ying Choon Wu, Enrique Carrillosulub, and Cory Stevenson. The thesis author was the primary author of this chapter.

ABSTRACT OF THE THESIS

Free-Moving Gaze-Related Electroencephalography for P300 Detection in Immersive Virtual Reality

by

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Master of Science in Bioengineering

University of California San Diego, 2026

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Eye movements provide a useful window into visual attention because they reveal when and where a person engages with objects in the environment. In traditional event-related potential (ERP) studies, electroencephalography (EEG) activity is usually time-locked to the moment a stimulus is presented. However, this approach becomes less precise in natural and dynamic settings, where people move their eyes and head before fully engaging with an object. To address this, I studied alternative time-locking methods that use eye position and movement,

and assessed fixation-related potentials (FRPs) under free-head-movement conditions in immersive virtual reality (VR).

In the primary study, participants completed a three-dimensional visual oddball task in VR, viewing standard and deviant targets while shifting their eyes toward near-peripheral targets or turning both head and eyes toward far-peripheral targets. Simultaneous EEG, eye-tracking, and head-movement data were collected, along with derived gaze-intersection points (GIPs), defined as the moments when gaze intersected the target. A second preliminary study examined whether these patterns remained consistent. ERPs were computed and compared across three event-locking methods: stimulus onset, fixation onset, and GIP onset.

During eye-shifting trials, fixation-locked and GIP-locked ERPs showed clearer centro-parietal P300 effects than stimulus-locked ERPs, indicating that target-related neural activity was better timed to gaze reaching the object than to the object first appearing. In head-turning trials, P300 effects were smaller and less consistent, likely due to increased movement variability and vestibulo-ocular reflex dynamics. Still, GIP-locking provided an earlier marker of target engagement than fixation onset.

Chapter 1. Introduction

Event-related potentials (ERPs) are a foundational method for studying the temporal dynamics of human cognition using electroencephalography (EEG). In traditional ERP paradigms, neural activity is time-locked to externally presented stimuli, such as visual images, auditory tones, words, or task cues [1]. By averaging EEG activity across repeated trials, researchers can isolate neural responses associated with sensory processing, attention, decision-making, and memory. This approach has been especially useful because EEG provides millisecond-level temporal resolution, allowing researchers to examine the timing of cognitive processes as they unfold.

However, traditional ERP paradigms often rely on highly controlled experimental conditions that differ substantially from natural behavior. Participants are typically seated in front of a two-dimensional display, instructed to minimize movement, and presented with stimuli at precisely controlled times. Although this approach supports experimental control, it limits ecological validity. In everyday life, visual attention is rarely directed only by externally timed stimulus presentation. Instead, people actively explore their environments through coordinated eye, head, and body movements. Naturalistic eye-tracking research has emphasized that laboratory-based paradigms can alter gaze behavior when they simplify the stimuli, task, or required responses, motivating methods that better preserve natural perceptual behavior [2]. Therefore, understanding cognition under naturalistic conditions requires methods that can align neural activity to behaviorally meaningful events, rather than only to externally imposed stimulus onsets.

Fixation-related potentials (FRPs) offer one approach for aligning EEG to natural visual behavior. Rather than time-locking the EEG activity to stimulus onset, FRPs align neural activity

to the onset of a visual fixation. This enables researchers to study neural activity during self-directed visual exploration, including reading, scene perception, and visual search [3], [4]. Prior work has shown that FRPs can reveal target-detection responses during natural visual search and can distinguish target from nontarget fixations, including at the single-trial level [5], [6]. By using gaze behavior as the temporal anchor for EEG analysis, FRPs provide a more naturalistic alternative to traditional stimulus-locked ERPs.

Despite these advantages, FRP analysis depends critically on accurate fixation detection. Fixations and saccades are typically identified from eye-tracking data using velocity- or dispersion-based algorithms. These algorithms assume that fixations are periods of relatively stable gaze and that saccades are periods of rapid eye movement. However, this distinction becomes more complicated when head movement is unconstrained. During head turns, the vestibulo-ocular reflex (VOR) produces compensatory eye movements that stabilize the visual scene on the retina [2]. As a result, the eyes may continue to move relative to the head even when the gaze is stable relative to the external environment. In natural settings, VOR, smooth pursuit, optokinetic responses, and other stabilizing eye movements may occur together, making gaze behavior more complex than in isolated laboratory tasks [2]. Under these conditions, conventional fixation detection algorithms may misclassify or delay the onset of fixation because they rely on eye-in-head movement rather than object-centered visual engagement.

This problem is particularly relevant for immersive virtual reality (VR). Modern head-mounted displays with integrated eye tracking enable the study of visual attention and cognition in three-dimensional (3D), interactive environments. VR provides a controlled experimental environment while still allowing more natural behaviors, such as head and body movement and exploration of 3D scenes [7]. These systems also allow the experimenter to

compute the participant's gaze direction as a 3D vector and determine where that vector intersects objects in the virtual environment. Prior work in 3D eye movement analysis has shown that gaze direction, head position, and head orientation can be combined to compute gaze locations in virtual environments while accounting for six degrees of freedom of head movement [8]. This gaze-intersection point (GIP) provides a direct, object-centered measure of where the participant is looking.

The central approach of this thesis is to evaluate whether GIP onset can serve as an event-locking marker for EEG analysis in immersive VR. GIP onset can be defined as the earliest moment when the participant's gaze ray intersects the target object. Unlike fixation onset, which is derived from eye-movement classification, GIP onset reflects the moment of object contact in the virtual environment. This makes it especially useful in VR, where visual engagement depends on the combined contributions of eye and head movement. Recent work using simultaneous EEG, eye tracking, and head tracking in VR found that steady-state visual evoked potential (SSVEP) detection was most closely aligned with GIP onset and that visual processing could begin before fixation onset was detected [9]. By aligning EEG activity to GIP onset, it may be possible to capture neural responses associated with object-directed attention even when the traditional fixation detection is disrupted by head movement.

The P300 biomarker provides a useful test case for evaluating gaze-based event locking because it is a centro-parietal positive ERP component associated with attention, target detection, and context updating, and is typically larger for rare or task-relevant deviant stimuli than for frequent standard stimuli [5], [10]. Previous work has shown that P300-like responses can be observed in fixation-locked EEG during visual search and can distinguish target from nontarget fixations, supporting the use of gaze-locked EEG in target detection studies [5], [6]. Therefore,

P300 analysis provides a way to test whether stimulus-, fixation-, and GIP-locked EEG capture behaviorally meaningful differences in visual attention during immersive VR tasks.

This thesis is organized around two related VR studies. The primary study, described in Chapter 2, tests whether stimulus-, fixation-, and GIP-locked ERPs differ during a 3D visual oddball task with eye-shifting and head-turning conditions. Then, Chapter 3 builds on this work with a secondary preliminary study using a modified VR paradigm. After presenting both studies separately, Chapter 4 discusses what the findings mean together for naturalistic EEG, mobile brain/body imaging, and BCI research. Chapter 5 closes with the main conclusions and future directions.

Chapter 2. Primary Study

The primary study evaluated whether GIP onset can serve as an alternative event-locking marker for EEG analysis in immersive VR. To test this approach, participants performed a 3D visual oddball task while simultaneous EEG, eye-tracking, head-movement, and GIP data were recorded. Participants viewed targets appearing either near the center of gaze, requiring primarily eye movement, or farther into the periphery, requiring coordinated head and eye movement. Each target contained either a standard or deviant cue, yielding a classic oddball design expected to elicit a P300 response. By comparing stimulus-locked, fixation-locked, and GIP-locked ERPs across eye-shifting and head-turning trials, this study tested whether gaze-based event locking could improve detection of P300 responses when visual engagement occurs after stimulus onset, and whether GIP onset provides a useful object-centered marker of target engagement during free eye and head movement.

2.1 Methods

2.1.1 Participants

Eighteen healthy adults participated in the primary study. All participants reported normal or corrected-to-normal vision and no history of neurological disorders. Written informed consent was obtained before the experiment, and participants were compensated at a standard hourly rate. Data were excluded when poor EEG quality or technical issues affected one or more synchronized data streams.

2.1.2 Experimental design and task

Participants completed a 3D visual oddball task in immersive VR. The task was designed to compare neural responses of eye-shifting and head-turning gaze behaviors. Immersive VR was selected because it allows experimental control over stimulus timing and placement while also

supporting more naturalistic gaze, head, and body behaviors than conventional two-dimensional screen-based paradigms [7], [11], [12]. This is especially relevant for visual search and attention research, where natural behavior often involves coordinated eye, head, and body movements in a 3D environment rather than isolated eye movements on a computer screen [12].

Participants wore an EEG cap and a head-mounted VR display. They were seated in a chair positioned within the tracking area defined by the VR base stations. A handheld controller was used to record behavioral responses.

Each trial began with a two-second orienting period in which participants fixated on a blue cube at the center of the scene. A green target cube then appeared for two seconds in one of four peripheral locations: above, below, left, or right of center, as shown in Figure 1. Participants were instructed to shift their gaze to the target and identify the shape displayed on it.

