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Research Statement

Research Vision: Privacy-Preserving XR Telemetry and Spatial AI

My research builds privacy-preserving extended reality systems that transform gaze, movement, gesture, spatial behavior, and interaction traces into trustworthy spatial AI for high-stakes learning, health-care, cybersecurity, scientific visualization, and cyber-physical training. I work at the intersection of human-computer interaction, virtual and augmented reality, computer graphics, visualization, artificial intelligence, and secure data infrastructure.

The central question driving my research is:

ow can immersive systems collect, model, protect, and interpret embodied human behavior so that they support learning, adaptation, and expert decision making without creating unnecessary surveillance?

Virtual and augmented reality systems are no longer only display or visualization technologies. They are becoming data-rich human-centered computing environments. In immersive systems, a user's gaze, movement, hesitation, spatial strategy, hand motion, posture, collaborative behavior, and interaction history can reveal attention, skill, stress, intent, identity, expertise, and learning. These traces can support adaptive instruction, medical planning, cybersecurity exercises, infrastructure simulation, collaborative scientific reasoning, and training for rare but consequential events. They also create new privacy and security risks because immersive telemetry is behavioral, biometric-like, contextual, and difficult for users to inspect or control.

My research treats immersive environments as both interfaces and measurement systems. I design XR platforms, evaluate how people use them, build analytics pipelines for embodied behavioral data, and study how such data can be transformed, synthesized, protected, and interpreted. The long-term goal is to create immersive systems that are technically rigorous, human-centered, privacy-aware, and useful in domains where errors have real consequences.

Research Foundations: Usable, Portable, and Evaluated Immersive Systems

My early research developed the **Ubiquitous Collaborative Activity Virtual Environment** (UCAVE), a lightweight smartphone-based VR framework for portable, untethered immersive experiences. This work grew from a core HCI problem: immersive systems often promise realism and engagement, but their real value depends on comfort, accessibility, input design, spatial fidelity, and the user's ability to act effectively inside the system.

Through systematic studies, I examined how design choices affect user behavior and task performance in immersive environments. This work investigated:

- how untethered VR designs influence ergonomic comfort and user performance;
- how environmental fidelity, including outdoor realism, affects spatial task outcomes;

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- how prior gaming experience and input-device familiarity shape VR usability;
- how head-mounted display deployment changes user trajectories in navigation tasks;
- how immersive systems can support collaboration without requiring expensive fixed infrastructure.

These studies established the foundation for my current research philosophy: XR systems must be evaluated as embodied human-centered systems, not only as graphics or visualization platforms. The interface, the body, the sensing pipeline, the environment, and the task all shape what the system can measure and what users can accomplish. This perspective now motivates my work on longitudinal VR learning, privacy-aware XR telemetry, secure immersive training, and spatial decision support.

Research Thrust 1: Longitudinal Learning and Adaptation in XR

A major strand of my research studies how people learn, adapt, and make decisions in immersive environments over time. Much VR research evaluates users in single-session studies, but real learning and expertise development are longitudinal. Users adapt to the interface, become more comfortable with spatial interaction, develop new strategies, and sometimes show strong early engagement that does not translate into durable learning.

My recent IEEE Transactions on Visualization and Computer Graphics paper, *From Novelty to Knowledge: A Longitudinal Investigation of the Novelty Effect on Learning Outcomes in Virtual Reality*, accepted at IEEE VR 2025 and recognized with Best Paper Honorable Mention, directly addresses this issue. The project asks whether high initial engagement in VR reflects durable learning or temporary novelty. By studying repeated exposure rather than a single interaction session, we examine how novelty, attention, memory, and performance evolve over time.

This work contributes to immersive learning research in three ways. First, it shows that evaluation of VR learning systems must account for adaptation and novelty, not only immediate engagement. Second, it demonstrates the value of longitudinal behavioral traces for distinguishing temporary excitement from meaningful knowledge formation. Third, it motivates new models of spatial learning that combine user behavior, task performance, and time.

