Towards the Automatic Detection of Vection in Virtual Reality Using EEG

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Abstract—Vection, the visual illusion of self-motion, provides a strong marker of the VR user experience and plays an important role in both presence and cybersickness. Traditional measurements have been conducted using questionnaires, which exhibit inherent limitations due to their subjective nature and prevent real-time adjustments. Detecting vection in real time would allow VR systems to adapt to users' needs, improving comfort and minimizing negative effects like cybersickness. This paper investigates the presence of vection markers in electroencephalographic (EEG) brain signals using evoked potentials (brain responses to external stimuli).

We designed a VR experiment that induces vection using two conditions: (1) forward acceleration or (2) backward acceleration. We recorded electroencephalographic (EEG) signals and gathered subjective reports on thirty (30) participants. We found an evoked potential of vection characterized by a positive peak around 600 ms (P600) after stimulus onset in the parietal region and a simultaneous negative peak in the frontal region. This result paves the way for the automatic detection of vection using EEG as well as a better understanding of vection. It also provides insights into the functional role of the visual system and its integration with the vestibular system during motion-perception. It has the potential to help enhance VR user experience by qualifying users' perceived vection and adapting the VR environments accordingly.

Index Terms—Human-centered computing, Human computer interaction (HCI), Interaction paradigms, Virtual reality.

I. INTRODUCTION

In Virtual Reality (VR), vection – the visual illusion of self-motion induced in a stationary observer [31] – plays a critical role in shaping user experience. This phenomenon occurs when a person experiences a sensation of movement because of a visual stimulus while actually remaining stationary. An everyday example of this phenomenon is when an individual mistakenly perceives their own motion as a train departs from an adjacent platform, or when watching a river flow from a bridge. Vection as a phenomenon has interested the scientific community for over a century [7], [14], and has furthered our understanding of how we perceive motion.

More recently, vection has been studied for its role in simulated environments such as driving or flight simulators, video games, and VR [35], [39]. Many have highlighted the need for a deeper understanding of this phenomenon [2], [31]. The study of vection holds significant importance for several reasons. First, vection research elucidates the neural processes involved in the perception of speed and direction.

Second, it is linked to postural control, where visual input plays a crucial role in stabilizing postural balance. In addition, investigating vection contributes to our knowledge of the neural underpinnings of motion perception.

Moreover, vection is a key factor in the effectiveness of simulation and training environments. Specifically, research is exploring whether vection can enhance the transfer of skills acquired in simulations to real-world scenarios [17]. Finally, understanding vection is crucial for addressing motion sickness, potentially leading to improved prevention and treatment strategies [7], [31]. It has been positively correlated with the sense of presence [18], [40], which refers to the psychological state of "being there" [5] and serves as a key indicator of user experience in VR. It is a direct response to the degree of immersion provided by the VR environment [44]. Vection offers a functional perspective on brain mechanisms, particularly concerning the integration of visual and vestibular sensory information, thereby enhancing our understanding of sensory conflict resolution [7]. Therefore, the examination of vection encompasses a multitude of implications for various related fields.

Cybersickness, commonly experienced in VR, shares many similarities with motion sickness and frequently co-occurs with vection [19], [21], [28], [35]. While research has established that vection can exacerbate cybersickness symptoms [36], [45], the precise mechanisms underlying this relationship remain poorly understood. This relationship warrants careful investigation, as understanding how vection influences cybersickness is fundamental for developing more comfortable and user-friendly VR experiences. To quantify these experiences, researchers typically employ the Simulator Sickness Questionnaire (SSQ) [15], which provides standardized measures of both cybersickness and related phenomena.

Questionnaires also have a central place in vection research, as they are currently the best method for assessing a user's perceived experience. There is however a need to identify alternative indicators to complement and validate traditional self-report measures. A recurring challenge in vection studies lies in the lack of well-validated, objective measures capable of consistently identifying or characterizing the vection experience [31]. Currently, researchers often rely on non-standardized [17] subjective rating scales, leading to substantial variability across subjects and studies [1], [31]. Recent endeavors have emphasized the need for objective measurements of vection, arguing that subjective questionnaires for measuring vection suffer from misreported onset latencies, difficulty in obtaining real-time measurements,

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susceptibility to experimenter influence, potential confusion with other sensations, and the need for confidence in capturing true self-motion perception [31]. Effectively measuring vection would lead to more accurate data on self-motion perception by reducing reliance on subjective reports, enabling the use of objective indicators like eye movements and EEG. This is important because vection plays a crucial role in tasks like navigation, spatial orientation, and improving the user experience of virtual environments and simulators [31].

Brain-Computer Interfaces (BCIs) are widely employed in the scientific literature to record, interpret, and convert brain signals into system inputs. BCIs use various techniques to measure brain activity, including electroencephalography (EEG), which records electrical potentials generated by neuron populations. EEG is particularly suited for VR applications due to its relative ease of use and the allowance for user movement compared to other BCI methods. A recent trend involves passive BCIs, which monitor brain activity and adjust the system in response to the user's mental state. This approach has been applied in VR to assess aspects of user experience, such as presence [42]. This paper focuses on two types of EEG signals often used in passive BCIs: evoked potentials and brain rhythms. Under specific conditions, distinct brain activation patterns, known as neuromarkers, can be identified. An *evoked potential* (EP) is a neuromarker that occurs in response to an external stimulus [4]. In the spectral domain, patterns vary depending on the frequency range, reflecting conventional brain rhythms. These rhythms are typically categorized as Delta (1–4 Hz), Theta (4–7 Hz), Alpha (8–13 Hz), and Beta (13–30 Hz).