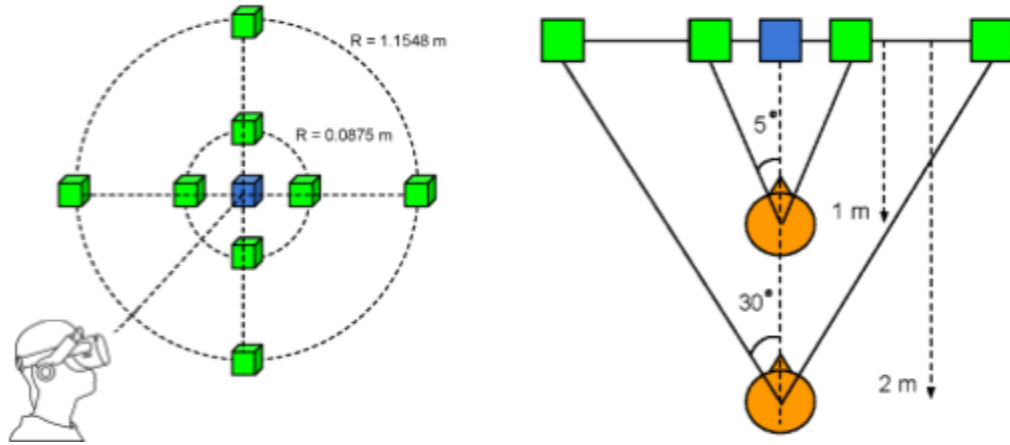


Figure 1. Experimental setup. Participants completed a visual oddball task in immersive VR while seated, wearing an EEG cap, a VR headset, and a handheld controller. Each trial began with fixation on a central blue cube, followed by the appearance of a peripheral green target cube containing either a standard or deviant shape. Targets appeared in either a low-excursion eye-shifting condition or a high-excursion head-turning condition, and participants responded by pressing the controller trigger when they detected the deviant target. The left image is an isometric view, the right image is a top-down view.

Two target eccentricity conditions were used. In the low-excursion condition, targets appeared approximately 5° from the central fixation point. These targets can be viewed primarily

with eye movements and are referred to as eye-shifting trials. In the high-excursion condition, targets appeared approximately 30° from the center. These targets required coordinated head and eye movement and are referred to as head-turning trials.

Each target contained either a standard cue or a deviant cue, shown as a stock image of a triangle or circle, respectively. Standard cues appeared on 80% of trials, while deviant cues appeared on 20% of trials, following a visual oddball design intended to elicit P300 responses to rare, task-relevant events [5], [13]. Participants were asked to respond to deviant targets as quickly as possible using the controller trigger. Low- and high-excursion trials were presented in blocks of 100 trials, and block order was counterbalanced across participants.

2.1.3 Data acquisition

EEG was recorded at 512 Hz using a 64-channel BioSemi ActiveTwo system. Electrodes were positioned according to the extended international 10–20 system [14]. Participants wore the EEG cap underneath the VR headset, allowing neural activity to be recorded during the immersive task.

Visual stimuli were presented using an HTC Vive Pro Eye head-mounted display. The headset provided integrated binocular eye tracking as well as head position and orientation tracking. Eye-tracking data were used to estimate gaze direction vectors, and a custom-coded Unity environment was used to compute GIPs by determining where gaze rays intersected objects in the virtual scene. Similar vector-based approaches have been used in 3D eye-movement analysis in VR, where gaze direction, head position, and head orientation are combined to estimate gaze locations in virtual space [8]. Recent VR-EEG work has also used GIP onset as an event marker for visual processing under free eye and head movement [9].

EEG, eye tracking, GIP, head position, head orientation, stimulus markers, and behavioral responses were synchronized using the Lab Streaming Layer (LSL), a framework for real-time, synchronized multimodal data acquisition [14]. This synchronization allowed gaze and movement events to be inserted into the EEG timeline and used as event-locking markers for ERP analysis.

2.1.4 Eye-tracking preprocessing

Reliable preprocessing is especially important in mobile and naturalistic eye-tracking settings, where data quality can be affected by head movement, partial pupil occlusion, calibration drift, and changes in viewing geometry [2], [15]. Eye-tracking preprocessing was performed to improve the reliability of gaze-direction estimates and to remove unreliable samples associated with blinks, signal dropout, or poor pupil tracking.

Gaze direction was estimated from normalized pupil direction vectors. Samples with eye openness values below 0.1 were marked as unreliable [9]. Short gaps lasting less than 75 ms were linearly interpolated. Gaps lasting between 75 and 150 ms were classified as blinks, while gaps longer than 150 ms were treated as missing data. The remaining gaze time series were smoothed using a 40 ms window to reduce high-frequency noise. These preprocessing criteria followed the general approach used in prior VR-based GIP analyses, including eye-openness thresholds, blink/missing-data classification, and temporal smoothing of eye, head, and GIP signals [9].

These preprocessing steps produced continuous gaze-direction estimates suitable for fixation detection, GIP computation, and angular-dispersion/velocity analyses.

2.1.5 EEG preprocessing

EEG preprocessing was performed using EEGLAB and associated artifact-removal tools [16]. Raw EEG data were first band-pass filtered from 1 to 50 Hz using a finite impulse response filter. The data were then re-referenced to the mastoid electrodes.

Bad channels were identified and removed using the EEGLAB `clean_rawdata` plugin. Channels were rejected if they showed prolonged flatline activity, excessive line noise, or poor correlation with neighboring channels. Artifact Subspace Reconstruction was then applied with a burst threshold of 10 to remove transient high-amplitude artifacts [17].

Independent Component Analysis (ICA) was performed to separate neural and non-neural sources [18]. Components associated with artifacts, including eye blinks, muscle activity, or other non-brain sources, were identified using ICLabel and removed if the artifact classification probability exceeded 80% [19]. The cleaned EEG data were then used for epoching and ERP computation.

2.1.6 Fixation detection

Fixation detection was performed using a velocity-threshold approach based on the Tobii I-VT fixation filter. Velocity- and dispersion-based algorithms are commonly used to classify fixations and saccades from eye-tracking data, although their performance can vary depending on threshold choices, signal quality, and task context [20], [21]. Angular velocity was calculated from gaze vectors, and candidate fixations were identified using an angular speed threshold of $30^{\circ}\cdot\text{s}^{-1}$.

Adjacent fixations were merged if the temporal gap between them was less than 75 ms and the angular difference between them was less than 1° . After merging, fixations shorter than 200 ms were removed. These criteria were intended to exclude unstable or ambiguous fixation events while preserving meaningful periods of gaze stabilization. The same fixation-detection

logic, including a $30^{\circ} \cdot \text{s}^{-1}$ angular-speed threshold, a 75 ms merging interval, a 1° angular-difference criterion, and a 200 ms minimum duration criterion, has been used in recent VR-based GIP analyses [9].

Because fixation detection based on eye velocity may be affected by head movement, fixation onset was treated as one of several possible event markers rather than as the sole indicator of visual engagement. This distinction is important because, during head movement, VOR dynamics can produce compensatory eye movements even when gaze remains stable relative to the external environment [2], [9], [14].

2.1.7 Gaze-intersection-point onset detection

GIPs were computed in the virtual environment by projecting the participant's gaze ray into the scene and identifying the nearest object intersected by that ray. For each trial, GIP onset was defined as the earliest time point after stimulus onset when the gaze ray intersected the target cube.

This event marker differs from fixation onset in an important way. Fixation onset is derived from eye movement stability, whereas GIP onset is derived from object contact in the virtual environment. Therefore, GIP onset provides an object-centered measure of visual engagement that incorporates both eye and head position. Prior VR eye-tracking work has emphasized that eye tracking in VR enables gaze to be calculated in 3D space and linked to regions or objects of interest [7], while previous 3D eye-movement analysis methods have shown the value of computing gaze locations using head and gaze vectors in virtual environments [8].

For trials in which the gaze ray intersected the target before fixation was detected, GIP onset was interpreted as an earlier marker of target contact. This was particularly relevant for head-turning trials, where the participant's gaze could reach the target before eye-in-head

velocity stabilized enough to satisfy fixation criteria. Recent work by Liu et al. demonstrated that visually evoked responses in VR can align closely with GIP onset and that fixation onset may occur later than GIP onset, particularly under conditions involving head movement [9].

2.1.8 ERP computation

ERPs were computed using three event-locking strategies: stimulus-locking, fixation-locking, and GIP-locking. For stimulus-locked ERPs, time zero was defined as target onset. For fixation-locked ERPs, time zero was defined as the onset of the first detected fixation on the target following stimulus onset. For GIP-locked ERPs, time zero was defined as the first gaze-ray intersection with the target cube.

EEG epochs were extracted from -300 ms to 800 ms relative to each event-locking point. Baseline correction was performed using the -300 to 0 ms pre-event interval. ERPs were then computed separately for standard and deviant trials for each participant, condition, electrode, and event-locking method.

Epochs were excluded if the latency between stimulus onset and the corresponding GIP or fixation event was shorter than 100 ms or longer than 1000 ms. These criteria removed events that were implausibly early or excessively delayed relative to stimulus onset.

Analyses focused on electrodes Cz and Pz because the P300 component is typically largest over centro-parietal scalp regions and occurs approximately 250 – 500 ms after detection of a rare or task-relevant stimulus [5], [13]. Prior fixation-related potential studies have also shown that target and nontarget fixations can be distinguished using P300-like activity during active visual search [5], [6]. Grand-average ERPs were then computed across participants for visualization and statistical analysis.

