Experiential geosimulation

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ABSTRACT

We introduce experiential geosimulation as a medium for co-exploring embodied behavioral geography, physical locomotion and sensorimotor control, and spatial vision and perception. Methodologically, this convergence is approached through interconnection of high-fidelity geographic automata systems, running in virtual geographic environments within virtual reality head-mounted displays, while spatial telematics and neural activity are collected through eye tracking on a single-board computer and encephalography (EEG) is processed from a scalp-mounted brain-computer interface. Data exchange between these diverse geographic information systems allows for the creation of synthetic simulation scenarios that can evoke realistic locomotion and task behavior from real, physically involved human users. Here, we show that the system also entices people's realistic neural activity, which can provide insight into users' experiences as navigation, agency, spatial vision, landmark salience, non-verbal communications, and cognitive where/what reasoning.

CCS CONCEPTS

• Computing methodologies ~ Modeling and simulation ~ Simulation types and techniques

KEYWORDS

Geosimulation, virtual reality, brain-computer interface

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1 Introduction

As geosimulation moves to virtual reality (VR) and mixed reality (MR) platforms, the question of whether the synthetic embodiment that simulations may conjure could ever meaningfully elicit matching behavior from users is a topic that assumes growing currency. In prior work [1, 2], we have examined this question by testing immersed users' spatial behavior in geosimulation. Here, we push the idea deeper, examining the neural activity of users via a wearable encephalographic (EEG) brain-computer interface (BCI) coupled to an immersive geosimulation (Figure 1). In doing so, our aim is to empirically and factually probe whether immersive geosimulation can elicit real human behavioral geography (chiefly the vision and perception that informs cognition and readying of locomotion in response). Our expectation is that if experiential geosimulation could establish new parity to (real) neural signatures of cognition that are generated when people embody themselves to (synthetic) simulated geographies, this could establish very actionable pathways for geosimulation to support research at the interface of spatial behavior, behavioral geography, neuroscience, and psychology. Here, we show that this is indeed possible. We demonstrate a successful proof of concept on an immersive geosimulation of streetscape dynamics that includes diverse sensorimotor stimuli in a realistic geographic task environment.

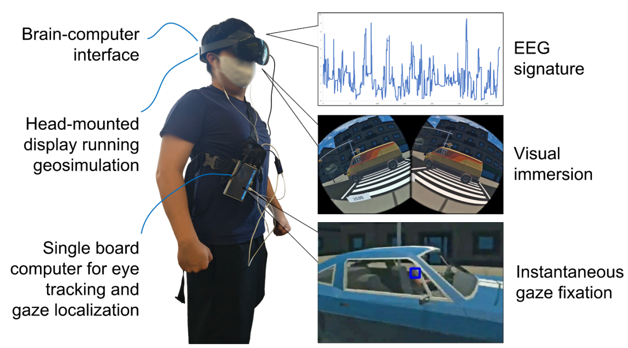

Figure 1: Our experiential geosimulation combines immersive mobile VR with wireless EEG brain-computer interfaces that allow us to examine neural correlates of spatial behavior in real-time.

2 Methods

To set the stage for embodied immersion, we developed a geosimulation to run in a streetscape-based Virtual Geographic Environment (VGE). The VGE was designed to form as the space between buildings, building façades, sidewalks, sidewalk and curbside civil infrastructure, a two-lane road, traffic lights, and a PELICAN (pedestrian light controlled) crossing. (Details of how this system is built generally are reported in [3, 4]; here, we restrict discussion to improvements that add methodological value to that base.) The VGE was mapped 1:1 to a tangible studio space, such that it also constituted a Virtual Reality Environment (VRE) that was traversable in the real world (Figure 1). We used a scene graph to render the space at a distance from user-positioned cameras to make the immersive VGE appear at city-scale. Level of detail for the appearance of the VGE was set to an intermediate phase, between simple block models and fully rendered detail, following earlier experiments showing that users' sense of embodiment was supported by high fidelity and high verisimilitude in the behavioral mechanics of the VGE [5] (that agents and environments act as they should in the real world and that the VGE evokes realistic actions from the user) at relatively modest levels of rendering detail.

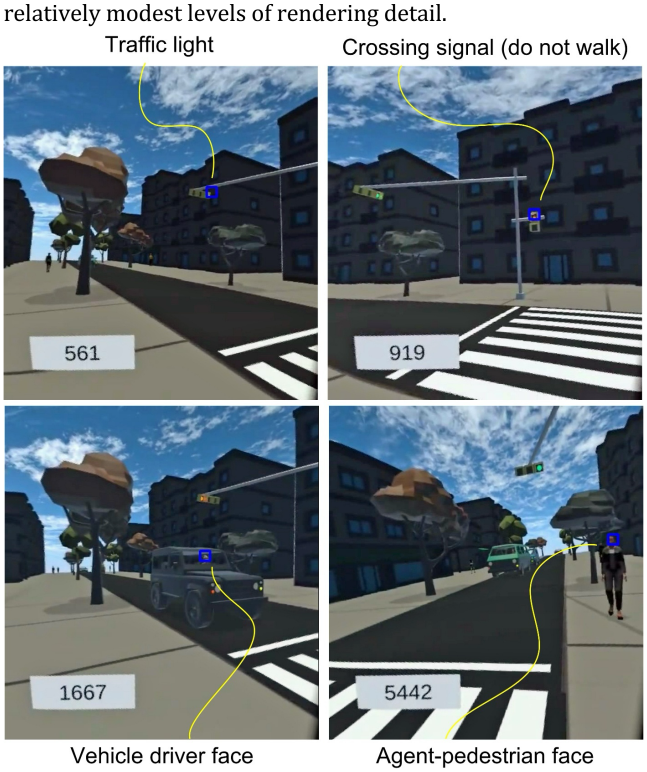

Figure 2: Screenshots of the experiential geosimulation from within the VR, with gaze-fixed targets localized the viewshed coordinate space (numbers are the frame time). Note that the blue squares are the real-time gaze fixations for users on objects in the geosimulation.