Our objective is to identify potential neuromarkers of vection through EEG. To the best of our knowledge, no evoked potential of perceived vection has been previously reported in the literature. In pursuit of this objective, we conducted an experiment that exposed participants to moving white spheres in VR, while recording EEG. Participants viewed visual stimuli depicting either a forward acceleration (with the spheres accelerating in the backward direction) or a backward acceleration (with the spheres accelerating in the forward direction). We then asked participants to rate the intensity of their perceived vection and analyzed how their self-reports correlated with their brain signals. Our analysis yields the following key contributions:

- We identify an evoked potential of vection. A bilateral pattern shows in both the frontal and centro-parietal regions that is distinct between vection conditions approximately 600ms after stimulus onset.
- We uncover significant differences in subject susceptibility to vection and acceleration direction.
- We replicate literature results finding bespoke signals of acceleration and showing an effect of vection on alpha power.
- We find a link between vection and Simulator Sickness Questionnaire answers, with subjects reporting strong vection having higher Simulator sickness scores.

The remainder of the paper is structured as follows: Section II highlights the related work on the measurement of vection in virtual reality. Section III describes our experimental setup and methods. Section IV presents the findings of the investigation into the results from the experiment. Finally, we discuss shortcomings and future works in Section V before concluding in Section VI.

II. Related Work

Vection as a term was first coined by Helmholtz in 1896 [49] by observing a river flow under a bridge. He hypothesized that it was an illusion, a failure of our senses. Eighty years later, significant advancements had been made in understanding this phenomenon, with clear trends beginning to emerge [7]. These showed that vection is more than an illusion, as visually induced motion is often necessary for an accurate representation of our movements through space. The vestibular system alone is only able to detect acceleration and cannot infer velocity. Thus, it cannot distinguish absence of motion from constant velocity, or a backward acceleration from a deceleration. Other senses are needed to supplement the vestibular system and inform the brain's perception of motion. The visual system plays an important role in informing our sense of motion along with the vestibular system. This implies that the vestibular and visual system converge in the same locus to integrate into a unique model of spatial orientation [7]. Thus, studying vection offers insights into how that integration occurs and how the brain understands self-motion.

It was not until the 1970s that studies began to explore it through a physiological lens, as evidenced by the pioneering work of Dichgans and Brandt [7]. Over time, the field has grown both in the number of publications, and in the breadth of applicable scenarios, ranging from simulators to rehabilitation. It can be used to monitor presence, improve sensorimotor training and rehabilitation [2], [17], [19]. A review by Berti and Keshavarz [2] highlights the relevance of neuropsychological vection research, outlining 4 major reasons: (1) it helps uncover the neuro-cognitive functioning of multisensory perception; (2) it presents an opportunity in other research areas; (3) it can help develop an objective measure of vection, complementing subjective assessments; and (4) it has potential in neurorehabilitation to facilitate the recovery process in sensorimotor training.

Building upon the importance of this research, several studies have investigated specific factors influencing vection. A study by Seno et al. demonstrated a significant positive correlation between the duration of exposure to optic flow stimuli and the perceived strength of vection. Vection magnitude systematically increases with longer exposure durations, supporting the influence of exposure duration on vection strength [43]. Kim et al. found that adding simulated visual movement, regardless of whether it was synchronized with head movements or viewed while stationary, consistently increased the strength and perceived speed of self-motion. This suggests that visual processing plays a dominant role in the perception of self-motion, particularly when low-frequency sensory stimuli are involved [20]. Furthermore, correlations between dizziness and vection duration have been found, as well as between general discomfort and sway

[35]. Moreover, unexpected vection significantly exacerbates cybersickness during HMD-based virtual reality, suggesting that unanticipated sensations of self-motion are a key predictor of cybersickness [45]. In many studies, a pivotal question remains: How to accurately measure vection?

To answer this question, we will investigate the existing literature on vection assessment. In the subsequent sections, we will look into publications relating to the two primary categories of vection assessment: subjective and objective measurements.

A. Subjective measures

Subjective self-reports of vection have traditionally played an important role in vection research [22], [33], where vection is commonly defined as the visual illusion of self-motion [31]. Questionnaire methods typically include binary choice responses, where participants indicate whether they experience vection, and onset time determination, which records when vection is first perceived. Intensity rating scales ask participants to rate the strength of their vection experience, while magnitude estimation involves quantifying the perceived intensity relative to a reference [22]. These methods have been used to assess vection's occurrence, timing, and strength in various contexts, including in VR. This enabled the investigation of various aspects of vection, including its correlation with simulator sickness [13] and its role in controlling self-motion and navigation [31].

However, these methods have limitations stemming from their reliance on self-reporting. While valuable, subjective measures can be influenced by individual differences and may lack the temporal precision required for detailed analysis. Vection also presents a dilemma for researchers, in that it is a subjective experience that would benefit from being studied across subjects. In 2015, Palmisano et al. [31] highlighted four major challenges in modern vection research, and urged the community to (1) address diverse definitions and their implications, (2) explore the functional roles of conscious vection experiences during self-motion, (3) enhance objective measures for vection, and (4) conduct further research on the neural basis of vection to better understand its neural underpinnings. Our paper aims to contribute to the third and fourth challenges identified by Palmisano et al.

Multiple additional papers have also highlighted the need for objective and real-time measures of vection for validating research and making cross-subject and cross-study comparisons more robust [17], [22], [33], citing various shortcomings, such as their unreliability, response biases or social desirability [22].

B. Objective measures

The need for objective measures of vection has been recognized early on, as they can reveal the neural underpinnings of vection and enhance the design of VR systems. Understanding these neurophysiological aspects is crucial for improving VR experiences, as it allows for more informed control of user experiences and interactions.

Notably, postural sway analysis has been successfully employed to estimate the impact of vection on postural balance [28], [35]. This method provides valuable insights into the physical consequences of vection. Such methods can be useful for understanding vection parameters. For example, Palmisano et al. (2014) [32] found that individuals who rely more on vision for postural stability tend to experience stronger vection. However, it is important to distinguish visually induced postural sway from visually induced vection, though this distinction can be challenging [31]. While these phenomena share similarities and often co-occur, they differ in fundamental ways. Visually induced postural sway represents an automatic postural response to visual motion stimulation that functions as a reflex-like mechanism for maintaining balance [7]. This postural response can be triggered by visual motion alone and does not require the conscious perception of self-motion. In contrast, vection is a conscious perceptual experience of self-motion that results from the integration of visual and vestibular information [7], [31]. The two phenomena can occur independently: visually induced postural sway can occur without any illusory vection, and conversely, vection can be experienced without significant postural instability [31]. The challenge in distinguishing them arises because both responses share similar dependencies on visual stimulus properties such as area, velocity, and spatial frequency of visual motion [31]. Moreover, when vection is experienced, it often produces postural sway as a secondary consequence, making it difficult to isolate the direct postural response to visual motion from the response to the illusory self-motion perception.