2.1.9 Permutation-based FWER max-T analysis

To identify time periods showing reliable differences between standard and deviant ERPs, we used a permutation-based max-T procedure controlling the family-wise error rate. This approach was selected because ERP analyses involve multiple statistical comparisons across time points, increasing the risk of false-positive results. Permutation-based mass-univariate approaches are commonly used in ERP analysis to control for multiple comparisons across time and/or electrodes while avoiding strong parametric assumptions [22].

For each condition, electrode, and event-locking method, paired-sample t-tests were computed at each time point comparing standard and deviant ERP amplitudes across participants. To generate the null distribution, condition labels were randomly permuted within participants 5000 times. For each permutation, t-statistics were recomputed across the analysis window, and the maximum absolute t-value was retained. This produced a null distribution of maximum t-values representing the largest effect expected by chance across time.

Observed t-values were then compared with the permutation-derived max-T threshold. Time points exceeding this threshold were considered significant at $\alpha = 0.05$ with family-wise error correction. This method controls for multiple comparisons while preserving sensitivity to temporally localized ERP effects.

Separate analysis windows were used for eye-shifting and head-turning trials. For eye-shifting trials, the primary analysis window was 0–400 ms after event onset. For head-turning trials, the primary analysis window was 200–600 ms after event onset to account for the additional latency introduced by coordinated head and eye movement. These windows were selected to capture the expected time course of post-engagement perceptual evaluation, target detection, and P300 generation while accounting for the additional temporal variability introduced by larger head-eye movements.

2.1.10 Parametric ERP analysis

To complement the permutation-based analysis, window-mean ERP amplitudes were also analyzed using paired-sample statistical tests. For each participant, condition, electrode, and event-locking method, mean amplitude was extracted within a predefined P300 time window. The P300 is commonly observed over centro-parietal electrodes within approximately 250–500 ms after rare or task-relevant stimuli, although latency can vary depending on task demands and stimulus processing requirements [5], [13].

Difference scores were computed as deviant minus standard, such that positive values reflected greater positivity for deviant trials. Paired-sample t-tests were used to compare standard and deviant amplitudes across participants. Because each comparison involved two repeated-measures levels, these tests are mathematically equivalent to a one-factor, two-level repeated-measures ANOVA.

Results were summarized using t-statistics, p-values, and Cohen's d_z effect sizes. These parametric analyses were not adjusted for multiple comparisons and provide interpretable statistics that complement the family-wise error rate (FWER) corrected permutation results.

2.2 Results

2.2.1 GIP, Fixation, and Response timing differed across trials

We first examined the timing of first GIP contact with the target, fixation onset on the target, and behavioral response relative to stimulus onset. This analysis was used to determine whether GIP onset and fixation onset captured the same behavioral event or whether they reflected distinct stages of visual engagement. During eye-shifting trials, GIP onset and fixation onset occurred within similar temporal ranges, whereas response trigger pulls occurred later and were more broadly distributed (Figure 2). As expected, the gaze ray generally intersected the

target before fixation onset, suggesting that GIP onset marked the earliest moment of target contact while fixation onset reflected subsequent gaze stabilization.

During head-turning trials, the temporal separation between GIP onset and fixation onset became more pronounced. GIP contact occurred earlier and with a more compact distribution, whereas fixation onset was delayed and also broadly distributed (Figure 2). This pattern indicates that during head movement, fixation onset may reflect a later stage of head-eye stabilization rather than the initial moment of visual engagement with the target. Behavioral responses occurred later than both gaze-related events, indicating that GIP- and fixation-locked analyses were not simply aligned to motor output.

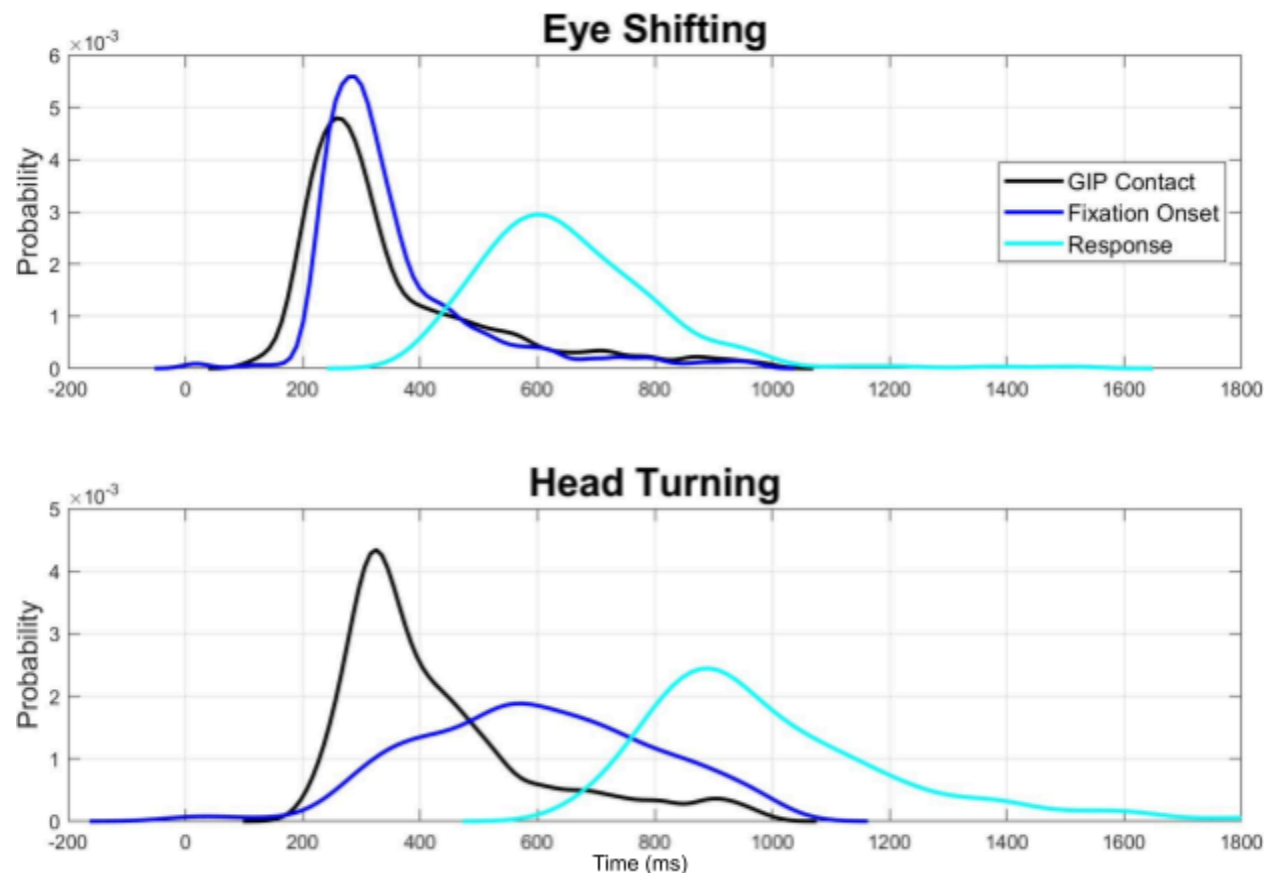


Figure 2. Event onset timing during eye-shifting and head-turning trials. GIP contact is onset.

The distributions show event timing relative to stimulus onset for GIP contact, fixation onset, and controller trigger response. During eye-shifting trials, GIP and fixation timing were

relatively similar, with a low Kolmogorov-Smirnov (KS) statistic of 0.1463 (lower is better). In head-turning trials, fixation onset was delayed and more broadly distributed than GIP onset, with a KS statistic of 0.4498. Behavioral responses occurred later than both gaze-related events.

2.2.2 Head-turning trials produced greater angular dispersion and delayed gaze stability

To characterize the movement dynamics underlying these timing differences, we looked at angular dispersion of head, eye, gaze, and GIP-related signals during both trial types. During eye-shifting trials, gaze and eye trajectories stabilized rapidly after target engagement (around 50 ms for GIP locking and at time zero for fixation-locking), consistent with efficient saccadic redirection. In Figure 3.1, the GIP distance from the target center decreased rapidly and remained low (green line), confirming that gaze converged on the target after onset.

