# Brain Dynamics of Balance Loss in Virtual Reality and Real-world Beam Walking

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## Abstract

Virtual reality (VR) aims to replicate the sensation of a genuine experience through the integration of realism, presence, and embodiment. In this study, we used mobile electroencephalography to quantify differences in anterior cingulate brain activity, an area involved in error monitoring, with and without VR during a challenging balance task to discern the factors contributing to VR's perceptual shortcomings. We found a major delay in the anterior cingulate response to self-generated loss of balance in VR compared to the real world (reflecting less effective detection of balance loss). We also found a very strong response in the anterior cingulate when loss of balance was generated by an external physical disturbance. These findings contribute to our comprehension of the constraints associated with VR in replicating real-world experiences.

**Index Terms:** Human-centered computing—Virtual Reality—Mixed / augmented reality

## 1 Introduction

The realism provided by high-fidelity displays and natural interaction of immersive virtual reality (VR) is valued for the ability to increase user engagement, effective training, and elicitation of emotional responses. Much research has studied users' sense of *presence*—the feeling of "being there" in the virtual location and feeling the simulated experience is really happening despite the user knowing it is a simulation [6], and the related concepts of *embodiment* and *body ownership* for the feeling that user's virtual body is their own [4]. Motion tracking devices and body-based interaction contribute to the immersive experience, allowing users not only to see but also to feel their presence in the virtual world. But the provided realism of VR is never perfect, and discrepancies from the real world will affect human perception of the experience and cognitive processing during interaction [2, 4]. The time lag between visual and vestibular information, slower than physiological visual refresh rate, reduction in field of view, and/or a lack of binocular vision depth perception may inhibit motor learning by disrupting natural multisensory integration [3].

While common approaches for studying presence and embodiment looks to self-report questionnaires and behavioral measures to study human cognitive processing in VR [6], identification of brain processes affected by differences in VR can allow further understanding of human responses [1, 5]. Our research employs mobile brain imaging with electroencephalography (EEG) to quantify differences in brain dynamics with and without VR. EEG has high temporal precision and is relatively lightweight and portable. With recent advances in signal processing and hardware approaches, it is now possible to localize components of brain activity from EEG data with about 5 mm of spatial resolution and 1 ms of temporal resolution.

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Figure 1: (left) Virtual beam walking environment for the full immersion condition. (right) A participant wearing the Meta Quest Pro headset and balancing on the physical beam.

The anterior cingulate cortex is a brain area involved in error monitoring. We focused our analysis on the anterior cingulate cortex since we wanted to assess cognitive demands (i.e., does VR disrupt multisensory integration, increase motor planning requirements, and provide less effective error detection). Through this analysis, we gain insights into the reasons why virtual reality (VR) falls short of replicating the sensations experienced in the real world.

In our study, we used a balance beam-walking paradigm and created a custom virtual beam-walking simulation to replicate the real-world environment. Past studies show that both self-generated and externally generated loss of balance during beam walking cause anterior cingulate theta (4-7 Hz) synchronization [8-9]. We hypothesized that loss of balance during virtual reality beam walking would result in less theta (4-7 Hz) synchronization, and with less advanced timing to stepping off the beam in the anterior cingulate cortex (reflecting less effective detection of loss of balance) compared to real-world beam walking. We also performed an exploratory analysis with external perturbations to elicit balance loss. We present results from a pilot study.

The findings of this study contribute to our comprehension of the reasons behind the limitations of virtual reality (VR) in mimicking real-world sensations. Subsequently, alternative methodologies are employed to gauge the degree to which VR can replicate the authentic sensory experiences of the real world.

## 2 Experiment

Participants (n=4) walked in three 15 min. conditions: full immersion (VR environment), pass-through (headset video of real environment), and no immersion (no headset). The full immersion and passthrough conditions used the Meta Quest Pro headset (90 Hz refresh, 1800x1920 resolution per eye, and color mixed reality). The immersive environment (Figure 1, left) had a 1 in. height x 1 in. width x 121.5 in. length beam, which replicated the dimensions of the real-world beam (Figure 1, right). Participants walked on the physical beam in all three conditions. The order of full immersion and passthrough conditions was randomized, while the no-heaset condition was always the second block to give participants a break from being in VR and reduce cybersickness. For this study, we only focused on the full and no immersion conditions.

In our virtual environment, we approximated real-world elements (e.g., room size, shape, and color of beams and floors) to enhance the sense of realism. The headset's camera-based hand tracking was used to provide virtual hands mirror real hand movements, fostering a heightened feeling of presence and embodiment. For the walking task, the virtual beam was aligned to match the positioning of real physical beam. Head-tracked viewing was enabled.

After 7.5 min. in each condition, we introduced external perturbations that pulled participants off the beam. We used a 5 lb. weight, connected to the participant by a cable over a pulley to the participant's waist, which we randomly dropped during a beam pass. Due to equipment malfunction, we could only analyze 2 of the 4 participant's external perturbation trial data.