My future work in this area will develop general models of spatial learning and expertise in immersive environments. Key questions include:

- How do users develop spatial strategies across repeated XR exposure?
- Which behavioral traces predict durable learning rather than short-term engagement?
- How can immersive systems adapt to expertise without overfitting to noisy behavioral signals?
- How should AI models represent uncertainty when interpreting embodied user behavior?
- How can XR systems support learning without reducing students or trainees to opaque scores?

This thrust supports applications in education, professional training, cybersecurity exercises, medical decision support, and scientific reasoning.

Research Thrust 2: Privacy-Aware XR Telemetry and Synthetic Behavioral Data

A second strand of my research focuses on privacy-aware analytics for immersive telemetry. XR environments can capture extremely rich behavioral data: gaze, hand motion, head movement, body posture, spatial trajectories, object interactions, timing, hesitation, proximity, and collaboration patterns. These data can power adaptive systems and scientific studies, but they also create risks because they can reveal identity, ability, intent, cognitive state, health-related information, and task strategy.
My students and I have built systems for real-time gaze analytics, spatial trajectory replay, and synthetic telemetry generation. In recent IEEE VR Workshop papers, we explored eye-tracking analytics using scalable data infrastructure, re-identification risks in VR telemetry, and synthetic data methods that preserve useful behavioral structure while reducing exposure of raw user traces.
The technical challenge is that immersive telemetry is not ordinary interaction data. It is high-dimensional, temporal, spatial, embodied, and context-dependent. A trace that appears harmless in isolation may become identifying when combined with task context, movement style, gaze patterns, or environmental features. Conversely, removing too much structure can make the data useless for learning analytics, training evaluation, or system adaptation. This creates a central research problem: how can XR systems preserve utility while reducing unnecessary observability?
My future work in this area will develop privacy-preserving immersive analytics along four directions:

1. **Telemetry representation.** I will develop representations for gaze, motion, trajectory, and interaction data that capture task-relevant structure while limiting unnecessary personal exposure.

2. **Synthetic XR behavior generation.** I will create methods for generating synthetic immersive telemetry that preserves aggregate spatial and temporal patterns without directly exposing raw user traces.

3. **Privacy and re-identification evaluation.** I will develop evaluation methods for measuring when XR telemetry can reveal identity, skill, health-related behavior, or sensitive task strategies.

4. **Auditable immersive data infrastructure.** I will build systems that make XR data collection, transformation, and use inspectable by researchers, instructors, and participants.

This research direction contributes a distinctive program in privacy-aware immersive telemetry as infrastructure for human-centered AI. My goal is not only to build compelling XR systems, but also to define responsible technical foundations for how immersive behavioral data should be collected, modeled, transformed, protected, and interpreted.

Research Thrust 3: Immersive Cyber-Physical Training and Human-in-the-Loop Security

A third strand of my work applies immersive systems to high-stakes training and cyber-physical readiness. I am a Co-Investigator on the U.S. Department of Energy-funded Cybersecurity Consortium for Innovation, where my role focuses on immersive industrial control systems cybersecurity training, workforce development, and cyber-physical simulation.
Industrial control systems and critical infrastructure environments are difficult to teach using conventional classroom methods alone. They involve distributed components, physical consequences, temporal dependencies, rare failure modes, and adversarial behavior. Immersive simulations can help trainees experience complex scenarios, practice incident response, and understand system interdependencies

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without risking real infrastructure. However, immersive training also creates a measurement problem: how should a system evaluate human performance in complex, uncertain, collaborative environments? My work addresses this by designing immersive cyber-physical simulations and analytics pipelines for training evaluation. The goal is to help instructors understand how trainees perceive threats, navigate complex environments, communicate with teammates, and recover from unexpected events. I am especially interested in developing analytics that support human judgment rather than replacing it. In high-stakes training, a useful system should help instructors inspect behavior, identify patterns, and provide feedback, not simply assign a simplistic score.
My future research in this area will develop human-in-the-loop security training and cyber-physical simulation systems around the following questions:

- How can immersive simulations represent cyber-physical infrastructure in ways that are technically meaningful and pedagogically useful?
- How can embodied telemetry reveal trainee understanding, confusion, collaboration, or situational awareness?
- How can AI-based training analytics support instructor interpretation without obscuring uncertainty?
- How can secure XR infrastructure support multi-user exercises involving sensitive scenarios or infrastructure models?
- How can privacy-aware telemetry protect trainees while still enabling meaningful assessment?