Recently, Padmanaban et al. [29] have initiated efforts towards predicting vection directly from stereoscopic video. They employed a convolutional neural network-based optical flow algorithm, to compute features that are directly linked to the user's vection experience.

While such approaches advance our ability to predict vection based on visual input, understanding the neurophysiological underpinnings remains crucial. These approaches lay the groundwork for understanding the neural mechanisms underlying vection. Berti and Keshavarz [2] review EEG and fMRI studies on visually induced vection, identifying key brain areas involved in vection processing. Their review emphasizes the involvement of a network in the neocortex in vection processing as well as a decrease in the alpha band.

Electroencephalography (EEG) has emerged as a promising tool for objective vection assessment [1], [2], [17]. EEG allows for the investigation of neural correlates during vection experiences. By exploring how vection is processed in the brain, VR developers can better control the environments, reduce cybersickness, and predict overall user experience. There are several ways to investigate vection using EEG. Looking at Evoked Potentials, Thilo et al. found a negative occipital response 70ms after optokinetic stimulation [46], but did not link this neuromarker to vection. Some studies looking into brain rhythms during vection confirmed that alpha suppression is correlated with vection [2], [12]. Keshavarz et al. [17] advocated for EEG as an objective measure of vection,

reviewing findings including early ERPs (P1, N2) correlated with Vection stimuli [16] and frequency-domain changes such as alpha and gamma desynchronization during vection [41]. In contrast to these early components and frequency-domain analyses, our work investigates an ERP component that correlates with the conscious experience of vection. It is important to note that, to investigate robust markers of vection in EEG, one still needs to rely on subjective measures, as there is no other ground truth measurement. Since vection is fundamentally a subjective experience, any objective measure of vection must be measured in conjunction with traditional self-measures reports [31]. Moreover, current EEG methods of studying vection still suffer shortcomings that prevent us from using them as a ground truth for vection detection. Many methods struggle to generalize across subjects. Moreover, techniques capable of isolating lower frequencies, as often reported in the literature, may require longer time windows for effective analysis. In this study, we focus on evoked potentials, as they provide a high temporal resolution and may reveal characteristic brain responses that are consistent across subjects, offering a potential objective measure of vection. Our paper proposes a path for objective measurement of vection using EEG by leveraging the established field of Evoked Potentials. Our proposition utilizes acceleration as a stimulus to explore EPs specific to the phenomenon of vection.

III. EXPERIMENT

The objective of this study is to investigate the neural correlates of vection in VR. Thus, we designed a user study to induce vection through two types of trials: one with forward acceleration and the other with backward acceleration. Building upon the methodological framework described in [48], this study adds questionnaires for assessing vection and simulator sickness.

The subject was exposed to visual stimuli depicting either (1) a sudden forward acceleration FA_1, with the environment moving in the posterior direction, or (2) a sudden backward acceleration BA_1, with the environment moving in the anterior direction. After each trial, the subject was asked to report vection on a 4-point Likert scale.

A. Participants and ethics

Thirty healthy participants with normal or corrected-to-normal vision took part in the experiment (18 men, 12 women aged $\mu = 26$, $min = 18$, $max = 56$, $\sigma = 7.38$). This study was approved by the University of Lille Ethics Committee with approval number 2021-526-S97 and adheres to the principles outlined in the Declaration of Helsinki. All data was anonymized, and participants provided written informed consent. They were also explicitly informed of their right to withdraw from the experiment at any time without any repercussions.

B. Apparatus

The virtual environment was displayed on a Valve Index HMD with a 1440x1600 resolution screen for each eye running
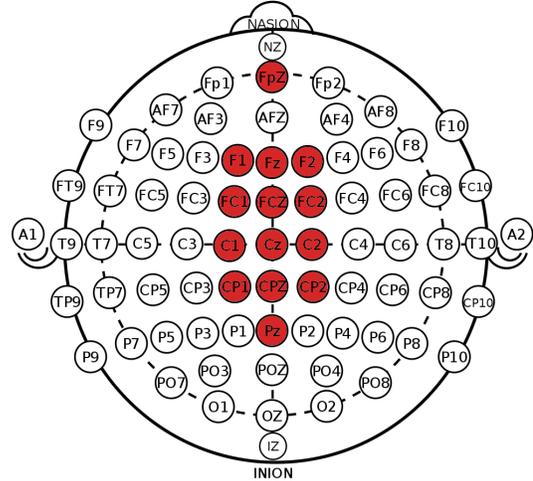

Fig. 1: Electrode Placement in the 10–20 International System. Highlighted electrodes indicate sites used in this study: FPz, Fz, F1, F2, FCz, FC1, FC2, Cz, C1, C2, CPz, CP1, CP2, and Pz.

at 144Hz and a DELL PRECISION 3640 personal computer with an NVIDIA GeForce RTX 3080 video card.

EEG was measured using a cap g.GAMMAcap2 from g.tec medical engineering GmbH® (Austria) with 14 recording electrodes, plus a reference electrode attached to the earlobe and ground electrode located at AFZ. The recording electrode configuration was the following: FPz, Fz, F1, F2, FCz, FC1, FC2, Cz, C1, C2, CPz, CP1, CP2 and Pz. The central distribution of the electrodes was purposefully chosen as we expected a non-lateralized signal along the frontal-occipital axis as seen in Figure 1. The software used to record EEG data and events is OpenVibe 3.1.0 [38]. The virtual environment (VE) was created using the version *2020.3.11f1* of the Unity game engine software. Data analysis was performed using the MNE-python library [25] and the seaborn visualization library [24].