Two distinct geographic automata systems were developed to provide dynamic, adaptive, and interactive synthetic agency in the VRE. The first was a driver model, tasked with controlling the position, velocity, acceleration, and jerk of vehicles, based on a modified sensorimotor control function. We instantiated vehicles as mobile objects in the VRE, controlled by synthetic drivers running a modified version of the Intelligent Driver Model [6]. The salient components of this behavior involve sensitivity to the acceleration profile of the vehicle being driven (we distinguished between cars, vans, buses, and trucks), as well as dynamic reaction to other vehicles, road geometry, traffic light sequences, and pedestrians. We modified the IDM to produce realistic individual profiles for two-lane vehicle dynamics, as well as aggregate patterns of platooning, bunching, and congestion waves. The second geographic automata system was used to generate synthetic pedestrian behavior. For individualized agency, this included a full-hierarchy movement and motion model that began with path-planning and resolved wayfinding to intermediate features of the streetscape, then to steering and collision detection and avoidance via Reciprocal Velocity Obstacles (RVOs) [7, 8], and to pseudo-kinematics realized on animation-cycled motion controllers drawing on motion capture data. We included specialized crossing routines for pedestrian agent road-crossing, including reaction to crossing signals and risk-taking in crossing behavior (including jaywalking). Personality profiles were used to parameterize pedestrian agents with sets of behaviors that matched real-world coded observations from a long-term field experiment to study streetscape crossing actions [9].

Interactions between the spatial and geographic reference frames for the VGE, VRE, driver agents, vehicle models, pedestrian agents, and pedestrian models were accommodated by slipstreaming to a shared Geographic Information System (GIS) [10]. Slipstreaming in this case allowed for interoperability between geometry scene graphs, planning graphs, navigation meshes, view frustums, vector spaces, Velocity Obstacles, and motion graphs. In addition, telematics data from experiments with the system were slipstreamed to the same GIS for interoperability between real and simulated spaces.

We included real human users in the geosimulation through inverse augmentation [2]. In short, this was accommodated through the use of mobile VR on HMDs running the entire geosimulation pipeline by sideloading. Human users were therefore able to physically walk and run around a studio space while engaged directly with the simulation. The human user was instantiated in the geosimulation as a user-embodied agent, with users directly controlling the three-dimensional head motion of the agent as well as two-dimensional movement of the body through their own innate gaze and locomotion. We used an untethered wireless HMD to provide unconstrained mobility.

We collected telematics and geomatics from the user, in real-time synchrony to the geosimulation, using inertial measurement (gyroscope and accelerometer) and marker-less inside-out tracking to the tangible space by availing of the HMD's outward-facing cameras. In addition, we used a wireless electroencephalogram (EEG) device to record users' brainwaves in Delta, Theta, Alpha, Beta, and Gamma frequencies. EEG data is known to correlate with a range of navigation and spatial task functions. EEG data were slipstreamed to the geosimulation by time-synchrony.

The end-product is a geosimulation of a dynamic streetscape, equipped with scenario-adjustable and individually-tunable agent models that can algorithmically interact both with each other and with the real-time spatial behavior of the user (Figure 2). To establish experiential interactivity, we relied on non-verbal communications (NVCs), as expressed in gesturing, to establish reciprocity between fleeting movements and intention signaling of synthetic pedestrians, synthetic drivers, and real human users. Synthetic pedestrian agents were programmed to engage in purposeful environment-based gazing [1], looking in the directions of forward motion vectors, at waypoints, at the roadside when waiting to cross, and at the PELICAN crossing while moving through a crossing epoch. In the interim, they were programmed to engage in furtive glances via animated motion cycles. For each vehicle, we coupled a human driver model, complete with view-based head motion and eye motion. When the IDM detects that a pedestrian is within neighborhood-based collision consideration, the position of the potential collider is passed to the driver character model and its head and eyes are invoked in a gaze and stare behavior. In this way, an agent driver will seek to make eye contact with the human user.

Combined, these elements of the geosimulation, we reason, could form the basis for assessing the experiences of users in geosimulation in ways that could directly inform ideas in human and urban geography centered on embodiment and Non-Representational Theory [11, 12], as well as related themes in embodied computing [13-15]. In particular, opening-up experiential interactions between human users and synthetic agents in ways that embody them to realistic VREs (as situational embodiment) [16], while also embodying them to synthetic pedestrians and drivers (as social embodiment) [17] allows us to potentially examine how users enact their embodiment as spatial and geographic behaviors, as a form of cognition through active externalism [18]. Because we have complete access to all data from the VRE and geosimulation, as well as slipstreamed telematics and geomatics from the HMD and EEG, we may additionally begin to build data corpuses for empirical analysis.

3 Testing

To evaluate the usefulness of experiential geosimulation, we recruited 18 human users (under an approved human subjects protocol from our Institutional Review Board) and ran an eight-set experiment of experiential geosimulation of a suburban main street setting, which we launched tangibly in an indoor studio space. In total, testing was performed over 144 experiments, during about two weeks of user interaction with our system. For each experiment, users without ambulatory difficulties or VR-induced motion sickness were recruited by convenience and snowball sampling, with a roughly even balance of male and female participants ranging from early to late twenties in age. Users were instructed on the purpose of the exercise, but not given much detail of what to expect from the geosimulation.

The geosimulation was delivered to users via a wireless HMD, with spatial audio. In the experiments, users were asked to physically walk along a sidewalk, to a PELICAN crossing, and to proceed through the crossing to the other side of a road. Trials within the experiment were drawn to a close if the agent was either struck by a car in the simulation, or when they successfully crossed the road and reached an assembly point on the sidewalk. If struck by a car, users would be guided by the geosimulation via visual and audio prompts to return to a starting location to retake the trial. If they successfully crossed the road, they would be directed by prompts to cross "back" in the reverse direction. The amount of space required to proceed along a sidewalk, to a crossing site, and through the crossing to an opposing sidewalk location was a direct match to the amount of physical space that we deployed in a tangible studio. While engaged in the geosimulation, users also wore a wireless EEG headband, which collected brainwave data using four electrodes at sites TP9, AF7, AF8, and TP10 on the scalp.

Users' requirement to physically walk through the geosimulation brought them into experiential and embodied contact with simulations of the built geography of the suburban scene (sidewalk, sidewalk texturing as a visual effect, sidewalk segments, crossing sites, curbs, buildings, building façades (doors, windows, trim), roads, road markings). We additionally added vegetation to the streetscapes. At PELICAN crossings, users encountered marked (zebra) road-crossings, pedestrian crossing signals (with walk, get ready to stop, and do not walk lights controlled by simulation), and dynamic traffic lights (go, prepare to stop, stop). Overall, the entire scene was lighted to reproduce late afternoon effects, with relatively long shadowing of streetscape objects. As an experimental control, we designed sets of crossing behaviors for agents, including risk-averse strategies that asked them to wait at crossing sites, adhere to all crossing signals, look at traffic, and cross by walking. Risk-taking strategies relaxed these behaviors, allowing agents to ignore crossing signals and run through crossings while accepting very tight traffic gaps. Additionally, we varied the number of pedestrian agents that engaged in crossing, to produce dyads as well as groups. This variation was designed chiefly to introduce realistic peer effects.

