Looking for Answers: Gaze and Brain Activity as Simulation Outputs

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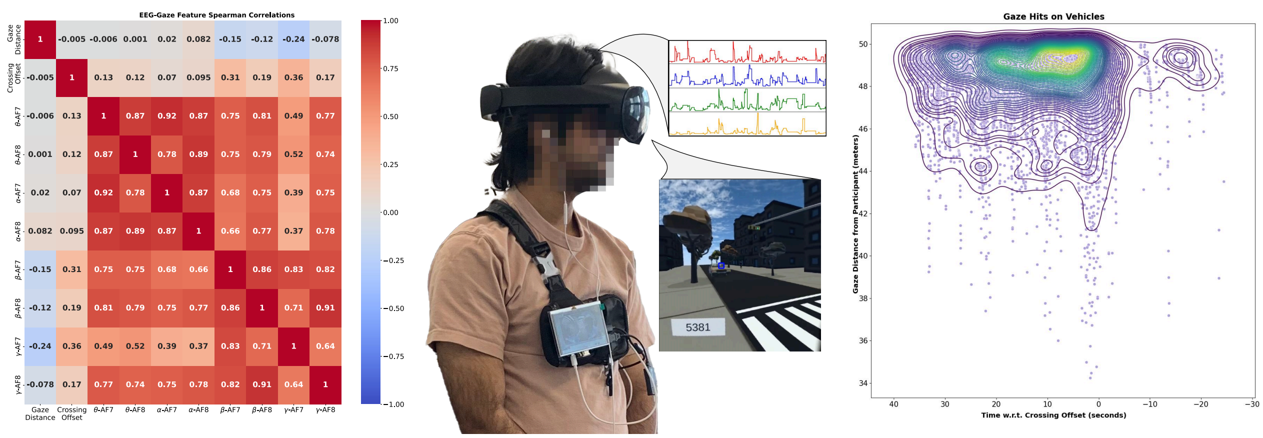

Figure 1: End-to-end VR simulation pipeline (center) expanded with EEG (left) and gaze sensing (right).

Abstract

Behavioral agency relies on our ability to observe and mentally interpret our surroundings. However, interactions between gaze and brain activity often escape data capture and are difficult to model, as their dynamics are sensitive to individual differences and situational context. We examine how immersive virtual reality (VR), brain-computer interfaces (BCIs), and agent-based models (ABMs) can combine to overcome these limitations. We show that electroencephalography (EEG), coupled to VR head-mounted displays (HMDs) and single-board computers (SBCs), can inform simulations of road-crossing with mixtures of real, thinking humans and synthetic agents.

CCS Concepts

• **Computing methodologies** → **Modeling methodologies**.

ACM Reference Format:

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1 Introduction

It is important to look around and pay attention when crossing roads. In streetscapes buzzing with distractors, crossers are likely to *reinforce their spatial perception*, e.g. via social cues drawn from non-verbal communications (NVCs). This raises questions of how crossers may interpret streetscapes differently due to perspective and circumstance. Immersive virtual reality (VR) environments provide opportunities to examine this differentiation, emphasizing users' agency in simulations of real-world scenarios [4, 5]. VR head-mounted displays (HMDs) with eye tracking facilitate analysis of the by-products of this agency, such as gaze dynamics and ray-tracing during gaze fixation. In tandem, mobile brain-computer interfaces (BCIs) that measure brain activity can offer novel neuroscience-based interpretations of this explanatory mix. Here, we aim to (1) couple EEG BCIs to HMDs to (2) support connections between simulation events, user gaze, and brain activity in (3) an end-to-end pipeline for road-crossing experiments. We explore this avenue for simulation-assisted knowledge discovery via (4) an immersive VR simulation with (5) behavioral agent-based models (ABMs) of pedestrian/crowd and vehicle/traffic agents.

2 Methodology

Progress on aims (4)–(5) was presented at last year's SIGSIM PADS [2], which featured an immersive VR-ABM road-crossing simulation in *Unity3D* with built environment features, Intelligent Driver Model (IDM) vehicles, and NavMesh pedestrian agents. The system was validated for fidelity and verisimilitude. Here, as an improvement, we implemented synthetic gaze gestures in new driver agents that we placed within vehicles. Driver agents will thus "look" at users who walk in front of their vehicles and appear to facilitate eye-to-eye NVC cues between users and drivers. Below, we focus on enhancements to accomplish aims (1)–(3).