C. Trial design

A visual representation of a single trial is represented in Figure 2. The Valve Index headset with Base Station tracking provided absolute position tracking with sub-millimeter accuracy, automatically positioning the virtual camera at each participant's actual eye level based on the floor plane calibration performed during room setup. All dimensions in this paper are reported in meters.

Each trial, lasting 19 seconds, was divided into four distinct phases. First, during the *Static phase*, the virtual environment gradually appeared over the course of 2 seconds and remained stationary. In the *Slow speed phase*, the environment accelerated to a speed of 3 m/s within 2 seconds and sustained this speed for a variable time of 1, 3 or 5 seconds, providing a baseline for EEG measurement under low-speed conditions. The *Acceleration phase* then followed, where the visual environment depicted either a forward (FA_1)
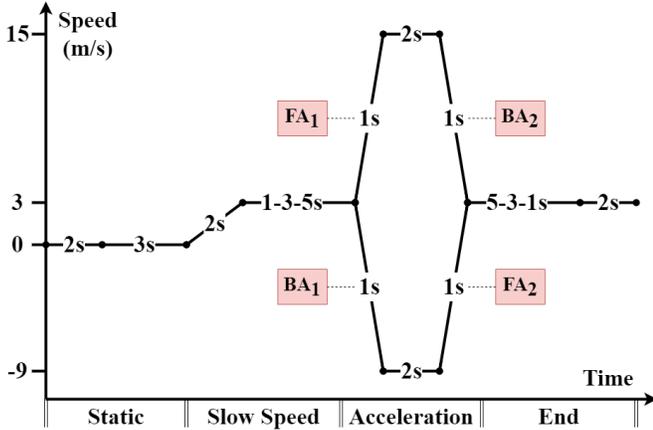
Fig. 2: Evolution of speed over time during a trial. Dashed lines represent variable delays, with one of three delays chosen pseudo-randomly. The second delay ensures the cumulative sum of delays equals 6 seconds.
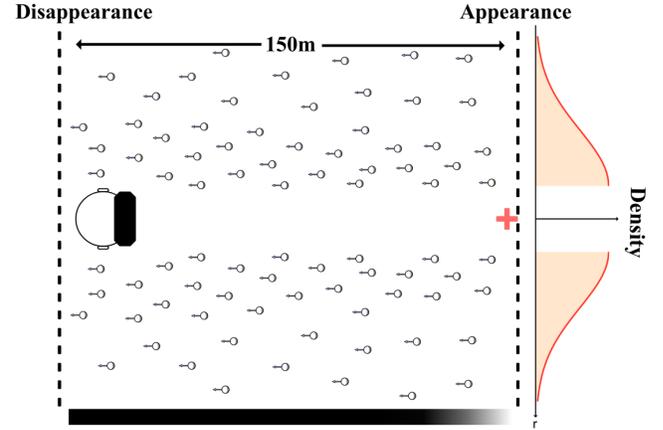

Fig. 3: Top-down view of the sphere distribution in the virtual environment.

Fig. 4: Participant view of the virtual environment showing the spheres and central crosshair.

or backward acceleration (BA_1) of 12 m/s^2 for a duration of 1 second. These parameters were designed to ensure the visual acceleration appears sudden and the resulting speed appears fast while remaining within plausible everyday ranges, such as those encountered in typical car travel. Additionally, evoked potentials typically occur within 1 second of stimulus onset, and prolonged exposure to visual acceleration has been shown to produce diminishing perceptual effects [10]. The speed was then held for 2 seconds before slowing back to the initial speed, either by forward (FA_2) or backward acceleration (BA_2). Finally, in the *End phase*, the environment continued moving at 3 m/s, mirroring the slow-speed phase, before gradually disappearing over a 2-second fade-out.

D. Experimental setup

For the design of the VE we could either induce vection in a realistic environment, which is more engaging for the participants, or we could do it in a minimalist environment. The minimalist environment of white spheres arranged like a star field is more widely used in the literature [2]. This is because it works well at inducing vection while keeping potential confounding factors at a minimum. We chose to proceed with a minimalist environment.

Our VE was similar to that used by Keshavarz et al. to induce vection [18]. The experimental protocol involved seating the participant within a virtual environment surrounded by stationary white spheres. Figure 3 shows the visual representation of sphere placement. Initially, the participant remained static, but as the experiment progressed, they experienced either forward or backward acceleration, which served as stimuli to induce vection. This was realized using a 3D cloud composed of 2000 white spheres arranged cylindrically around the participant against a dark background in a virtual reality environment. Each sphere has a diameter of 0.20 meters. The distribution is centered 1.2 meters above the ground, corresponding to typical seated eye level.
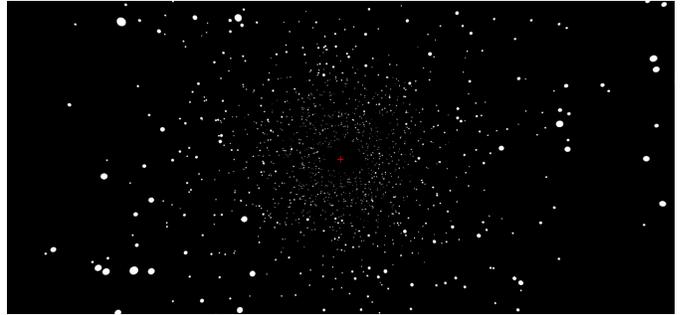
Spheres were distributed using cylindrical coordinates: uniformly in depth (0 to 150 meters along the motion axis) and uniformly in angle (around the full 360° azimuth). The radial distance from the central axis followed a Gaussian distribution with a standard deviation of 5 meters, creating a natural concentration of spheres near the participant's travel path while maintaining peripheral visual coverage. To prevent collisions with the participant, spheres were kept at least 1.8 meters away from the radial center. Spheres gradually appeared over 30 meters starting at 150 meters forward to prevent distracting pop-in effects in the participant's field of view, then faded out after passing behind the participant.