For each experiment, we collected data from the geosimulation (all state conditions of all agents at all times) and from the users' manifestations in the geosimulation GIS (position, velocity, acceleration, orientation, rotation, gaze target, gaze location, gaze fixation) and from the hardware telematics (three-dimensional position of the head; roll, pitch, and yaw; acceleration in three dimensions). Many of these variables were then composited to produce event data (near-interactions, collisions, steering decisions, hesitation, returned gaze, etc.) which were then additionally indexed to the GIS. From the EEG, we recorded continuous brainwave activity in frontal and dorsal positions on left-side and right-side scalp locations. EEG data were then binned into frequency bands and normalized to resting states (standing still without engagement with the geosimulation) and to all trials. Additionally, users were asked to complete a questionnaire survey at the end of the experiments, and based on these results they were invited to engage in a structured interview to follow-up on their answers in a free-form questioning session. (For brevity, we do not report on the questions or results here.)

We validated the synthetic agent pedestrians by measuring the motion metrics of each agent space-time path, and then compared the results to both metrics of heuristic movement routines that are well-covered in the geosimulation literature (Brownian motion, correlated random walks, short-range Lévy flights, movement by social force, steering behaviors, and movement by computer gaming capture the flag motion). (Validation results for the general agent routines in the model (but not necessarily the simulation scenario) are reported in [3].) We then calculated the same metrics for space-time paths of real walkers in streetscape settings around the world (New York City, NY; Salt Lake City, UT; and Tempe, AZ in the USA; and Tokyo and Yokohama in Japan) (additionally, see [19, 20] for details of the trajectory analyses for these sites). Performance of our pedestrian agents against trajectories of heuristic movement and real-world pedestrians is reported in [4, 5, 9], with fractal dimension, mean fractal dimension (forwards and backwards), probability of turning in the same direction, and correlation of adjacent turning angles showing that our agents are significantly distinct from random in their trajectories at path-scale, waypoint-scale, and stride-scale, while conforming well to real-world benchmark movement and avoiding known over-fitting and exaggerated sinuosity problems of heuristic approaches. Methods for the tests were built on procedures described in [20]. We additionally evaluated the trajectories of real human users in the simulation, and we compared them specifically to crossing phases of streetscape traversal for real human pedestrians in suburban main street sites in New York City for 657.72 meters of road crossing. Trajectories of crossing motion in the geosimulation and VRE were a match to its real-world counterparts (details are described in [3]).

Using the inertial measurement geomatics and ray-tracing within the scene graph data of the VRE, we built a hyper-detailed picture of what users were looking at in the geosimulation, as measured by their gaze targets and gaze fixation. We then conflated those findings with brainwave data from the EEG, which we attributed to different loci of spatial attention and reasoning. An important point that we note here is that this allows us to build individualized statistical connections between the users' experiences of the geosimulation with respect to (1) urban geographic features of the VGE, (2) synthetic agent-pedestrians, and (3) synthetic agent-vehicles. Moreover, we may tie these connections to space-time events in the simulation for many varied products and compounds of these individual associations. Again, we stress that we may gather detail for gaze associations of users to the geosimulation, as well as measures of the spatial cognition that was invoked when (and where) those connections were made. This is instantaneous and can be studied in live, streaming form during experiments.

4 Results

The geosimulation instances, user trials, and related data and analysis products produce a large volume of data that can be referred to. For brevity, here we report results for associations between users' attentional/visual foci; their corresponding actions, reactions, and interactions with geosimulation elements; and the relative spatial cognitive areas of their brain that were engaged. For geographical insight relative to streetscapes, we highlight results for geographic elements (as embodiment targets in relativistic space), distance (as absolute space), and crossing behavior (as action space). Together, this 3-tuple of target, distance, and behavior can be useful in forming key ingredients for geographic agency (as empirically-sourced returns for queries of "What?", "Where?", "When?", "How?", and "Why?" inputs to agent routines or real-world evaluation functions). These can be mapped directly to automata frameworks for methodological uptake: as entities, neighborhoods, and transition rules in general automata functions [21, 22], for example. As we will show, the massive amount of detail and explanatory inference that is possible in rule-based geosimulation allows for significant population-level insight into potential spatial and geographic agency, as well as individual-scale insights. There are many ways to parse these results: here, we examine spatial tasks (navigation and agency) and behavioral geography (spatial vision, landmark salience, non-verbal communications, and neural generators of "what" and "where" cortical networks).

We note that in what follows, all EEG signals are discussed in their normalized form. For each user, a base (resting by standing still) EEG was recorded and subsequent EEG recordings from the experiential geosimulation were normalized to that condition (in the few instances where the EEG turns negative, this represents a reduction in EEG oscillation relative to the resting state).

4.1 Navigation

The neural generators of spatial navigation in EEG are well-examined in much of the clinical neuroscience literature [23-26], particularly using VR model environments as frames of visual reference. As collections of neurons in the brain fire together in assembly form, they produce energy fields that can sweep across different localized regions of the brain. Much of this activity takes place in deep brain tissue, but several energy waves manifest in the cortex (the outer layer of the brain), at sites that are invoked in the activation of neural networks that are known to associate with spatial behavior. EEG signals of these fields can be captured on the human scalp, which we have done for this paper. By binning the energy signals into frequency bands (Delta (0.5 – 4 Hz), Theta (4 – 8 Hz), Alpha (8 – 13 Hz), Beta (13 – 30 Hz), and Gamma (30 – 100 Hz)), we can isolate the possible (neural) generators of the energy field in the brain. Clinical work to tie EEG signals to spatial behavior routinely uses VR environments for navigation tasks, but it is fair to say that most models are relatively basic by geosimulation standards, lacking realistic task environments for things like urban geography or human geography. Notably, most clinical models lack counterpart agents (they are effectively ghost towns, and usually ghost mazes) and often constrain users to staring at two-dimensional screens or using VR on limited-range (essentially step-scale) treadmills. Our use of immersive geosimulation establishes many more degrees of experimental control, including multi-party interactions as well as free mobility by tangible locomotion through real 1:1 spaces that match the synthetic space represented in virtual form in the geosimulation. Thus, effects such as effort, abrupt turns, leaning, speeding and slowing, as well as parallax and optical flow, are all represented in hybrids of the geosimulation and reality. This greatly enhances the experimental substrate for the modeling architecture over most VR-maze type settings. The addition of realistic-behaving synthetic pedestrians and vehicles adds even more experimental control relative to real-world counterparts.