We recorded dual-layer EEG (240 channels), instrumented insoles to mark timing of footsteps, inertial measurement units, video, and loadcell data to mark timing of pull perturbations. Each system independently logged data, and the data were synchronized with pulses from an Arduino.

We processed data with custom MATLAB scripts and functions from EEGLAB, an open-source toolbox for EEG analysis. Heel strikes were defined as the first instance in each step when the instrumented insoles exceeded 20 N. The cable pull events were marked as the peak loadcell force in a 200-sample window around manually labelled cable pull events from the video. Using an independent component analysis approach, we converted the electrode channel data into source-localized components of brain activity. We focused on components in the anterior cingulate, and we epoched the self-generated balance loss data -0.5 to 1.5 seconds around the heel strike on the beam (i.e., beam contact) before losing balance. The externally perturbed balance loss data were epoched -0.5 to 1.5 seconds around the cable pull event. Event-related spectral perturbation plots were our outcome measure. Single-trial spectrograms were calculated using Morlet wavelets whose cycles increased linearly with frequency. The mean spectrograms were averaged across components (i.e., across participant's anterior cingulate brain area) to create a grand-average plot. Since we were interested in theta synchronization, we focused on the frequency band 4-7 Hz.

## 3 Results and Discussion

The anterior cingulate grand-average event-related spectral perturbation for self-generated balance loss showed strong theta (4-7 Hz) synchronization between the beam contact (BC) before losing balance and ground contact (GC) (see Figure 2). In the no-immersion condition, theta synchronization occurred around 500 ms post-BC, whereas in the VR condition theta synchronization occurred around 1000ms post-BC.

For the externally perturbed trials, the anterior cingulate event-related spectral perturbation plots showed strong theta synchronization right after the cable pull event which coincided with ground contact ("GC") (see Figure 3). The timing of the theta burst was about the same in both conditions, but the magnitude of theta power in full VR was greater than in no-headset real-world.

In line with our central hypothesis, we found delayed theta synchronization in the anterior cingulate cortex while participants were immersed in virtual reality as compared to the real world. Readers are cautioned to interpret the data given the limitations of our study. It is possible that the weight of the VR headset caused artifacts in the EEG data. In the future, we could use a weighted head piece in the no immersion condition to reduce artifactual confounding factors. Secondly, we did not rigorously control walking speed. We demonstrated a desired pace (0.22 m/s), but it may be helpful to use a beam-mounted treadmill instead of an over-ground beam.

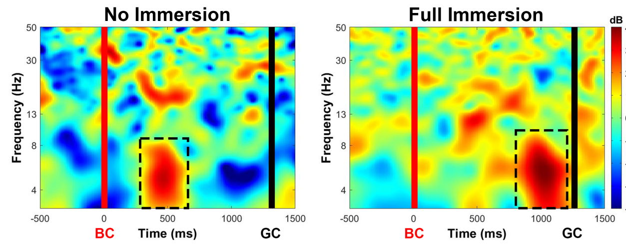


Figure 2: Anterior cingulate cortex grand-average event-related spectral perturbation plots for self-generated loss of balance (n=4). Time is on the x-axis, where beam contact "BC" (red) is the step before losing balance and ground contact "GC" (black) is the average step time to regain balance. Frequency is on the y-axis. Change in power from a spectral baseline is on the z-axis. Increases in power (red) are called "synchronization". The brain's response to balance loss (i.e., theta synchronization) has a black dashed box around it.

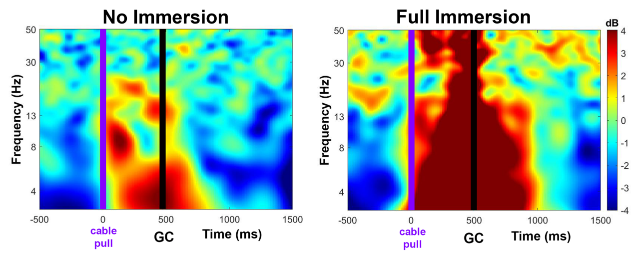


Figure 3: Anterior cingulate cortex grand-average event-related spectral perturbation plots for externally perturbed loss of balance (n=2). Epochs were centered around the cable pull event (purple, time 0). Ground contact "GC" (black) is the average time to regain balance. Theta synchronization occurred almost immediately after the cable pull event in both immersion conditions.

Though our study had a very small sample size, this pilot study validated our experimental approach, supported one of our main hypotheses, and made significant strides towards flushing out a full study. In future work, a larger sample size would allow us to draw more conclusions. We also aim to broaden the study of a variety of differences contributing to realism in VR. Potential influencing factors include visibility of tracked legs and feet for the user's virtual body or display differences such as field of view or simulation fidelity may also influence. We are also interested in direct comparisons to alternative measures of embodiment.

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