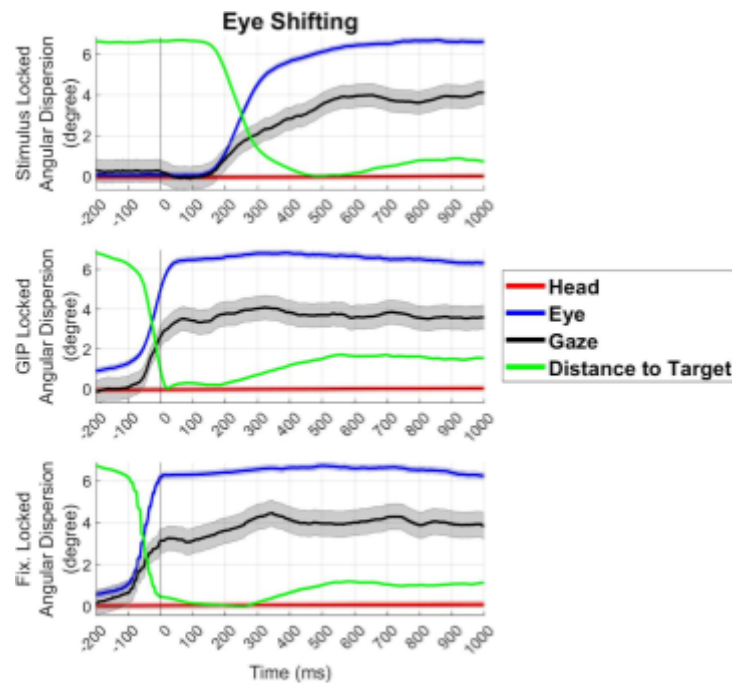


Figure 3.1. Angular dispersion traces for eye, head, gaze, and gaze-intersection-point (GIP) distance during eye-shifting trials. Signals are plotted relative to event onset to illustrate changes in eye, head, and gaze orientation over time as participants redirected gaze toward the target.

In contrast, head-turning trials exhibited greater angular dispersion and slower stabilization in head, eye, and gaze signals, characterized in Figure 3.2. These effects were

particularly evident in the head-movement signal, reflecting the greater motor effort required to orient toward far-peripheral targets. The broader dispersion patterns indicate greater spatial and temporal variability during head-turning trials, likely contributing to reduced ERP robustness in subsequent analyses.

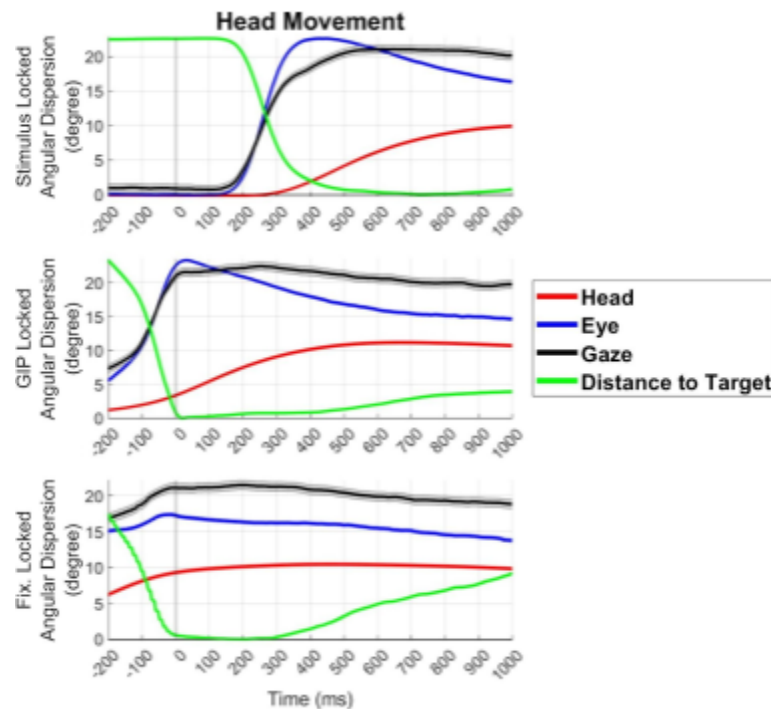


Figure 3.2. Angular dispersion traces for eye, head, gaze, and gaze-intersection-point (GIP) distance during head-turning trials. Signals are plotted relative to event onset to illustrate changes in eye, head, and gaze orientation over time as participants oriented toward far-peripheral targets.

Angular dispersion of eye, head, gaze, and GIP-related signals shows rapid stabilization during eye-shifting trials and broader, more variable movement profiles during head-turning trials. These patterns indicate that far-peripheral target viewing required more prolonged head-eye coordination and produced greater variability in gaze stabilization.

Angular velocity analyses further demonstrated that eye-shifting and head-turning trials involved distinct movement dynamics. Eye-shifting trials showed brief, sharply time-locked velocity transients consistent with rapid saccadic redirection. In contrast, head-turning trials exhibited broader and more sustained velocity profiles, especially in the head-movement signal.

In the fixation-locked and GIP-locked head-turning analyses, eye angular velocity crossed the zero-velocity threshold and reversed direction around the period of target engagement (Figure 4). This suggests that the eyes moved backward in the opposite direction while the head continued to rotate, a pattern consistent with compensatory VOR activity during head movement [2]. Gaze stabilization during head-turning trials appears to involve coordinated eye-head dynamics rather than only saccades.

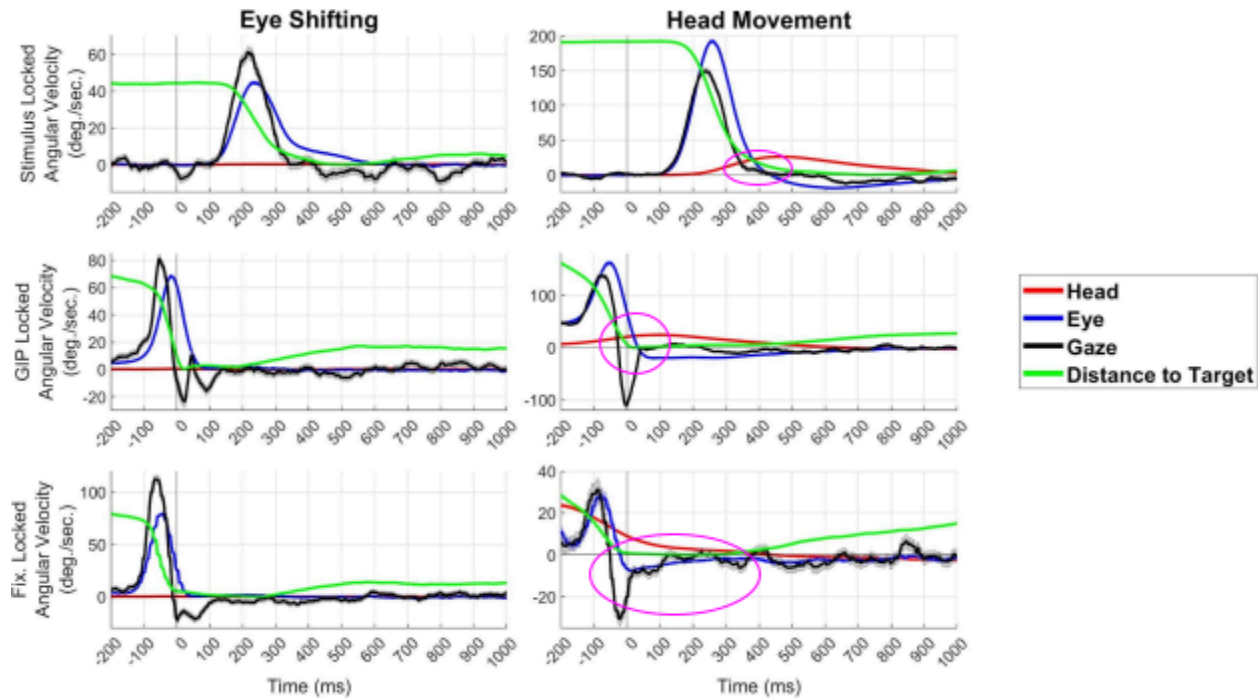


Figure 4. Angular velocity traces for eye, head, and gaze signals during eye-shifting and head-turning trials. The plots show velocity changes relative to event onset and allow comparison of the temporal profiles of eye, head, and gaze motion across the two movement conditions. Pink ovals indicate when the angular velocity crosses the zero-velocity threshold (direction reversal).

2.2.3 Permutation-based FWER max-T analysis confirmed reliable gaze-locked ERP differences

During eye-shifting trials, the FWER-corrected analysis confirmed reliable standard-deviant differences most consistently in the GIP-locked and fixation-locked conditions.

As shown in Figure 5, corrected effects were most apparent over centro-parietal electrodes, particularly Pz, and occurred within the expected post-engagement P300 latency range. In contrast, stimulus-locked ERPs showed fewer corrected effects. These effects confirm that aligning EEG activity to gaze-based events improves the temporal consistency of the P300 response compared with aligning activity to stimulus onset alone.