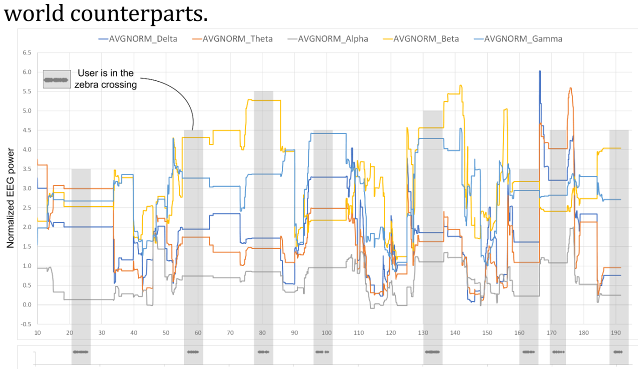

Figure 3: Variation in EEG oscillation for a single user during shifting crossing phases.

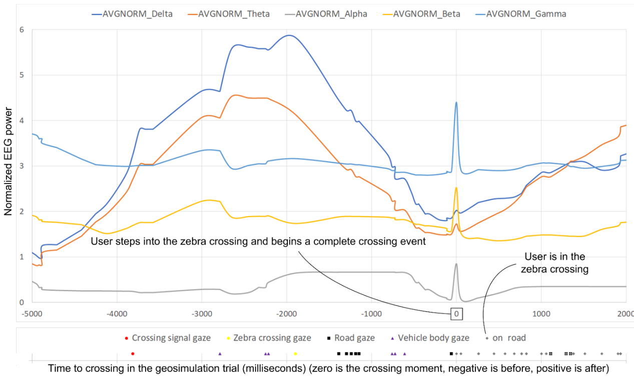

Figure 4: The onset of a crossing decision is evident down to the millisecond in EEG.

Our results show that distinct task phases of navigation can be identified in EEG, even over small bouts of locomotion. This echoes the main findings from the neuroscience literature in general conclusions [27-30]. Here, we discuss the results with regards to their potential for insight into geosimulation-based behavioral agency in particular. Doing so requires that we identify distinct behavior-states, that we tie them to time geography, that we consider varied neighborhoods of geographic information as input, that we consider scaling, and that we compound these together in ways that could help to establish transition rules. Figure 3, for example, shows the EEG signatures for a single user. Perturbation in EEG oscillations are evident during road-crossing approach and assembly phases (as the user takes in dynamic spatial stimuli), but smooth out during periods of crossing (when the user focuses on locomotion and reaching their crossing target). Indeed, distinct phase shifts in (spike-induced) spatial behavior is clear in the EEG, down to the millisecond, for example, when a crossing epoch ends and a user begins to intake information from their embodied surroundings as shown in Figure 4, or at the onset of crossing locomotion as shown (for a different user) in Figure 5. These types of insights are reported generally in the neuroscience literature with explanation of a shift from ego-centric spatial behavior (e.g., while crossing) to allocentric (navigation, wayfinding, steering) locomotion when engaging decision making in spatial working memory or while updating that memory (e.g., when on sidewalks) [31-33].

4.2 Agency

Different navigational agencies are also evident in the EEG signature. For example, compare the oscillations of a participant who jaywalked and used risk-taking behavior in the geosimulation (comparatively slow waves in Figure 3) to those of a risk-averse and signal-abiding user in Figure 5 (faster waves, indicative of higher relative attention). There are clear and distinct neural signatures that can distinguish the two agencies. One behavioral agency (jaywalking) would generally be thought of as eschewing attention to the surroundings in favor of preserving either or both of locomotion and heading [34-36]. The other agency (rule-accepting) is generally associated with spatial behavior that is curious of surroundings and in particular is associated with watching for change in potential embodiment to ambient geography [37, 38]. All of these factors can be sourced in the data that the experiential geosimulation generates, with the implication that geosimulation could be used to experiment with the varying influence of different crossing factors on the neural substrate for risk-taking and risk-aversion at the roadside.

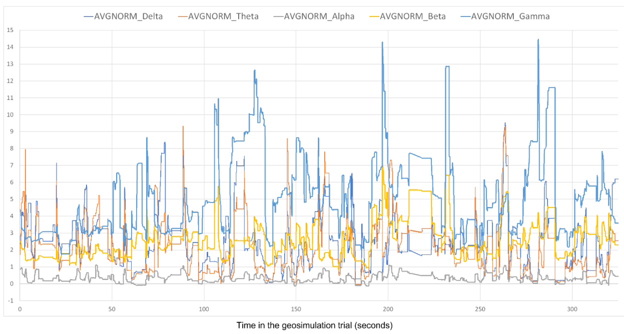

Figure 5: Relatively fast EEG waves indicate heightened spatial attention.

4.3 Spatial vision

EEG signals are heavily influenced by visual stimuli, and spikes and entrainment have been well-associated with visual enticement of different spatial behaviors, including locomotion, landmark-based wayfinding, spatial view, turning, and homing [25, 27]. Using a combination of user eye-tracking (via in-built HMD cameras) and ray-tracing to geosimulation entities, we space-time synchronized meaningful gazes (gaze that was fixed over small bouts of space-time) and associated them with EEG oscillations (see Figure 6 for statistical results, and note that these results are for instantaneous gaze).

Across all users, there was a negative correlation between EEG signals and gaze (essentially deliberate spatial attention by eye contact) upon vehicles, different parts of vehicles, other synthetic agent pedestrians, and vehicle drivers. In other words, generalized attention dropped when looking at dynamic features of the geosimulation, showing that participants focused their attention on those features (and switching from appreciation of static streetscape features to dynamic features, back and forth, can be captured in the signature, as in Figures 3 and 5). This effect is further explainable by examining individual EEG frequencies, e.g., negative correlation with vehicles is relatively strong in Delta and Theta, which are most reliably associated with locomotion as movement through space and time (in geographic-scale space) [39]: users reduced excitation of the neural networks for locomotion when they gazed upon vehicles (i.e., a cognitive and behavioral switch to referential-scale space), perhaps because they were getting prepared to change their locomotion behavior. This is patently evident in an individual user's EEG signature (Figure 4), which shows that a road-crosser approaches a crossing site at the curb (t = 5000 ms before crossing), and there is a narrowband spike in EEG oscillation for Theta and Delta that peaks and troughs as they shuffle to a stop in their locomotion. This is followed by a broadband drop in all EEG for ~0.5 seconds as the decision to cross is made, after which there is a return to increased broadband oscillation in Theta and Delta. The relative spike in Alpha frequency, after what is essentially a very slow wave oscillation over the crossing epoch, is evidence of pulsed inhibition [25] in which increases in Alpha act to focus attention energy [40] and serve to enable preferential processing of particular visual stimuli, which in this case affords the user's selective attention to roadside dynamics. This selective attention is also evident in the gaze sequence of the user (colored dots in Figure 4), which goes through distinct visually induced phase transitions of identifying the crossing signal → studying vehicles → examining the road gaps between vehicles → returning to studying vehicles → making a decision to cross (EEG drops but Alpha spikes) → making the crossing. In this case, hopefully the reader can envisage that the transition rules for agent-based crossing could be literally pulled directly from this EEG sequence.