This thrust connects XR, HCI, security, systems, and AI. It also provides opportunities for externally funded work through agencies and partners interested in workforce development, infrastructure resilience, and secure cyber-physical systems.

Research Thrust 4: Medical and Scientific Spatial Decision Support

A fourth strand of my research uses immersive visualization and spatial AI to support expert decision making in medical and scientific domains. I lead NSF EPSCoR DART-supported work on robust 2D-to-3D cardiac arterial mapping and visualization for surgical preplanning. This project develops interactive 3D arterial representations from conventional medical imagery so clinicians and researchers can inspect, reason about, and communicate complex spatial structures.
The broader motivation is that many high-stakes expert decisions involve spatial reasoning over complex, uncertain, multi-scale data. In cardiology, clinicians must understand vascular geometry, occlusions, branching structures, and intervention pathways. In agriculture and environmental decision support, stakeholders must interpret satellite-derived phenology, climate variables, soil conditions, and management practices. In scientific infrastructure, researchers need tools that help them move between predictive models, raw data, and interpretable visual representations.
My approach is to design immersive and interactive visualization systems that do more than present AI outputs. They help users inspect assumptions, compare alternatives, understand uncertainty, and reason spatially. This is especially important in medical and scientific settings, where a prediction is only useful if experts can understand when and how to trust it.
Future work in this thrust will develop end-to-end immersive visualization pipelines that integrate:

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- 2D-to-3D reconstruction and conformal mapping for anatomical and scientific structures;
- interactive visual analytics for inspecting uncertainty and model outputs;
- spatial AI models that support expert reasoning rather than opaque automation;
- privacy-aware data handling for sensitive medical and behavioral information;
- collaborative XR interfaces for multidisciplinary decision making.

This research has applications in surgical planning, medical education, agricultural decision support, infrastructure analysis, and scientific visualization. The unifying goal is to help experts interact with complex data spatially while maintaining rigorous attention to usability, uncertainty, privacy, and decision context.

Unifying Technical Agenda

Although my projects span learning, privacy, cybersecurity, and medical visualization, they are unified by a common technical agenda: building secure spatial AI systems from embodied interaction data. Across domains, I focus on the same core problems.

Modeling Embodied Behavior

XR systems produce behavioral data that are temporal, spatial, multimodal, and context-sensitive. I develop models that combine gaze, motion, gesture, task events, and environmental structure to infer learning, expertise, attention, strategy, and uncertainty. This work draws on machine learning, sequence modeling, spatial analytics, and human-centered evaluation. The goal is not merely prediction, but interpretable support for adaptation and decision making.

Protecting Immersive Telemetry

Because immersive telemetry can reveal sensitive information, future XR systems need privacy-aware data pipelines. I develop methods for transforming, synthesizing, aggregating, and auditing immersive behavioral data. This work studies the tradeoff between utility and exposure, especially in settings where data support training, health, or research.

Building Complete Interactive Systems

My research is system-building oriented. I build prototypes, deploy them with users, collect data, evaluate performance, and refine the system based on empirical evidence. This includes Unity-based XR systems, telemetry infrastructure, distributed visualization pipelines, AI-assisted analytics, and collaborative training environments.

Evaluating Human Consequences

A technically successful immersive system can still fail if it produces misleading interpretations, increases discomfort, reduces user agency, or creates surveillance risks. My research therefore combines system design with user studies, longitudinal evaluation, privacy analysis, and domain expert feedback. This is central to my identity as an HCI and immersive systems researcher.

Future Research Program

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My long-term goal is to build an externally funded research group in secure spatial AI and human-centered immersive systems. The group will pursue three connected research questions:

1. **How can immersive systems model learning, expertise, and decision making from embodied interaction data?**

   This question extends my work on longitudinal VR learning, novelty effects, spatial cognition, and adaptive XR systems. It will produce models and systems for understanding how people acquire embodied skills over time.