The participant's view can be seen in Figure 4. A red crosshair was positioned at the center of the visual field, and participants were instructed to maintain their gaze fixed upon it to avoid ocular movements. Participants were seated and instructed to minimize head movements during trials. No chin-rest was used, as keeping participants' heads unconstrained and positions natural allowed for a comfortable, personalized, and ecologically valid experimental condition typical of VR contexts. Potential motion artifacts were mitigated through participant instruction and the artifact rejection procedures described in Section III-F. The spheres were controlled via Unity scripts which determined their speed and acceleration, which varied depending on the trial type.

E. Experimental procedure

Upon entering the experimental room, participants were briefed on the study's objective: detecting self-motion patterns in EEG data. Participants self-reported the absence of epilepsy or implanted electrical devices. Next, participants were briefed on the study's procedure and its various stages, including the devices, environment, stimulations, and the questions regarding vection. Prior to the experiment, vection was explained to each participant using the train example (as described in Section I), defining it as the visual illusion of self-motion induced in a stationary observer [31]. Participants were then informed that they would be asked to rate their vection strength on a four-point Likert scale (explained as described in Section III-E), and were explicitly instructed to distinguish between object motion (the environment moving around them while they feel static) and self-motion (feeling that they themselves were moving in a static environment). Participants were informed that both interpretations of the visual stimuli are equally valid, that there is no "right" answer, and that their responses should reflect their subjective experience in that moment.

Then, informed consent was obtained, and each participant received a unique identification number and completed a demographic questionnaire, as well as a Simulator Sickness Questionnaire (SSQ) [15]. The Simulator Sickness Questionnaire (SSQ) consists of 16 questions, each using a 4-point Likert scale to assess the severity of various symptoms. Participants rate each symptom as either 'None,' 'Slight,' 'Moderate,' or 'Severe.' This questionnaire was originally designed to assess simulator sickness in aviators. It was selected due to its extensive use in cybersickness research, allowing for comparative analysis with other studies. It is a widely used tool that provides granular insights into participant well-being by categorizing responses into Oculomotor, Nausea, and Disorientation scores, thus enabling a focused assessment of symptoms related to cybersickness. The relationship between an identification number and the subject's name is only known to the subject. Sensors were then affixed to record EEG.

Subsequently, participants were seated and viewed 78 vection-inducing trials organized into four blocks. To ensure an equal representation of both acceleration directions, the experiment included 39 trials with forward acceleration (FA) and 39 trials with backward acceleration (BA). Within each of these trial types, the acceleration started after a delay of 1, 3, or 5 seconds. These delays were also balanced, resulting in 13 trials for each delay within both the FA and BA conditions. The trials were then organized into four blocks, with each block containing 20 trials, except for the fourth block, which consisted of 18 trials, to maintain a total of 78. The specific order of these 78 trials was pre-determined using a pseudo-random algorithm, ensuring that each of the six possible combinations of acceleration direction and delay were equally distributed throughout the experiment.

Following each block, participants were given a rest period of minimum 5 minutes to recover, during which they completed the SSQ. The next block began once the participant indicated their readiness.

Each trial comprised a 19-second visual simulation (see Section III-C) followed by a brief period for oral rating. The participant was asked to rate the perceived vection intensity on a four-point Likert scale, staying consistent with the SSQ's scale.

- **NO VECTION**, which we will refer to as `NV`, indicating subject only perceived object-motion.
- **WEAK VECTION**, which we will refer to as `WV`, indicating subject perceived slight self-motion and mostly object-motion.
- **MODERATE VECTION**, which we will refer to as `MV`, indicating subject perceived slight object-motion and mostly self-motion.
- **STRONG VECTION**, which we will refer to as `SV`, indicating subject only perceived self-motion.

These self-reports served as the foundation for comparison with our objective EEG measures since vection is a subjective experience [31].

F. Data Processing

The processing pipeline utilizes MNE-python [25] for data handling and filtering. First, channels exhibiting abnormally high variance and noise compared to others were manually identified. These channels were marked as bad and excluded from the analysis on a run-by-run basis. In total, 22 individual channels were identified as bad across all channels and runs for the 30 subjects. Of these, 17 were FPz channels, primarily due to muscular artifacts. Then the EEG data was re-referenced using common average referencing (CAR) and resampled to 128Hz. Finally, it was filtered in the 0.3 to 10Hz range using a 4th order IIR forward and backward Butterworth filter for all plots except the power spectral density (PSD) plot. Epochs range from 0.5s before stimulus onset to 1s after stimulus onset. Epochs were excluded if the peak-to-peak amplitude of the EEG signals in any channel exceeded 125 µV, following standard practices in ERP literature [8]. This criterion led to the rejection of 89 out of 2340 epochs, or 3.8% of the total.

The data was stored using the EEG Brain Imaging Data Structure (BIDS) format [11], [34], a standard for organizing and describing brain imaging datasets. It allows researchers to readily organize and share study data within and between laboratories. The experimental data of this study are available from the corresponding author upon request. Visualization was performed with the help of the seaborn library [24].

IV. RESULTS

The data acquired in this study underwent analysis through two approaches. Initially, we examined which factors influenced subject ratings. We then conducted an aggregate analysis across all subjects, focusing on EEG patterns related to vection. Furthermore, we extend our previous results [48] concerning responses to acceleration.

A. Subjective Results

We combine the subjects' responses to our questionnaires and analyze the results.

TABLE I: Totals for reports of vection for each subject across all trials. Each row is a subject, the last row represents the average for each column.