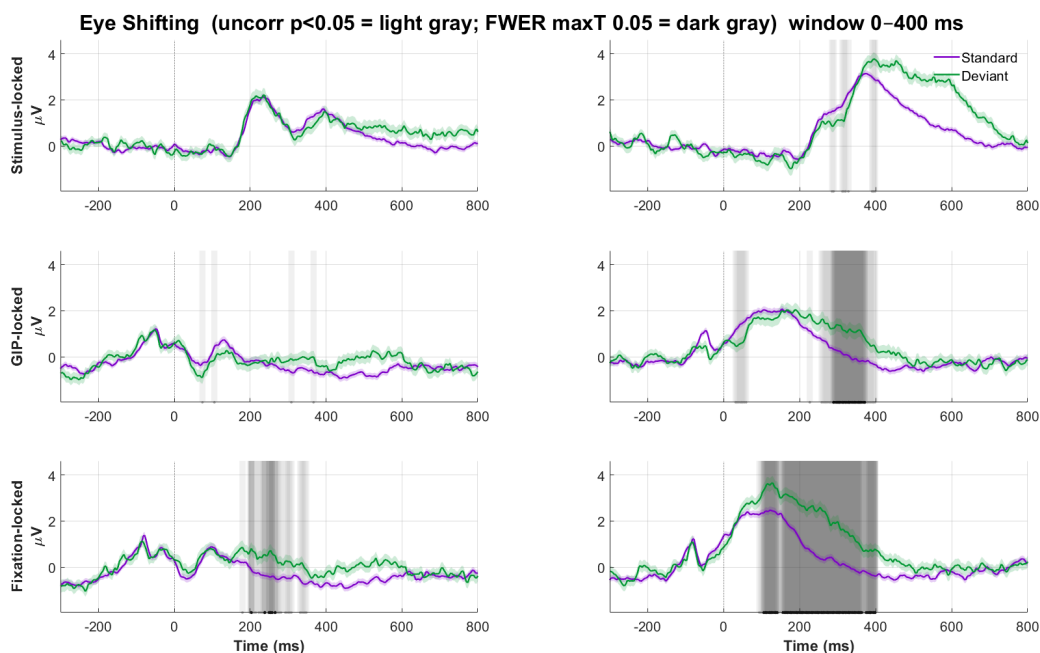


Figure 5. Eye-shifting ERPs with permutation-based FWER max-T correction. Grand-average ERPs at electrodes Cz (left column) and Pz (right column) for stimulus-locked, GIP-locked, and fixation-locked conditions during eye-shifting trials. Purple traces represent standard trials and green traces represent deviant trials. Light gray shading indicates uncorrected standard-deviant differences, while dark gray shading and black markers indicate time points surviving permutation-based max-T family-wise error rate correction at $\alpha = 0.05$.

During head-turning trials, fewer time points survived FWER correction, and the effects were less consistent across event-locking methods. In Figure 6, corrected standard-deviant differences were weaker than those observed in the eye-shifting condition and varied more across Cz and Pz. Although GIP-locking still provided an earlier object-centered marker of target engagement than fixation onset, the reduced consistency of the ERP effects indicates that head

movement added variability to the EEG response. This variability likely reflects a combination of head-eye coordination, gaze stabilization, VOR activity, and movement-related EEG noise.

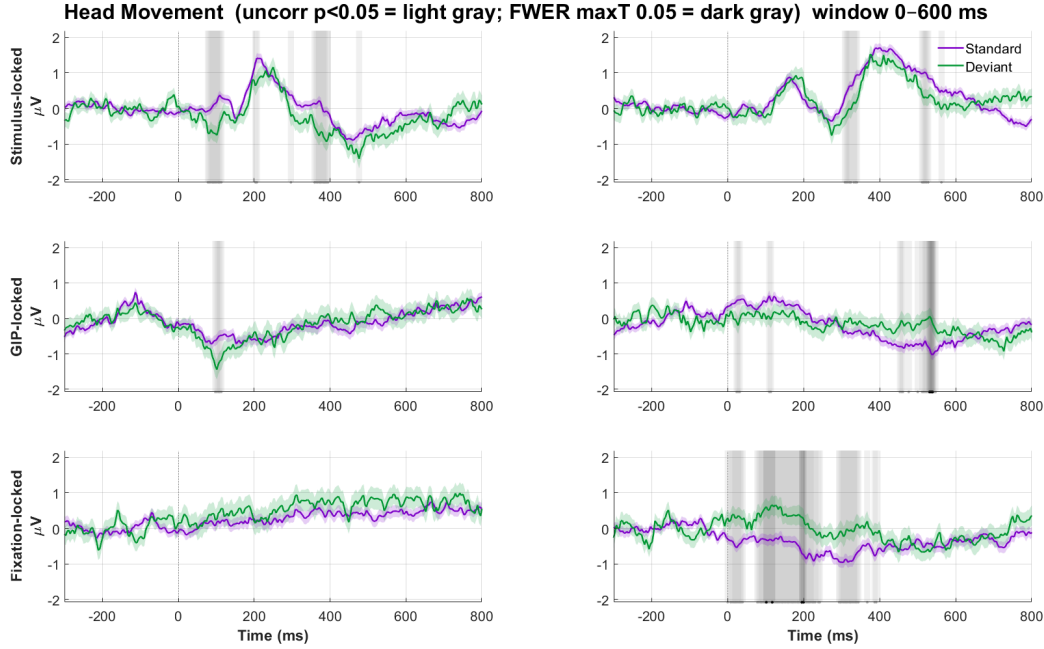


Figure 6. Head-turning ERPs with permutation-based FWER max-T correction. Grand-average ERPs at electrodes Cz (left column) and Pz (right column) for stimulus-locked, GIP-locked, and fixation-locked conditions during head-turning trials. Purple traces represent standard trials and green traces represent deviant trials. Light gray shading indicates uncorrected standard-deviant differences, while dark gray shading and black markers indicate time points surviving permutation-based max-T family-wise error rate correction at $\alpha = 0.05$.

2.3 Discussion and motivation for Secondary Preliminary Study

The primary study demonstrated that gaze-based event locking can improve the detection of P300 responses during active visual engagement in immersive VR. During eye-shifting trials, both GIP-locked and fixation-locked ERPs showed clearer standard-deviant differences than stimulus-locked ERPs, particularly over centro-parietal electrodes. The permutation-based FWER max-T analysis further supported this interpretation by showing that reliable corrected effects were most consistently observed in gaze-locked conditions during eye-shifting trials. These effects reveal that when participants must redirect their gaze toward a peripheral target,

neural responses are more closely aligned with gaze engagement than with the stimulus's physical onset. In contrast, head-turning trials showed weaker and less consistent ERP effects, highlighting that coordinated head-eye movement introduces additional variability, making P300 responses more difficult to isolate.

These results also support that conventional velocity-based fixation detection becomes less reliable when head movement is present. During head turns, the participant's gaze may already be directed toward the target in world-centered coordinates while the eyes continue to move relative to the head, likely due in part to compensatory VOR dynamics. This can delay the detection of fixations even when visual engagement has already begun. GIP onset, therefore, provides a complementary object-centered marker of gaze engagement in immersive VR. However, ERP reliability was reduced during head-turning trials; a secondary preliminary study was conducted to evaluate the same gaze-based event-locking framework in a modified paradigm with reduced motor and timing demands.

Chapter 3. Secondary Preliminary Study

The secondary preliminary study is currently ongoing and follows the same general procedures for data acquisition, preprocessing, event detection, and ERP analysis as described in Chapter 2, with several task-specific modifications. The paradigm included a central fixation condition and replaced the controller-trigger response with a passive viewing condition to mitigate potential overlap between motoric and visual categorization processes. Therefore, the methods below focus only on procedures that differ from those in the primary study.

3.1 Methods

3.1.1 Participants

Six healthy adult participants took part in the secondary preliminary study. Participants self-reported normal or corrected-to-normal vision and had no history of neurological disorders. All participants provided written informed consent before beginning the experiment. Because this study was preliminary and ongoing, the sample size was smaller than in the primary study and was used to evaluate whether the gaze-based event-locking framework could be extended to the modified VR paradigm without an overt classification task.

3.1.2 Experimental design and task

The secondary preliminary study used a modified version of the immersive VR visual oddball paradigm described in Chapter 2. As in the primary study, participants viewed different standard and deviant visual cues (an image of a flower and a pair of pliers, respectively, embedded in the target cubes) in the same 3D VR environment while simultaneous EEG, eye-tracking, head-movement, and GIP data were recorded (Figure 7). However, the paradigm was modified to include a central fixation condition in addition to peripheral target conditions. This central fixation condition provided a more traditional P300 comparison in which

participants could attend to target and non-target stimuli without requiring large gaze shifts or head turns.



Figure 7. Standard and deviant visual cues in the secondary preliminary study. Standard trials contained an image of a flower (left), deviant trials contained an image of a pair of pliers (right).

Unlike the primary study, participants were not required to respond using a controller trigger. Instead, they were instructed simply to look at the stimuli when they appeared, and then return their gaze to the central location. This approach allowed the preliminary study to focus more directly on visual engagement and stimulus-related neural responses across the modified VR conditions.

3.1.3 Data acquisition and preprocessing

Data acquisition and preprocessing followed the same general procedures used in the primary study. EEG was recorded with a 64-channel system, and eye tracking, head position, head orientation, stimulus markers, and GIP streams were synchronized using Lab Streaming Layer. Visual stimuli were presented in immersive VR via a head-mounted display with integrated eye tracking.

EEG preprocessing followed the pipeline described in Chapter 2, including band-pass filtering, re-referencing, bad-channel rejection, Artifact Subspace Reconstruction, ICA, and ICLabel-based artifact component removal. Eye-tracking preprocessing also followed the approach described in Chapter 2, including removal of unreliable samples, interpolation of short gaps, blink and missing-data classification, and temporal smoothing.

3.1.4 Event detection and ERP analysis

Event detection and ERP computation followed the same general approach as in the primary study. Stimulus, fixation, and GIP onset events were synchronized with time series EEE and used as event-locking markers where applicable. Stimulus-locked ERPs were aligned to visual stimulus onset, fixation-locked ERPs were aligned to the onset of the first detected fixation on the target, and GIP-locked ERPs were aligned to the first gaze-ray intersection with the relevant target object.