Pearson correlation between gaze target fixation and EEG frequency (for all participants in all geosimulation trials)

	Vehicle gaze	Traffic light gaze	Crossing signal gaze	Pedestrian gaze	Vegetation gaze	Zebra crossing gaze	Sidewalk gaze	Pole gaze	Road gaze	Driver gaze	Front wheel gaze	Rear wheel gaze	Car body gaze
AVGNORM Delta	-0.13	-0.07	-0.04	-0.07	0.04	0.16	0.07	0.01	-0.05	-0.05	-0.02	-0.02	-0.13
AVGNORM Theta	-0.11	-0.02	0.04	-0.06	0.02	0.06	0.06	0.01	-0.01	-0.05	-0.01	-0.01	-0.10
AVGNORM Alpha	-0.02	0.08	0.07	-0.04	0.01	-0.04	0.00	0.00	0.07	-0.02	0.03	0.01	0.00
AVGNORM Beta	0.02	0.15	0.04	-0.01	0.00	-0.06	-0.02	0.00	0.10	-0.03	0.04	0.01	0.05
AVGNORM Gamma	0.00	0.13	0.05	-0.02	-0.01	-0.04	0.01	0.00	0.09	-0.04	0.02	0.00	0.03

Pearson correlation between gaze target fixation and EEG frequency (individual users; P06 is risk-taking)

P03 (n = 3148 fixes)	Vehicle gaze	Traffic light gaze	Crossing signal gaze	Pedestrian gaze	Vegetation gaze	Zebra crossing gaze	Sidewalk gaze	Pole gaze	Road gaze
AVGNORM Delta	-0.03	0.01	0.02	-0.02	0.01	0.15	0.17	0.01	-0.03
AVGNORM Theta	-0.02	0.00	0.00	-0.03	0.00	0.10	0.25	-0.01	-0.03
AVGNORM Alpha	0.00	0.03	-0.03	-0.03	-0.04	0.15	0.13	0.00	-0.04
AVGNORM Beta	-0.05	0.04	0.02	-0.01	-0.06	-0.02	0.03	0.05	-0.05
AVGNORM Gamma	-0.05	0.03	-0.06	0.01	-0.04	-0.03	0.04	0.03	-0.04

P04 (n = 3001 fixes)	Vehicle gaze	Traffic light gaze	Crossing signal gaze	Pedestrian gaze	Vegetation gaze	Zebra crossing gaze	Sidewalk gaze	Pole gaze	Road gaze
AVGNORM Delta	-0.15	-0.05	0.10	0.00	0.01	0.00	-0.02	0.05	0.01
AVGNORM Theta	-0.14	-0.07	0.12	-0.01	-0.01	0.03	-0.04	0.06	-0.02
AVGNORM Alpha	-0.07	-0.05	0.06	-0.03	0.03	-0.04	0.01	0.02	0.00
AVGNORM Beta	0.08	0.06	-0.13	0.10	0.01	-0.06	-0.04	0.00	0.04
AVGNORM Gamma	-0.01	0.03	-0.03	0.09	-0.07	0.00	0.07	-0.01	0.02

P05 (n = 1826 fixes)	Vehicle gaze	Traffic light gaze	Crossing signal gaze	Pedestrian gaze	Vegetation gaze	Zebra crossing gaze	Sidewalk gaze	Pole gaze	Road gaze
AVGNORM Delta	-0.29	-0.03	-0.08	-0.17	0.02	0.05	0.40	0.01	0.09
AVGNORM Theta	-0.27	-0.06	-0.03	-0.17	0.04	0.04	0.25	0.01	0.10
AVGNORM Alpha	-0.21	-0.08	-0.01	-0.14	0.02	0.01	0.24	0.02	0.04
AVGNORM Beta	-0.19	0.00	-0.04	-0.15	0.05	0.00	0.16	-0.02	0.12
AVGNORM Gamma	-0.09	-0.01	0.09	-0.08	0.06	-0.02	0.01	0.06	0.02

P06 (n = 1791 fixes)	Vehicle gaze	Traffic light gaze	Crossing signal gaze	Pedestrian gaze	Vegetation gaze	Zebra crossing gaze	Sidewalk gaze	Pole gaze	Road gaze
AVGNORM Delta	-0.12	-0.01	0.02	-0.07	0.06	N/A	0.08	-0.04	0.02
AVGNORM Theta	-0.12	-0.01	0.02	-0.06	0.05	N/A	0.08	-0.02	0.00
AVGNORM Alpha	-0.16	-0.02	0.02	-0.03	0.03	N/A	0.06	-0.07	0.01
AVGNORM Beta	-0.18	0.02	0.04	0.07	-0.01	N/A	0.04	-0.01	0.01
AVGNORM Gamma	-0.27	0.00	-0.02	0.11	0.00	N/A	0.11	-0.01	0.05

Distribution of gaze targets

Gaze target	Percent of hits
Sidewalk	33.52%
Vehicle body	29.15%
Crossing signal	8.56%
Road	8.52%
Zebra crossing	4.98%
Traffic light	4.57%
Pedestrian	4.16%
Driver	2.95%
Vegetation	1.82%
Pole	0.82%
Back wheel	0.55%
Front wheel	0.39%

Figure 6: Gaze target distribution and Pearson correlations between fixed gaze targets and EEG oscillations.

4.4 Landmark salience

Most human walkers are known to employ landmark-based wayfinding as a component of their navigation [41] and this is well-established in EEG-based neuroscience literature [42-44]. Given the amount of insight-based detail that we can muster in geosimulation, where all entities are known at all locations and times in the scenegraph of the VGE, we can examine the salience of specific landmarks with respect to gaze and behavior. We have demonstrated the utility of gaze as a simulation output generally in prior work [45], but again here we delve deeper into details.