No Vection	Weak Vection	Moderate Vection	Strong Vection
8	19	22	28
1	11	35	30
16	25	15	22
10	40	24	1
14	27	28	9
0	25	39	14
38	28	10	1
0	4	33	41
3	32	8	33
0	1	14	65
0	6	38	36
1	11	24	42
4	14	35	24
0	30	31	17
57	21	0	0
0	12	24	42
1	28	31	18
3	21	36	18
0	0	52	26
36	42	0	0
14	31	27	6
1	19	40	20
0	23	37	18
13	27	27	10
3	19	31	25
0	39	39	0
0	3	19	56
0	13	48	17
52	26	0	0
1	8	26	43
9	20	26	22

The distribution of responses to the vection questionnaire can be found in Table I. The results show that some participants exhibited greater sensitivity to vection than others, reinforcing the need for VR systems that can adapt to individual user responses in real time to improve comfort and reduce cybersickness. As seen in Figure 5, there are relatively fewer trials where a subject experienced **NV**. A Kruskal-Wallis test revealed a significant difference in reported vection between subjects ($H = 184.78$, $p < 0.001$, $\epsilon^2 = 0.406$), emphasizing the variability in vection reporting across individuals. Similar results are reported in the literature [1], [31]. Figure 5 shows the distribution of reported vection for FA_1 and BA_1. Chi-squared testing reveals that acceleration direction (FA_1 versus BA_1) has a strong influence on reported vection ($\chi^2 = 82.06$, $p < 0.001$, $df = 3$), with forward acceleration (FA_1) correlating with stronger reported vection.

Our objective is to examine the neural markers of vection and how they relate to subjective vection reports. We also analyze the differences between conditions where vection was reported and those where it was absent. The four-point vection scale provides valuable granularity; however, for the purpose of distinguishing the presence or absence of vection, a binary categorization is more appropriate. The goal is to clearly separate trials where participants did not feel substantial self-motion from those where they reported strong self-motion. This approach helps to draw a more distinctive boundary between object-motion perception and vection, reducing ambiguity in the analysis.
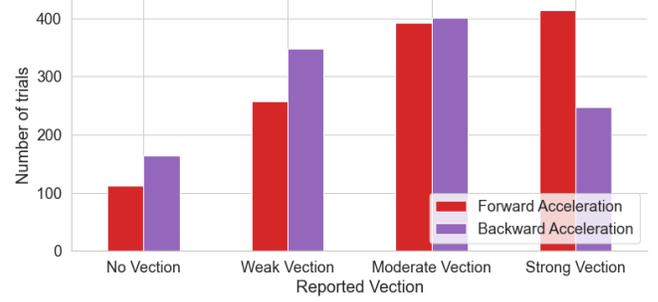

Fig. 5: Distribution of reported vection per trial for FA_1 (red) and BA_1 (purple).

The examination revealed variability in the perception threshold across subjects, with the **NV** category being notably underrepresented in the FA_1 condition, as evident in Figure 5. Given these considerations, we merged the **NV** and **WV** categories for comparative analysis against the **SV** category. **MV** was excluded and served as a demarcator to differentiate between the two classes.

B. Correlates of Acceleration

In this study, we divided the EEG data into different conditions. We set the baseline condition as the slow-speed phase, where the subject moved at a constant speed of 3 m/s, as shown in Figure 2. This ensures that some visual stimulus is also present in the baseline condition. Additionally, the conditions labeled FA_1, BA_1, FA_2, and BA_2 were defined as described in the *Trial Design* subsection.

To highlight the difference in EEG responses when vection occurs, we compare the median responses around accelerations and a baseline. We selected the median over the mean due to its greater robustness against outliers and because some artifacts bypassed the artifact rejection process, potentially distorting the mean. A Shapiro–Wilk test confirmed that the data is not normally distributed with a W statistic of 0.0247 and $p < 0.0001$.

We assess the significance of observed differences using a non-parametric bootstrapping method. We generate 10,000 resamples of our data with replacement, and then calculate 95% confidence intervals, defined as the range between the 2.5th and 97.5th percentiles of the resampled data. These confidence intervals are displayed as shaded areas around the median curves in the figures.

Our findings on acceleration reinforce previous results reported in the literature [48] by expanding the subject cohort and finding similar patterns of acceleration perception. Figure 6 shows EEG signals that present statistically significant differences when the subject is experiencing FA_1 or BA_1 compared to baseline on the FCz electrode. This signal is identical in both the FA_1 and BA_1 conditions, but it differs significantly from baseline. It represents a marker of visual acceleration. Figure 7 shows a significant difference between FA_1 and BA_1 on Cz. This presents a characteristic signal of the acceleration direction.
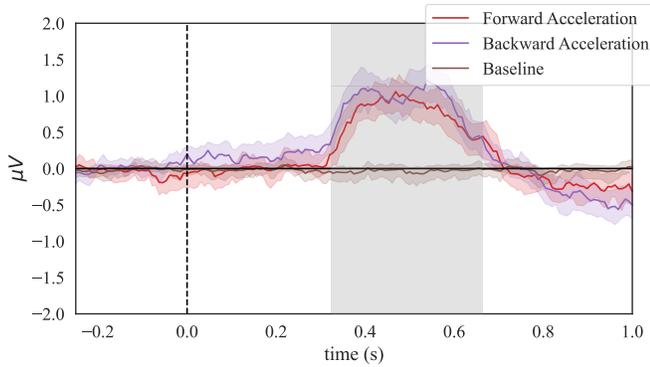
Fig. 6: Median FCz electrode response for FA_1 (red), BA_1 (purple), and baseline (brown). Dotted line indicates acceleration onset. Shaded grey area indicates significant difference. Both acceleration conditions show similar patterns distinct from baseline.
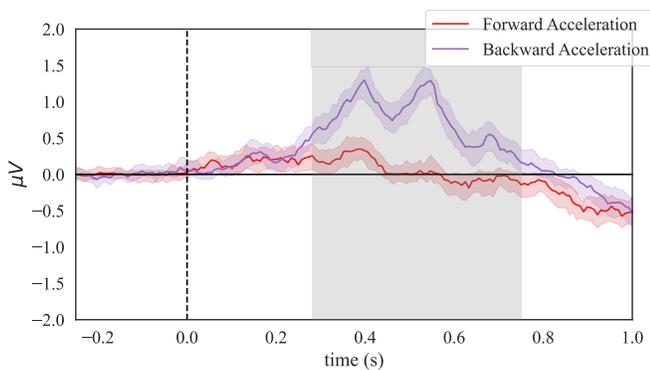

Fig. 7: Median Cz electrode response for FA_1 (red) and BA_1 (purple). Dotted line indicates acceleration onset. Shaded grey area indicates significant difference between forward and backward acceleration.