Epochs were extracted around each event marker and baseline-corrected using the pre-event interval. ERPs were computed separately for standard and deviant trials and averaged across participants for visualization. Analyses focused on centro-parietal electrodes, particularly Cz and Pz, to evaluate whether deviant stimuli elicited greater positivity than standard stimuli in the expected P300 latency range.

Because the secondary study was preliminary, statistical analyses were treated as exploratory. ERP results were interpreted primarily in terms of waveform morphology, timing, and consistency of standard-deviant differences across event-locking methods, rather than as definitive evidence of group-level effects.

3.2 Results

3.2.1 GIP and fixation onset timing differed across preliminary study conditions

We first examined GIP and fixation onset timing relative to stimulus onset in the secondary preliminary study. Because the study removed the controller-trigger response, behavioral response timing was not measured in this paradigm. During eye-shifting trials, GIP and fixation onsets occurred within similar temporal ranges (KS statistic of 0.1107), with GIP contact occurring slightly earlier on average than fixation onset (Figure 8). In head-turning trials,

this separation became more pronounced: GIP onset occurred earlier with the majority of onsets occurring before 600 ms post-stimulus, whereas fixation onsets tended to occur later than 600 ms post-stimulus (KS statistic of 0.5347). This pattern is consistent with the primary study and indicates that GIP onset captured the earlier moment of object-centered target contact, while fixation onset reflected a later stage of gaze stabilization during coordinated head-eye movement.

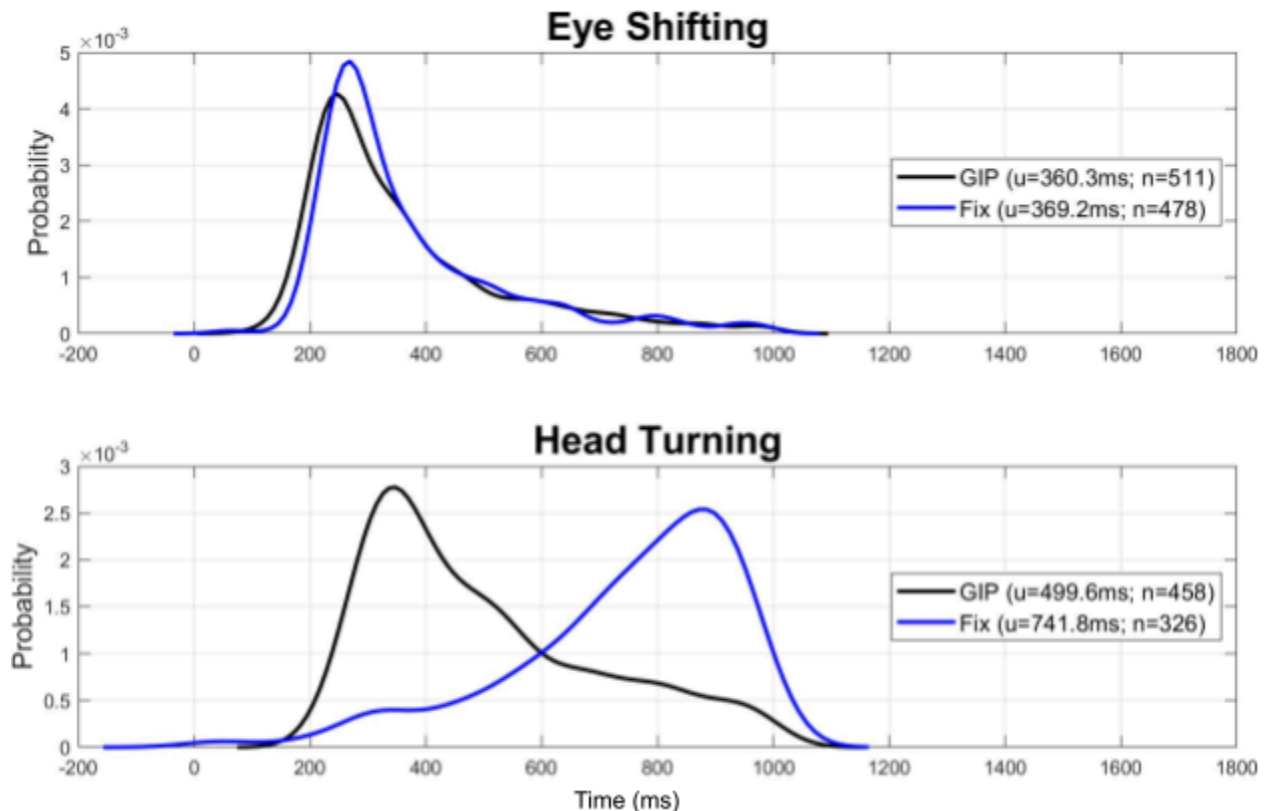


Figure 8. Event onset timing during eye-shifting and head-turning trials in the secondary preliminary study. Response is not measured due to the lack of a trigger pull.

3.2.2 ERPs showed clear standard-deviant differences

The secondary preliminary study was conducted to evaluate whether the gaze-based event-locking framework would yield clearer P300-like responses in a modified VR paradigm that removed the controller-trigger response and reduced potential response-related overlap in the EEG signal. Despite the smaller preliminary sample size of six participants, the grand-average ERPs in Figure 9 showed clear separation between standard and deviant trials across multiple

conditions, particularly over the centro-parietal electrodes Cz and Pz. In general, deviant trials elicited greater positivity than standard trials within the expected P300 latency range, particularly in the center-fixation and eye-shifting conditions. These effects were most visually apparent at Pz, consistent with the expected parietal distribution of the P300.

Permutation-based max-T family-wise error rate correction confirmed reliable standard-deviant differences in several conditions. In the center fixation condition, stimulus-locked ERPs showed a clear deviant-related positivity at Pz, with FWER-corrected effects occurring in the post-stimulus window. This pattern provides a useful reference for a more traditional P300-like response in VR, where participants could attend to the stimuli with reduced demands on gaze redirection. GIP-locked and fixation-locked center responses showed more limited effects, which is expected by reduced need for gaze-based temporal realignment.

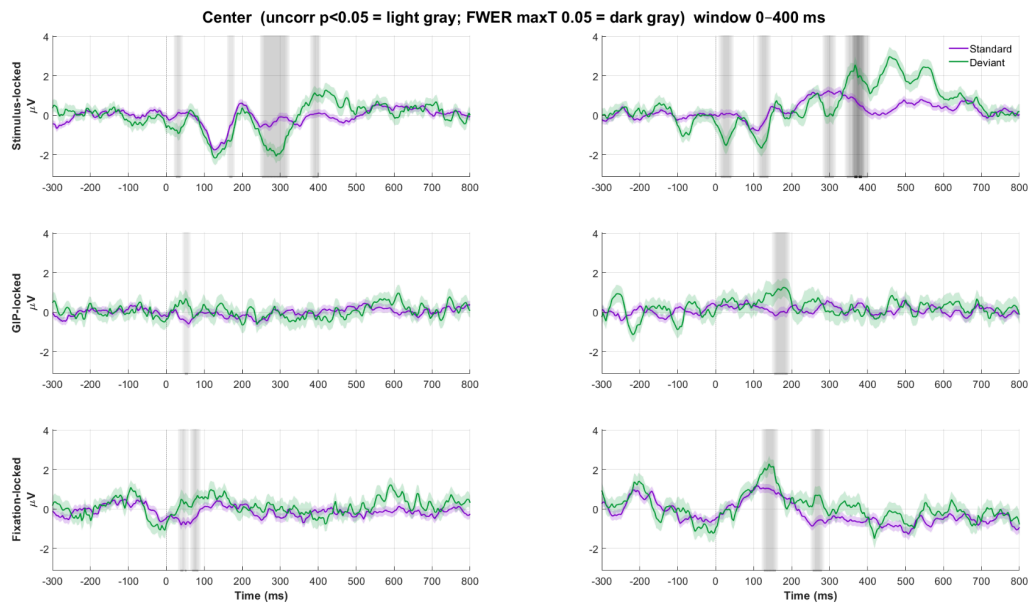


Figure 9. Center fixation ERPs with permutation-based FWER max-T correction. Grand-average ERPs at electrodes Cz (left column) and Pz (right column) for stimulus-locked, GIP-locked, and fixation-locked analyses in the center fixation condition. Purple traces represent standard trials and green traces represent deviant trials. Light gray shading indicates uncorrected standard-deviant differences, while dark gray shading and black markers indicate time points surviving permutation-based max-T family-wise error rate correction at $\alpha = 0.05$.

3.2.3 Eye-Shifting Trials Showed Strong Gaze-Locked P300-Like Effects

The eye-shifting condition produced the clearest support for gaze-based event locking in the secondary preliminary study. Found in Figure 10, deviant trials showed greater positivity than standard trials, particularly over Pz, across stimulus-locked, GIP-locked, and fixation-locked analyses. However, this effect was reliable only with GIP- or fixation locking within the expected post-engagement P300 latency range, with several time points surviving FWER max-T correction. This pattern indicates that when participants redirected gaze toward nearby peripheral targets, aligning EEG activity to gaze-based events improved the consistency of target-related ERP differences.