Using an institution-approved human subjects protocol, we recruited six participants to engage the simulation in a set of road-crossing trials. Participants were embodied in scenarios against a set of varied traffic congestion presets. Meanwhile, agent-pedestrians were configured to simulate pedestrian flow along sidewalks and act as visual distractors. During runtime, we captured participants' gaze behaviors via the *Meta Quest Pro's* (MQP's) gaze tracking SDK at 60Hz. While using the HMD, participants also wore InteraXon Inc.'s *Muse S* headband BCI which records raw EEG signals at 256Hz along the AF7, AF8, TP9, TP10, and FPz electrodes. We denoised the raw EEG data through a 60Hz notch filter and transformed the filtered signals to the log form of power spectral densities (PSDs) in 0.5sec windows using the *Mind Monitor* application on a paired bluetooth phone. Simultaneously, we recorded participants' visual field videos with a single-board computer (SBC) consisting of a wearable *Rasberry Pi 4B* running Genymobile's *scrcpy*. Finally, the space-time trajectories of participants and all dynamic agents in the simulation were recorded at approximately 60Hz.

To initialize the system, we recorded participants' baseline EEG data during a 30sec "rest" trial. Thereafter, participants were asked to cross a virtual road with agent-pedestrians, traffic lights, crossing signals, driving vehicles, and watchful drivers in dynamic simulation. Every time the participant successfully crossed the road, they were given an audio cue to turn around and cross in the opposite direction. This pattern continued for a total of 1 acclimation trial and 8 experimental trials per participant.

3 Results and Discussion

The goal of this paper is to demonstrate that meaningful and actionable data can be collected through simulations, BCIs, and VR HMDs. To scaffold this endeavor, we conducted a preliminary exploration of how these tools can link event–gaze–response dynamics to interpretable explanations of road-crossing behavior. We contextualize our results across *gaze distances (meters)* between participants and their gaze targets as well as *crossing offsets (seconds)* before participants start their road-crossing attempts. Illustrations of our findings are shown in Figure 1.

Our first class of findings unpacks participants' **gaze hits on vehicles**. Participants demonstrated an increasing frequency of gaze fixations on vehicles as participants drew closer (in space and time) to their crossing attempts. Distinct patterns within this tendency are evident. *Prior to crossing*, gaze frequency is greatest for vehicles that are *far away from the participant.* This finding corroborates observations of naturalistic walking in the real world, for which longer total fixations on vehicles are concentrated within 5–20m [7]. Visual analysis of participants' gaze tendencies, manually identified via reviewing gaze footage, indicated that participants observe *drivers* more often than they do actual vehicles. Post-experiment discussions with participants reveal this is because they engaged in bi-directional gaze transfer between themselves and drivers, relying on NVC cues to identify whether (1) the driver has noticed them, as an indicator/check of (2) whether the vehicle will stop.

Our second class of findings **ties gaze phenomena to brain activity** through Spearman correlations between gaze distances, crossing offsets, and EEG frequency bands. We base our analysis on the knowledge that Theta frequencies (4–8Hz) are indicative of navigational difficulty [3], Beta frequencies (13–30Hz) are correlated with corrective submovements during locomotion [1], and Gamma frequencies (30+Hz) are associated with information processing [6]. We identified positive, statistically significant correlations between crossing offsets and Theta, Beta, and Gamma frequencies. These correlations represent trade-offs in brain activity as participants shift from being passive observers — engaging in spatial understanding, planning, and information processing — to active crossers. In contrast, we identified negative correlations between gaze distances and Beta and Gamma frequencies. We reason that participants demonstrated higher levels of attention and concentration toward closer vehicles in response to the potential threat of pedestrian-vehicle collisions. These findings were validated by participants, who remarked that they had to concentrate on approaching cars due to difficulties in assessing their estimated speed and whether the drivers "noticed" them on approach.

4 Conclusion

We extend immersive ABM-VR simulations to stream run-time biometric data (user gaze and brain activity). Combined, these modalities of experimentation allow for deep investigation of significance among events and user behaviors. As a proof of concept, we show an end-to-end pipeline, running on commercially-available hardware, that can support experimentation with road-crossing scenarios.

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