C. Correlates of vection

Additionally, we find novel results concerning correlates of self-motion perception. The data shows significant differences in EEG signals between trials where participants reported self-motion and those where they reported object-motion. Figure 8 shows the difference between the runs where subjects reported **SV** versus the ones where subjects reported **WV** & **NV**. However, we also observed that vection events induce high signal variance. Since the signal displays similar patterns along the lateral axes and in order to mitigate the impact of bad electrodes across different subjects, we chose to first aggregate electrodes. We first calculate the median for each row of electrodes for every subject. We then take the median of these values across all subjects to reduce additive noise.

We plot the spatial differences using topographic maps between the vection conditions in Figure 9. The topographic maps highlight the stronger frontal positivity in the **WV** & **NV** condition 600ms after acceleration onset, as well as the lingering parietal negativity in the **SV** condition.

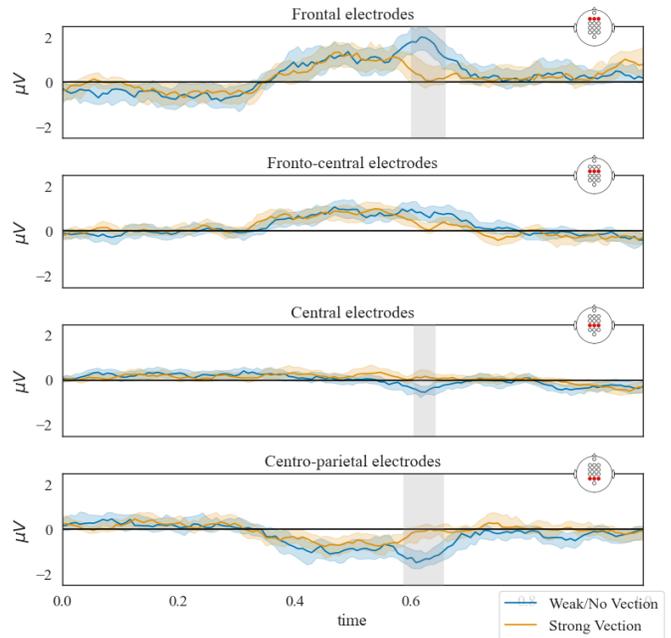Additionally, Figure 10 shows EEG rhythms associated

Fig. 8: EEG responses for weak/no vection (blue) versus strong vection (orange) during FA_1. Shaded grey area indicates significant difference. Strong vection shows positive parietal deviation and negative frontal deviation at 600ms post-onset, while weak/no vection shows the opposite pattern.
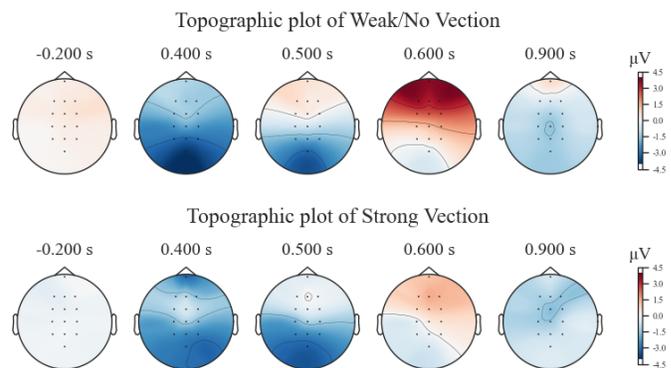

Fig. 9: Topographic maps during FA_1 for weak/no vection (top) and strong vection (bottom). Strong vection shows parietal negativity until 600ms; weak/no vection shows frontal positivity at 600ms.

with **SV** compared to **WV** & **NV**. Patterns consistent with the literature [2], [12] are found, with alpha rhythm suppression during perceived self-motion.

Finally, we observe a link between reported vection and subject responses to the SSQ. Responses from each subject's pre-experiment questionnaire were subtracted from subsequent questionnaires for baseline correction. There is a strong positive correlation between **SV** and the SSQ total score as evidenced by the Pearson correlation ($r = 0.55$, $p < 0.01$). More precisely, this correlation can be broken down into the SSQ subcategories: Oculomotor ($r = 0.45$, $p < 0.04$), Disorientation ($r = 0.51$, $p < 0.02$) and Nausea ($r = 0.62$,
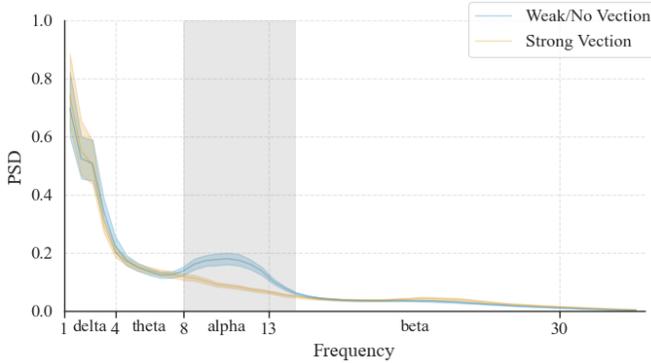
Fig. 10: Power spectral density comparing weak/no vection (blue) to strong vection (orange) during FA_1 before filtering. Shaded grey area indicates significant frequency differences. Alpha rhythm increases during acceleration but is suppressed during strong vection.

$p < 0.003$). Thus, we observe that vection correlates the strongest with Nausea and Disorientation, which is consistent with the symptoms of cybersickness [37].