We considered four easily distinguishable landmarks in the geosimulation: vegetation (trees), civil infrastructure (poles holding signs), and traffic lights and crossing signals (which are dynamically controlled relative to traffic). Crossing signals and traffic lights emerged as the most frequently attended landmarks. Analysis of EEG stimulation relative to the crossing signals reveals their salience. There is a relatively strong positive correlation between Gamma frequency oscillations and dynamic guiding lights (Figure 6), which echoes findings in neuroscience that suggest that Gamma is enticed when observers need to make sense of the meaning of a whole object in their vision (as opposed to the object's simple, perhaps convolutional, features such as color and texture) [23, 46]. Consider, for example, that a crossing signal will illuminate different shapes (in our case, icon red hands or green pedestrians for "do not walk", "prepare to not walk", or "walk", respectively). These icon-displays, appearing dynamically (and meaningfully) within the "signal" object must be reasoned with by users and related to other features of the viewshed (traffic lights, vehicles, the locomotion behavior of other synthetic pedestrians, positions and occupancy status of zebra crossings, the location of adjacent curb that is the crossing target). This information must be resolved, in the mind, ahead of deciding a locomotion decision or behavior, and ahead of polling one's embodied surroundings for more information to check that your cognitive map is reliable in a small moment of space and time relative to any actions you are preparing.

4.5 Non-verbal communication

One of the advantages of deploying geosimulation as a testbed for behavioral geography is the ability to include life-like synthetic agents that can animate and enliven the environment. This is important for realism, but also for users who may rely on ambient pedestrians as cues for changes in the scene. In our geosimulation, agents were programmed with personality-based profiles for streetscape crossing (ranging from risk-taking to risk-averse), as well as with realistic appearances and motion-captured kinesiology and gestures. We have presented details on this previously in [1]. In this paper, we extend NVCs to drivers of vehicles in the IDM. Specifically, drivers, upon approaching a zebra crossing, will train their gaze on the user so that there is the possibility for mutual gaze exchange. By drawing rays between both parties, we can identify when these NVCs are enticed in the geosimulation, as well as their impact upon EEG signals, and indeed on behavior. Across all participants, driver gaze was shown to have weakly negative correlation with all EEG frequencies, indicating that users reduced their attention to spatial navigation when looking at drivers (again, possibly in preparation for a change in movement state depending on the returned signal that the NVC was interpreted as conveying). This connection between mutual gaze and locomotion is evident in the higher negative correlation results for Delta and Theta, in particular.

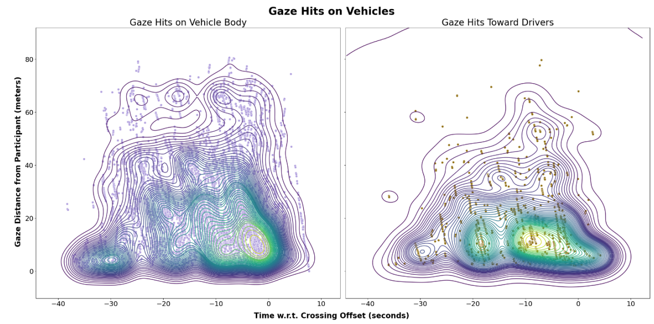

Figure 7: Signatures of the brain's "Where" system are evident in gaze fixation of vehicles and their drivers ahead of crossing decisions.

4.6 What and where neural networks

Following Gruber et al.'s identification of "What" and "Where" systems that distinguish visual processing in occipital cortex of the brain from integration of sensory processing in parietal cortex ahead of motor skill actuation [23], we examined anticipatory behavior and EEG oscillation. In particular, we focused on distance and timing factors. Taken together, these obviously yield time geography, but over fleeting moments of space and time that we then match to EEG-level scale. In this way, we attempt to reconcile the "atoms" of behavioral geography at new scales.

Some results are illustrated in Figure 7, showing that before crossing (negative values on the x-axis), participants focus attention on near things (dense contours near zero on the y-axis). Slightly ahead of a crossing decision, users' gaze also begins to attend to both near and far objects, involving wider sweeps for information from the streetscape that can inform their crossing (dense contour at positive time (after crossing) on the x-axis and between zero and 40 meters on the y-axis).

These results echo findings from the safety science literature that reveal that users train their information-gathering on the spacing and the timing of traffic gaps when crossing roads. Our results show specifically "where" this attention is trained in space and time. Further examination of this "Where" system, and its EEG correlates, could be incredibly useful in building simulation-based clinical knowledge for studying road-crossing error-making in very senior populations, for example.

5 Conclusions

In this paper, we introduced a proof of concept for a new form of geosimulation—experiential geosimulation—that makes use of advances in immersive computing via VR, as well as BCIs that can generate signal-based insight into activation of neural energy in different compartments of the brain, and across neural networks. We reason that this can be newly useful for the geosimulation community in developing novel insights into spatial behavior and in behavioral geography, in particular. Further, it opens-up new pathways for convergence between geosimulation research and parallel threads of inquiry in neuroscience, for which geosimulation's traditional attention to high-resolution entity-based representation of urban phenomena, specifically, could provide new test-beds with relative parity to clinical work.

An obvious limitation of our approach is the use of a relatively limited EEG BCI (four active electrodes). Most neuroscience work employs EEG with more than one hundred electrodes, which allows for examination of waves of oscillation (with potential additional bearing on cell-based generators, including place cells), and which can be coupled to fMRI and other deep tissue imaging to localize activation to specific parts of the brain (including lateralization, which is associated with selective attention). However, use of more sophisticated EEG requires either surgical approaches for intercranial sensing, or requires that users remain tethered to EEG machines and must necessarily limit their locomotion to sitting or standing in constrained treadmills. Our approach, of using mobile and wireless EEG alongside similarly portable immersive geosimulation, allows for a fusion of real human sensorimotor control and synthetic visual and task-based stimuli , which we consider as being a reasonable trade-off.

Some promising next steps could involve data science for better connecting neural sensing with geosimulation cyberinfrastructure [3, 47], and work on slipstreaming as we have shown in preliminary form here could be useful. A longer-term avenue for investigation could involve the convergence of neural sensing with accelerated computing for geosimulation [48], e.g., on Equation Free platforms [49], for which neural signals could inform manifolds of agency that can be run through ensembles of context in geosimulation. Other modalities beyond EEG could also prove promising, particularly surface electromyography (and we show an example of force-aware geosimulation in early stages in [50, 51]). The potential for convergence of neural sensing, geosimulation, and artificial intelligence [52, 53] is perhaps where significant advances on the prototype we have shown here could be started. This could include generative AI for adding interactive user experiences to 3D modeling, for example [54]. Ultimately, the greatest potential benefit of advancing geosimulation along the lines of experimentation that we have shown here would be in informing conceptual and theoretical geography, particularly in bringing geosimulation and hypothesis-driven geography into explanatory parity in new ways [55-60].

REFERENCES

[1] Torrens, P. M. and Gu, S. 2021.Real-time experiential geosimulation in virtual reality with immersion-emission. In *Proceedings of the 4th ACM SIGSPATIAL International Workshop on GeoSpatial Simulation*, 19–28. Beijing, China: Association for Computing Machinery.