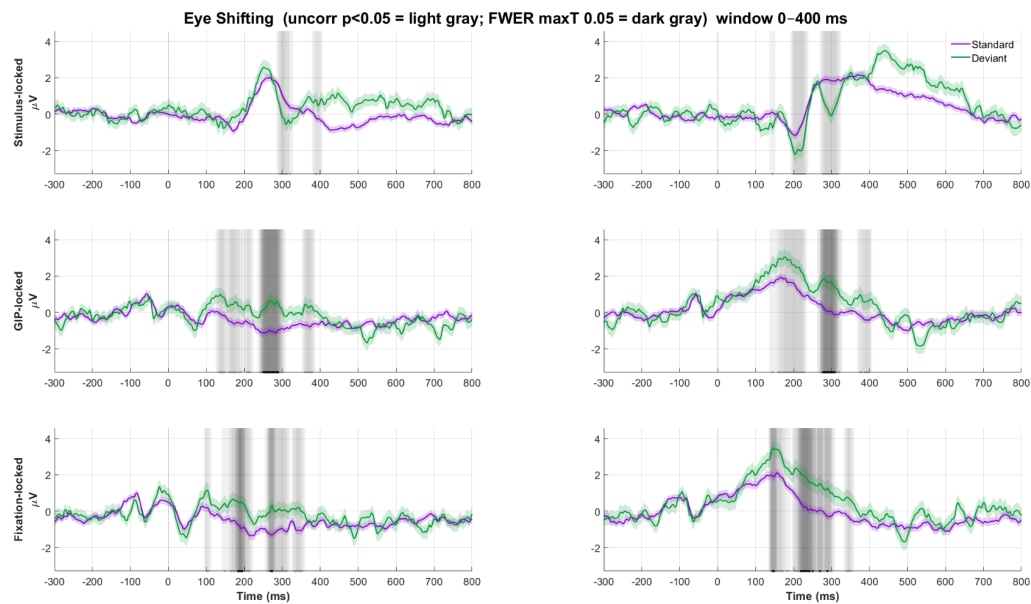


Figure 10. Eye-shifting ERPs in the secondary preliminary study with permutation-based FWER max-T correction. Grand-average ERPs at electrodes Cz (left column) and Pz (right column) for stimulus-locked, gaze-intersection-point-locked, and fixation-locked analyses during eye-shifting trials. Purple traces represent standard trials and green traces represent deviant trials. Light gray shading indicates uncorrected standard-deviant differences, while dark gray shading and black markers indicate time points surviving permutation-based max-T family-wise error rate correction at $\alpha = 0.05$.

Compared with the primary study, the eye-shifting results in the preliminary dataset appeared visually clearer despite the smaller number of participants. In keeping with the well-documented centro-parietal distribution of the visual oddball P300 [13], the strongest effects were observed over Pz, where deviant responses were larger and more sustained than standard responses. These findings provide additional support for the interpretation that GIP-locking and fixation-locking can improve detection of P300-like activity when visual engagement occurs after stimulus onset.

3.2.4 Head movement trials showed later and more variable corrected effects

As in the prior study, head-movement trials showed more variable ERP effects than the center-fixation and eye-shifting conditions. In Figure 11, standard-deviant differences remained present, but appeared later and were less consistent across locking methods and electrodes. In the stimulus-locked and GIP-locked Pz responses, deviant trials showed greater positivity than standard trials between roughly 500 and 600 ms post-stimulus, though FWER-corrected effects were obtained only in the case of GIP-locking. This timing is consistent with the onset distributions, where GIP contact in head-movement trials tended to occur around 500 ms or earlier, meaning that the observed ERP differences likely occurred shortly after gaze reached the target. Thus, target-related processing remained detectable during head movement, although with greater temporal variability.

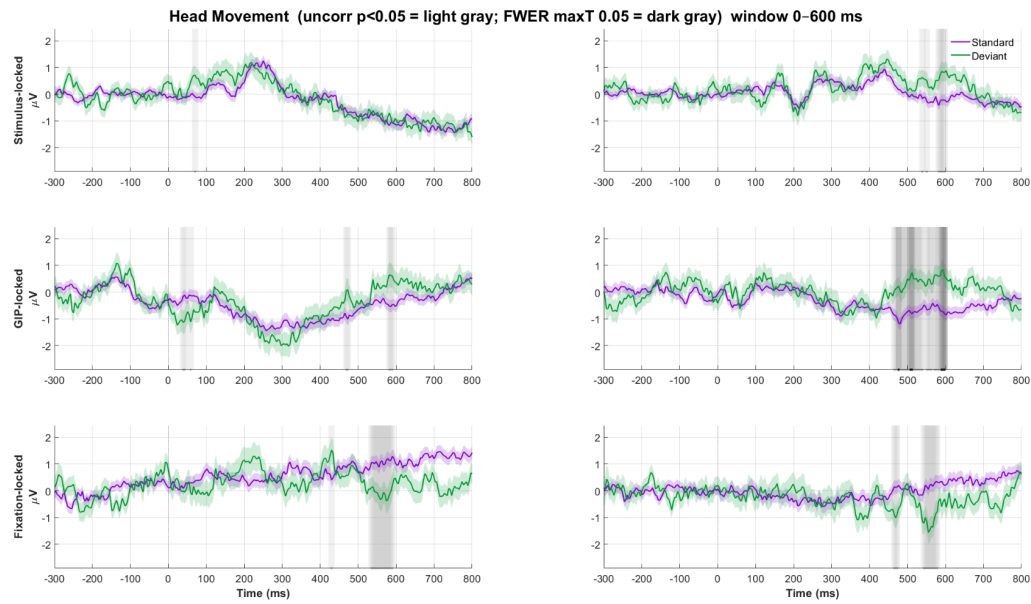


Figure 11. Head-movement ERPs in the secondary preliminary study with permutation-based FWER max-T correction. Grand-average ERPs at electrodes Cz (left column) and Pz (right column) for stimulus-locked, GIP-locked, and fixation-locked analyses during head-movement trials. Purple traces represent standard trials and green traces represent deviant trials. Light gray shading indicates uncorrected standard-deviant differences, while dark gray shading and black markers indicate time points surviving permutation-based max-T family-wise error rate correction at $\alpha = 0.05$.

The fixation-locked head-movement responses were less straightforward, with some corrected effects occurring later and showing less canonical P300 morphology. This is consistent with the primary study's interpretation that fixation detection is more complicated during head movement, likely because eye-in-head velocity can continue to change while gaze stabilizes in the virtual environment. Overall, the head-movement results support the idea that GIP-based alignment remains useful under more complex movement demands, while also reinforcing that free head movement remains a challenging condition for ERP analysis.

3.3 Discussion

The secondary preliminary study provided additional validation of the gaze-based event-locking framework under a modified VR paradigm. Despite including only six

participants, the study produced clear standard–deviant ERP differences, particularly in the center fixation and eye-shifting conditions. The center fixation condition showed a more traditional stimulus-locked P300-like response, while the eye-shifting condition showed strong GIP-locked and fixation-locked effects, especially at Pz. These findings support the interpretation that gaze-based event locking can improve the temporal alignment of target-related neural responses when visual engagement occurs after stimulus onset.

The head movement condition continued to show later and more variable effects, consistent with the primary study. In turn, weaker head-turning results in the primary study likely reflected the added complexity of coordinated head-eye movement, gaze stabilization, VOR dynamics, and movement-related EEG variability rather than a failure of the GIP-locking approach itself. Together, the primary and secondary studies demonstrate that GIP-locking is a promising object-centered method for aligning EEG activity to visual engagement in VR, while also emphasizing that large head movements remain a major methodological challenge for naturalistic ERP analysis.

Chapter 4. General Discussion

4.1 Overview of findings

This thesis evaluated whether gaze-based event locking can improve the detection of P300 responses during naturalistic visual behavior in immersive VR. Across the primary and secondary preliminary studies, the central question was whether EEG responses are better aligned to the physical onset of a stimulus or to the moment of actual visual engagement with a target. To address this question, stimulus-locked, fixation-locked, and GIP-locked ERPs were compared across VR oddball paradigms involving central fixation, eye shifting, and head movement.

Across both studies, gaze-based event locking provided a useful framework for analyzing target-related EEG responses in VR. In the primary study, GIP-locked and fixation-locked ERPs enhanced standard-deviant differences during eye-shifting trials, whereas stimulus-locked responses were weaker and less consistent. Head-turning trials were more variable, but they demonstrated an important dissociation between GIP onset and fixation onset, suggesting that GIP can provide an earlier object-centered marker of target engagement during coordinated head-eye movement. The secondary preliminary study extended these findings by using a modified VR paradigm with reduced motor and timing demands. Despite the smaller sample size, this study showed clearer P300-like standard-deviant differences, especially in the center fixation and eye-shifting conditions, providing additional support for the gaze-based event-locking framework.