V. Discussion

Our findings confirm previous results that identified distinct EEG markers associated with acceleration in VR. Specifically, we observed significant signal differences between forward and backward motion in the FCz and Cz electrodes, consistent with earlier studies. By analyzing EEG signals, we not only discerned the presence of acceleration but also identified the direction, with statistically distinct signals for forward versus backward motion.

For self-motion, we identified a notable neuromarker approximately 600 ms after the onset of acceleration, distinguishing strong vection experiences from weak or no vection experiences. We notice a pattern during sudden changes in speed that varies depending on whether the subject experiences vection. As illustrated in Figure 8, a robust positive deviation 600ms after stimulus onset in the parietal region during strong vection gradually transitions into a negative deviation towards the frontal region, whereas the reverse pattern is observed for weak or no vection.

Our patterns resemble those observed in vestibular oddball paradigms by Nolan et al. [27]. They investigated brain responses using a high-density EEG setup to an expected yet unpredictable event, also known as an oddball stimulus. In this case, the stimulus was a movement of the chair the participant was sitting in. The study found a robust P3 and P6 component, typical of oddball paradigms, indicating that vestibular changes in heading are processed similarly to oddball stimuli in other sensory modalities, with potential clinical relevance for assessing vestibular function. In their paper, Figure 2 depicts a similar P600 to that shown in our paper's Figure 8, we argue that the similarity in neural patterns hints at identical underlying cognitive processes. Note that their paper induced vection using actual movements of the chair, thus inducing motion perception through visual and vestibular stimulations. Consequently, we hypothesize that unpredictable vection in VR triggers cognitive processes similar to those seen in unpredictable real-world motion.

A similar pattern was also found in the resolution of incongruity in the existing literature [9], [47], [50]. Given that the sensation of vection originates from the brain interpreting the VR environment's acceleration as the participant's acceleration, we hypothesize that an incongruity arises due to sensory conflict. This effect, we argue, is meaningfully detectable, as it pertains to the active resolution of this conflict. Notably, the incongruity is absent when participants do not experience vection, as they accurately perceive the environment, not their body, as moving. The absence of such signals in this context can be attributed to the absence of such incongruity.

This interpretation aligns with the sensory conflict theory of cybersickness. Cybersickness is a major problem for widespread VR adoption, with 60–95% of users affected and 6–42% unable to finish their experiment [3], [26]. Understanding the nature of cybersickness is crucial to improving the VR experience and increasing its adoption. Sensory conflict theory is the most common theory of motion sickness and cybersickness [6], [30]. This theory posits that discrepancies between the visual, vestibular and proprioceptive senses cause cybersickness [6]. This includes scenarios like perceiving self-motion in VR while remaining physically stationary. Neural activation patterns found in this study may be indicative of the brain's active resolution of such sensory conflicts during vection experiences. They provide valuable insights into the neurophysiological mechanisms underlying cybersickness.

We also found a correlation between vection and Simulator Sickness Questionnaire (SSQ) scores, particularly with Nausea and Disorientation scores. Studies have highlighted the strong relationship between cybersickness and the Nausea and Disorientation scores [23], [26]. Therefore, the neuromarker associated with vection may serve as a precursor to cybersickness in VR participants. As vection has often been associated with motion sickness [28], a better understanding of vection will allow for a deeper comprehension of motion sickness, its causes and mechanisms, and help VR designers create experiences that are more comfortable and less likely to cause sickness. Moreover, detecting it in real time can help VR systems reduce motion sickness by adjusting content based on user experience.

While this work establishes a neuromarker for vection, translating it into a practical real-time detection system requires consideration of several factors. The 600ms latency of the P600 component makes it well-suited for applications like cybersickness prevention, where vection serves as a precursor and early intervention is valuable, particularly before repeated exposure leads to symptoms. However, this latency occurs during conscious processing, rendering it less suitable for real-time modification of the vection-inducing stimulus itself. The substantial individual variability in vection reporting observed in our results suggests that initial deployments would likely require per-user calibration, though larger cohort studies could establish population-level detection approaches. Our

decision to group weak and no vection responses was driven by the underrepresentation of no vection trials in our data, and future investigations could examine alternative grouping strategies or treat each vection rating as a separate category to refine detection boundaries. Furthermore, the emergence of VR headsets with integrated EEG sensors addresses previous deployment barriers, making neurophysiological monitoring increasingly feasible in consumer applications. Extending this paradigm to different motion profiles, including rotations and lateral movements, as well as ecological VR content types, represents a logical next step toward understanding the generalizability of these neuromarkers across varied acceleration scenarios. Our use of abstract spheres was designed to isolate vection by minimizing confounding factors such as semantic content and contextual processing. Future work could investigate how realistic stimuli, such as cars, terrain or roller coasters often seen in the literature might alter the observed EEG patterns. Such stimuli could potentially change the vection responses, and modulate the amplitude or timing of the P600 component by introducing additional neural processing related to object recognition and contextual interpretation, providing insight into how cognitive processing interacts with vection perception in ecologically valid scenarios.

This research also opens avenues for future exploration. A promising direction lies in investigating the specific neuromarkers associated with other types of motion. Using a similar setup, studies could explore if such signals can also be found in the case of backward vection, sideways motion or rotations. Additionally, the discovery of this neuromarker presents an exciting opportunity for the development of a classifier capable of determining whether a user is experiencing vection following an acceleration event. Finally, this new paradigm can help study the neural mechanisms of vection in the brain.

VI. Conclusion

In this paper we studied if and how electroencephalography (EEG) could be used to detect vection in VR. We conducted a VR experiment exposing participants to strong forward or backward acceleration while recording reported vection and EEG signals. Our results revealed substantial variability among individuals and a notable influence of the acceleration direction on reported vection. Replicating prior research, we observed a significant effect of vection on alpha power in EEG brain waves. Moreover, the recorded EEG signals exhibited distinguishable patterns for both acceleration and direction of motion. Finally, we identified a novel event-related potential of vection occurring 600ms after forward acceleration. These findings offer insights into vection's neural correlates, and pave the way to automatic techniques for measuring vection and self-motion sensations in VR using EEG recordings.

Acknowledgments

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