[2] Torrens, P. M. and Gu, S. 2023. Inverse augmentation: Transposing real people into pedestrian models. *Computers, Environment and Urban Systems*, 100, 101923.

[3] Torrens, P. M. and Kim, R. 2025. Sidewalk2Synth: generating synthetic embodied locomotion from real-world streetscapes. *Urban Informatics*, 4, 1, 16.

[4] Torrens, P. M. and Kim, R. 2024. Evoking embodiment in immersive geosimulation environments. *Annals of GIS*, 30, 1, 35-66.

[5] Kim, R. and Torrens, P. M. 2024. Building verisimilitude in VR with high-fidelity local action models: a demonstration supporting road-crossing experiments. In *Proceedings of the 38th ACM SIGSIM Conference on Principles of Advanced Discrete Simulation*, June 24-26, 2024, Atlanta, GA, USA, eds. M. Loper and A. Pellegrini, 119–130. New York, NY, USA: Association for Computing Machinery.

[6] Kesting, A., Treiber, M. and Helbing, D. 2010. Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 368, 1928, 4585-4605.

[7] van den Berg, J., Lin, M. and Manocha, D. 2008.Reciprocal Velocity Obstacles for real-time multi-agent navigation. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, May 19-23, 2008, Pasadena, CA, USA, ed. J. Triesch, 1928-1935. Los Alamitos, CA, USA: IEEE.

[8] Snape, J., Van Den Berg, J., Guy, S. J. and Manocha, D. 2011. The hybrid reciprocal velocity obstacle. *IEEE Transactions on Robotics*, 27, 4, 696-706.

[9] Torrens, P. M. and Kim, R. 2024. Using immersive virtual reality to study road-crossing sustainability in fleeting moments of space and time. *Sustainability*, 16, 3, 1327.

[10] Torrens, P. M. 2015. Slipstreaming human geosimulation in virtual geographic environments. *Annals of GIS*, 21, 4, 325-344.

[11] Thrift, N. 2008. Non-Representational Theory: Space, Politics, Affect. *Routledge*, New York.

[12] Torrens, P. M. 2024. Ten traps for non-representational theory in human geography. *Geographies*, 4, 2, 253-286.

[13] Dourish, P. 2001. Seeking a foundation for context-aware computing. *Human–Computer Interaction*, 16, 2-4, 229-241.

[14] Picard, R. W. 2000. *Affective Computing*. MIT press.

[15] Brooks, R. A. 1999. *Cambrian Intelligence: The Early History of the New AI*. MIT press, Cambridge, MA.

[16] de Lavalette, B. C., Tijus, C., Poitrenaud, S., Leproux, C., Bergeron, J. and Thouez, J.-P. 2009. Pedestrian crossing decision-making: A situational and behavioral approach. *Safety Science*, 47, 9, 1248-1253.

[17] Pfeffer, K. and Hunter, E. 2013. The effects of peer influence on adolescent pedestrian road-crossing decisions. *Traffic Injury Prevention*, 14, 4, 434-440.

[18] Clark, A. and Chalmers, D. J. 1998. The extended mind. *Analysis*, 58, 1, 7-19.

[19] Torrens, P. M., Li, X. and Griffin, W. A. 2011. Building agent-based walking models by machine-learning on diverse databases of space-time trajectory samples. *Transactions in Geographic Information Science*, 15, s1, 67-94.

[20] Torrens, P. M., Nara, A., Li, X., Zhu, H., Griffin, W. A. and Brown, S. B. 2012. An extensible simulation environment and movement metrics for testing walking behavior in agent-based models. *Computers, Environment and Urban Systems*, 36, 1, 1-17.

[21] Benenson, I. and Torrens, P. M. 2004. *Geosimulation: Automata-Based Modeling of Urban Phenomena*. John Wiley & Sons, London.

[22] Torrens, P. M. and Benenson, I. 2005. Geographic Automata Systems. *International Journal of Geographical Information Science*, 19, 4, 385-412.

[23] Gruber, T., Müller, M. M., Keil, A. and Elbert, T. 1999. Selective visual-spatial attention alters induced gamma band responses in the human EEG. *Clinical Neurophysiology*, 110, 12, 2074-2085.

[24] Bischof, W. F. and Boulanger, P. 2003. Spatial navigation in virtual reality environments: an EEG analysis. *CyberPsychology & Behavior*, 6, 5, 487-495.

[25] Mathewson, K. E., Lleras, A., Beck, D. M., Fabiani, M., Ro, T. and Gratton, G. 2011. Pulsed out of awareness: EEG alpha oscillations represent a pulsed-inhibition of ongoing cortical processing. *Frontiers in Psychology*, 2, Article 99, 1-15.

[26] Capotosto, P., Babiloni, C., Romani, G. L. and Corbetta, M. 2009. Frontoparietal cortex controls spatial attention through modulation of anticipatory alpha rhythms. *The Journal of Neuroscience*, 29, 18, 5863-5872.

[27] Chan, E., Baumann, O., Bellgrove, M. A. and Mattingley, J. B. 2012. From objects to landmarks: the function of visual location information in spatial navigation. *Frontiers in Psychology*, 3, Article 304, 1-11.

[28] Jacobs, J., Weidemann, C. T., Miller, J. F., Solway, A., Burke, J. F., Wei, X.-X., Suthana, N., Sperling, M. R., Sharan, A. D., Fried, I. and Kahana, M. J. 2013. Direct recordings of grid-like neuronal activity in human spatial navigation. *Nature Neuroscience*, 16, 9, 1188-1190.

[29] Do, T.-T. N., Lin, C.-T. and Gramann, K. 2021. Human brain dynamics in active spatial navigation. *Scientific Reports*, 11, 1, 13036.

[30] Rolls, E. T. 2023. Hippocampal spatial view cells for memory and navigation, and their underlying connectivity in humans. *Hippocampus*, 33, 5, 533-572.

[31] Plank, M., Müller, H. J., Onton, J., Makeig, S. and Gramann, K. 2010.Human EEG correlates of spatial navigation within egocentric and allocentric reference

frames. In *Spatial Cognition VII. Spatial Cognition 2010. Lecture Notes in Computer Science 6222*, eds. C. Hölscher, T. F. Shipley, M. Olivetti Belardinelli, J. A. Bateman and N. S. Newcombe, 191-206. Berlin, Heidelberg: Springer Berlin Heidelberg

[32] Chiu, T.-C., Gramann, K., Ko, L.-W., Duann, J.-R., Jung, T.-P. and Lin, C.-T. 2012. Alpha modulation in parietal and retrosplenial cortex correlates with navigation performance. *Psychophysiology*, 49, 1, 43-55.