2. **How can privacy-preserving telemetry, synthetic data, and secure analytics make XR systems measurable without making people unnecessarily observable?**

   This question extends my work on gaze analytics, telemetry replay, synthetic data, and re-identification risks. It will produce technical infrastructure for trustworthy immersive analytics.

3. **How can spatial AI support high-stakes training, healthcare, cybersecurity, and scientific decision making?**

   This question extends my work on cyber-physical training, digital cardiology, and scientific visualization. It will produce interactive systems that help experts inspect, question, and act on complex data.

The first five years of this program will focus on three major outcomes. First, my group will build open, extensible XR telemetry infrastructure for research on gaze, movement, interaction, and learning. Second, we will develop privacy-preserving methods for synthetic and transformed immersive behavioral data. Third, we will deploy and evaluate immersive spatial AI systems in high-impact domains such as cybersecurity training, medical visualization, and science education.

This program is designed to contribute to computer science through new methods, systems, and evaluations. It advances HCI by creating better models of embodied interaction and learning. It advances immersive computing by developing privacy-aware telemetry infrastructure. It advances AI by grounding spatial behavior modeling in human-centered evaluation. It advances visualization by supporting expert reasoning over complex data. It advances security and privacy by treating immersive behavioral data as a first-class object of protection.

Funding Strategy

My research program is designed to support a sustained externally funded lab. I have begun building this portfolio through funded and collaborative work, including NSF EPSCoR DART support for 2D-to-3D cardiac arterial mapping and surgical preplanning, the U.S. Department of Energy-funded Cybersecurity Consortium for Innovation, and industry research support including a Meta Project Aria research kit award.

I will pursue a focused funding strategy around trustworthy immersive computing, spatial AI, secure telemetry, and human-centered decision support. Likely funding targets include:

- NSF programs in HCI, cyber-human systems, smart health, AI, privacy, security, and STEM learning;
- NIH and medical research opportunities around spatial visualization, surgical planning, and human-AI decision support;

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- DOE and DHS opportunities in cyber-physical training, critical infrastructure, and workforce development;
- industry partnerships in AR/VR, wearable sensing, spatial computing, privacy-preserving analytics, and trustworthy AI.

The unifying funding narrative is that immersive computing is becoming core infrastructure for training, health, work, and scientific reasoning, but its data practices have not yet caught up with its sensing capabilities. My research addresses this gap by creating systems that are adaptive, measurable, privacy-aware, and useful to domain experts.

Broader Impact and Student Training

My research has strong broader impact because it addresses how future immersive systems will shape learning, work, health, and security. XR and spatial AI systems will increasingly be used to train workers, support clinical reasoning, teach complex concepts, and simulate critical infrastructure. These systems should be accessible, trustworthy, and accountable from the beginning.

I am also committed to training students as complete researchers. My students work on VR telemetry privacy, gaze analytics, spatial decision making, AI-assisted scientific discourse analysis, and immersive training systems. Several have published in IEEE VR venues. I mentor students to build systems, evaluate them carefully, analyze data rigorously, and ask what their systems measure, whom they affect, what assumptions they encode, and what forms of evidence justify their use.

My lab will train students who can move across HCI, graphics, AI, security, and domain applications. It will be a place for students who want to build real interactive systems, study human behavior, and develop responsible computational methods for sensor-rich environments. I also plan to create interdisciplinary opportunities for students to collaborate with researchers in medicine, data science, engineering, education, security, agriculture, and design.

Conclusion

My research advances immersive computing by treating XR environments as secure, measurable, human-centered systems. Across longitudinal VR learning, privacy-aware telemetry, cyber-physical training, and medical visualization, my work asks how embodied interaction data can be modeled, protected, and used responsibly. The next generation of immersive systems will not only display information; they will observe, adapt, infer, and intervene. My goal is to ensure that these systems are technically strong, human-centered, privacy-aware, and useful in domains where learning, trust, and decision quality matter. By building privacy-preserving XR telemetry systems and spatial AI methods, my research contributes a focused agenda for the future of immersive computing: systems that help people learn, reason, train, and make decisions while respecting the sensitivity of embodied human data.

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