4.2 Gaze-based event locking improves alignment to visual engagement

The main finding across is that gaze-based event locking can improve the temporal alignment of EEG responses during active visual behavior. In traditional ERP paradigms,

stimulus onset is usually an appropriate timing reference because participants are already fixating on the stimulus location. Under those conditions, stimulus onset and visual engagement occur almost simultaneously. However, in naturalistic visual tasks, especially in immersive VR, this assumption often does not hold. A target may appear in the periphery, but the participant may not fully evaluate its identity until gaze reaches the target.

Under these conditions, stimulus-locked averaging can introduce temporal jitter because the relevant perceptual event occurs at different times across trials. Fixation- and GIP-locking reduce this jitter by aligning EEG activity to gaze behavior rather than to stimulus onset alone. This was most clearly demonstrated in the eye-shifting conditions, where gaze-based alignment produced clearer standard-deviant separation and stronger P300-like effects. The secondary preliminary study further supported this interpretation, showing clear deviant-related positivity in the eye-shifting paradigm even with only six participants. Together, these findings support the central premise of fixation-related and gaze-related potential approaches: when participants actively move their gaze toward a target, target-related neural responses are more closely tied to gaze arrival than to stimulus onset.

4.3 GIP as an object-centered marker in immersive VR

A major contribution of this thesis is the use of GIP onset as an object-centered event marker for EEG analysis in immersive VR. Fixation onset and GIP onset are related, but they capture different aspects of visual behavior. Fixation onset is derived from eye-movement classification and depends on whether the eye-tracking signal satisfies stability criteria. GIP onset, by contrast, is defined as the first moment when the participant's gaze ray intersects a task-relevant object in the virtual environment. Therefore, GIP onset marks object contact rather than eye-movement stability.

This distinction became especially important during head-turning trials. During eye-shifting trials, GIP onset and fixation onset occurred within similar temporal ranges, suggesting that when gaze redirection is accomplished primarily through ocular saccades, traditional fixation detection remains a useful marker of visual engagement. However, during head-turning trials, fixation onset was delayed and more variable than GIP onset. This suggests that fixation detection becomes less reliable when head movement is involved.

The angular velocity results further support this interpretation. In head movement conditions, eye angular velocity crossed the zero-velocity threshold and reversed direction near target engagement, a pattern consistent with compensatory VOR dynamics during head rotation. In this situation, the participant's gaze may already be directed toward the target in world-centered coordinates while the eyes continue to move relative to the head. Conventional velocity-based fixation detection may therefore delay the onset of fixation even when visual engagement has already begun. GIP onset avoids part of this limitation by measuring gaze relative to the virtual object rather than relying only on eye-in-head stability.

This object-centered definition is one of the main advantages of GIP-locking. In immersive VR, the experimenter has access not only to eye position but also to head position, head orientation, gaze direction, and the geometry of the virtual scene. This makes it possible to determine when gaze intersects a specific object in three-dimensional space. Therefore, GIP-locking provides a meaningful event definition for studying object-directed attention during VR tasks involving free viewing, visual search, navigation, and embodied interaction.

4.4 Head movement remains a methodological challenge

Although GIP-locking provides a meaningful marker of object-centered visual engagement, head movement remains a major challenge for ERP analysis. In the primary study,

head-turning trials showed weaker and less consistent P300 effects than eye-shifting trials. The secondary preliminary study also showed that head-movement responses were later and more variable than center-fixation and eye-shifting responses, even though corrected effects were still observed.

This indicates that event alignment is only one part of the challenge. Head movement introduces additional sources of variability, including differences in movement onset, movement duration, gaze stabilization, neck and muscle activity, vestibular processing, and potential EEG artifacts. These processes may overlap with target-related neural activity, reducing the consistency of the averaged ERP. Head-turning trials also involve a more distributed sequence of perceptual and motor events: participants must detect the target onset, initiate a head turn, coordinate eye and head movement, stabilize gaze, identify the stimulus, and, in the primary study, execute a behavioral response. These processes vary across trials, making it more difficult to isolate a clean P300 response.

The secondary preliminary study helps clarify this interpretation. By adding a central fixation condition and removing the controller-trigger response, the modified paradigm reduced certain sources of motor- and response-related variability. The clearer P300-like effects observed in the center-fixation and eye-shifting conditions suggest that the weaker head-turning results in the primary study were likely attributable to movement-related variability rather than to a failure of the gaze-locking approach itself. Thus, GIP-locking remains promising, but robust EEG analysis during large head movements will likely require additional methods beyond event alignment alone.

One additional consideration to note is that the observed positivity in P300s may reflect multiple overlapping components of the broader P300 response. In the primary study,

participants make a controller response for the deviant targets, possibly leading to motor-response-related positivity. In contrast, the secondary preliminary study removes this trigger response, which could likely reduce later positivity in the waveform. This difference may help explain why the secondary study would produce clever P300-like responses, more-so in the head turning condition. This highlights the importance of separating visual target evaluation from response-related activity in future analyses.

4.5 Implications for naturalistic EEG and BCI

These findings have important implications for naturalistic neuroscience and BCI research. Traditional P300-based BCI paradigms typically rely on controlled stimulus timing and constrained gaze behavior. However, future BCI systems may need to operate in VR, augmented reality, or real-world environments where users move their eyes and heads freely while interacting with objects. In these contexts, externally defined stimulus onset may not be sufficient to determine when the user is actually attending to a target.

GIP-based event locking could help address this issue by identifying moments of object-directed visual engagement. Rather than responding only to what appears in the environment, future systems could use gaze-object interactions to determine what the user is attending to. This may be especially useful for VR- or augmented-reality-based BCIs, assistive technologies, neuroergonomics, and adaptive interfaces that need to interpret neural activity during active exploration.

More broadly, this work contributes to mobile brain/body imaging and naturalistic EEG research. As neuroscience experiments move beyond static displays and restrained behavior, researchers need methods that can handle the complexity of natural movement while preserving the temporal precision of ERP analysis. Combining EEG with VR-based eye tracking, head

tracking, and object-level gaze information enables the definition of neural events relative to behaviorally meaningful interactions in three-dimensional environments.

4.6 Limitations and future directions

Several limitations should be considered. First, although the primary study demonstrated the feasibility of GIP-based event locking, larger datasets are needed to fully characterize individual variability, especially during head movement. The secondary preliminary study, while ongoing, included only six participants in this analysis, so its findings should be interpreted as exploratory rather than definitive. However, the presence of clear standard-deviant differences and FWER-corrected effects in this small sample is promising and supports continued validation with additional participants.

Second, fixation detection depended on a velocity-threshold algorithm. Different fixation parsing methods may produce different onset estimates, especially under conditions involving head movement and VOR dynamics. Future work should compare multiple fixation detection approaches, including velocity-based, dispersion-based, machine-learning-based, and object-centered methods. This would help determine when fixation onset and GIP onset converge, when they diverge, and which marker is most appropriate for different VR task contexts.

Third, movement-related artifacts remain a challenge for EEG in VR. Although preprocessing methods such as ASR and ICA were used, additional artifact modeling may improve signal quality during head movement. Future studies could explicitly model head velocity, eye velocity, neck muscle activity, or other movement-related signals to better separate neural activity from movement artifacts. Regression-based deconvolution methods may also be useful for separating overlapping stimulus-, gaze-, fixation-, and response-related processes.

Fourth, the present analyses focused primarily on Cz and Pz because of the expected centro-parietal distribution of the P300. This focus was appropriate for the current research question, but future work should examine whole-scalp patterns and potentially use mass-univariate or cluster-based statistical approaches. This may help identify whether gaze-based event locking affects not only the P300 but also earlier sensory or attentional components.

Finally, future work should examine whether GIP-locking improves single-trial classification of target versus non-target events. This is especially relevant for BCI applications, where the goal is not only to detect group-level ERP effects but also to classify neural responses in real time. Machine-learning methods such as support vector machines, linear discriminant analysis, or regularized logistic regression could be used to compare classification performance across stimulus-, fixation-, and GIP-locked features. Features could include mean amplitude, peak amplitude, area under the curve, latency measures, and spatial patterns across electrodes.

Chapter 5. Conclusion

This thesis examined whether gaze-based event locking can improve the detection of P300 responses during visual attention in immersive VR. Across the primary and secondary preliminary studies, the findings support the central idea that neural responses in active viewing tasks are often better aligned to moments of visual engagement than to stimulus onset alone. In the primary study, GIP-locked and fixation-locked ERPs enhanced standard-deviant differences during eye-shifting trials, suggesting that gaze-based alignment reduced temporal variability between target appearance and target processing. During head-turning trials, GIP onset provided an earlier object-centered marker of target contact than fixation onset, although ERP effects were weaker and more variable due to the added complexity of coordinated head-eye movement, VOR dynamics, and movement-related EEG variability. The secondary preliminary study further supported this framework by showing clearer P300-like responses under a modified VR paradigm with reduced motor and timing demands, including a central fixation condition and no controller trigger response.

Together, these findings demonstrate that GIP-based event locking is a feasible and meaningful approach for EEG analysis in immersive VR. By defining neural events relative to object-centered gaze behavior, this method enables the study of attention, perception, and target detection during more naturalistic interactions in three-dimensional environments. While free head movement remains a major methodological challenge, GIP-locking offers a promising foundation for future VR-based EEG and BCI research. Moving forward, this approach can be extended to more complex VR tasks, with the long-term goal of detecting object-directed attention in real time during naturalistic behavior.

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