[33] Gomez, A., Cerles, M., Rousset, S., Rémy, C. and Baciu, M. 2014. Differential hippocampal and retrosplenial involvement in egocentric-updating, rotation, and allocentric processing during online spatial encoding: an fMRI study. *Frontiers in Human Neuroscience*, Volume 8 - 2014.

[34] Carol, H. and Roslyn, H. 2007. The effect of age, gender and driver status on pedestrians' intentions to cross the road in risky situations. *Accident Analysis & Prevention*, 39, 2, 224-237.

[35] Dommes, A. and Cavallo, V. 2011. The role of perceptual, cognitive, and motor abilities in street-crossing decisions of young and older pedestrians. *Ophthalmic and Physiological Optics*, 31, 3, 292-301.

[36] Sueur, C., Class, B., Hamm, C., Meyer, X. and Pelé, M. 2013. Different risk thresholds in pedestrian road crossing behaviour: a comparison of French and Japanese approaches. *Accident Analysis & Prevention*, 58, 59-63.

[37] Hess, P., Moudon, A., Snyder, M. and Stanilov, K. 1999. Site design and pedestrian travel. *Transportation Research Record: Journal of the Transportation Research Board*, 1674, 1, 9-19.

[38] Luu, D. T., Eom, H., Cho, G.-H., Kim, S.-N., Oh, J. and Kim, J. 2022. Cautious behaviors of pedestrians while crossing narrow streets: Exploration of behaviors using virtual reality experiments. *Transportation Research Part F: Traffic Psychology and Behaviour*, 91, 164-178.

[39] Barnes, L., Davidson, M. J. and Alais, D. 2023. The speed and phase of locomotion dictate saccade probability and simultaneous low-frequency power spectra. *bioRxiv*, 2023.2006.2022.546202.

[40] Large, E. W. and Jones, M. R. 1999. The dynamics of attending: how people track time-varying events. *Psychological Review*, 106, 1, 119-159.

[41] Golledge, R. A. 1999. *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes*. The Johns Hopkins Press, Baltimore.

[42] Hartley, T., Maguire, E. A., Spiers, H. J. and Burgess, N. 2003. The well-worn route and the path less traveled: distinct neural bases of route following and wayfinding in humans. *Neuron*, 37, 5, 877-888.

[43] Kato, Y. and Takeuchi, Y. 2003. Individual differences in wayfinding strategies. *Journal of Environmental Psychology*, 23, 2, 171-188.

[44] Spiers, H. J. and Maguire, E. A. 2008. The dynamic nature of cognition during wayfinding. *Journal of Environmental Psychology*, 28, 232-249.

[45] Kim, R., Shinozaki-Conefrey, K. and Torrens, P. M. 2025.Looking for answers: gaze and brain activity as simulation outputs. In *Proceedings of the 39th ACM SIGSIM Conference on Principles of Advanced Discrete Simulation*, June 23-26, 2025, Santa Fe, NM, USA, eds. E. Page and A. Uhrmacher, 186–187. New York, NY, USA: Association for Computing Machinery.

[46] Keil, A., Müller, M. M., Ray, W. J., Gruber, T. and Elbert, T. 1999. Human gamma band activity and perception of a Gestalt. *The Journal of Neuroscience*, 19, 16, 7152.

[47] Torrens, P.M. 2007. Behavioral intelligence for geospatial agents in urban environments. In *IEEE Intelligent Agent Technology (IAT 2007)*, eds. T. Y. Lin, J. M. Bradshaw, M. Klusch and C. Zhang, 63-66. Los Alamitos, CA: IEEE.

[48] Zou, Y., Torrens, P.M., Ghanem, R., and Kevrekidis, I.G. 2012. Accelerating agent-based computation of complex urban systems. *International Journal of Geographical Information Science* 26 (10):1917-1937.

[49] Torrens, P.M., Kevrekidis, I., Ghanem, R., and Zou, Y. 2013. Simple urban simulation atop complicated models: multi-scale equation-free computing of sprawl using geographic automata. *Entropy* 15 (7):2606-2634.

[50] Zhang, Y., Liang, B., Chen, B., Torrens, P., Atashzar, S.F., Lin, D., and Sun, Q. 2022. Force-aware interface via electromyography for natural VR/AR interaction. *ACM Transactions on Graphics* 41 (6):268: 1–18.

[51] Zhang, F., Zhang, Y., Peng, X., Achitoff, S., Torrens, P.M., and Sun, Q. 2024. May the force be with you: dexterous finger force-aware VR interface. In *Proceedings of the 2024 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, October 21-25, 2024, Bellevue, WA, USA, eds. A. Day, J. Powers and W. Mayol-Cuevas, 455-464. Los Alamitos, CA, USA: IEEE.

[52] Torrens, P.M. 2018. Artificial intelligence and behavioral geography. In *Handbook of Behavioral and Cognitive Geography*, ed. D. R. Montello, 357-372. Cheltnam: Edward Elgar Publishing.

[53] Torrens, P.M. 2016. Exploring behavioral regions in agents' mental maps. *The Annals of Regional Science* 57 (2-3):309-334.

[54] Li, Q., Torrens, F., Chen, K., and Sun, Q. 2025. BlendFusion: procedural 3D texturing assistant with view-consistent generative models. In *I3D Companion '25: Companion Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*, eds. M. Markus Billeter, B. Watson, R. Marroquim, L. Reznikov, Z. Sin and M. Vives, Article 3. New York, NY, USA: Association for Computing Machinery.

[55] Schwanen, T. 2023. Towards a Different Mode of Abstraction: The Diorama in Hägerstrand's Experimentation in Thought. *Tijdschrift voor Economische en Sociale Geografie (Journal of Economic and Social Geography)* 114 (3):219-226.

[56] Hägerstrand, T. 1970. What about people in Regional Science? *Papers in Regional Science* 24 (1):6-21.

[57] Tuan, Y.-F. 1979. Space and place: humanistic perspective. In *Philosophy in Geography (Theory and Decision Library, Volume 20)*, eds. S. Gale and G. Olsson, 387-427. Dordrecht: Springer.

[58] Golledge, R.A. 1978. Representing, interpreting and using cognized environments. *Proceedings of the Regional Science Association* 41 (1):168-204.

[59] Torrens, P.M. 2014. High-fidelity behaviours for model people on model streetscapes. *Annals of GIS* 20 (3):139-157.

[60] Torrens, P.M. 2015. Intertwining agents and environments. *Environmental Earth Sciences* 74 (10):7117-7131.