eXtended Cognition: Measuring, Modeling, and Modulating Perception in XR

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Abstract

The *extended mind* theory proposes a new perspective on human cognition by expanding it beyond organic, internal mechanisms to external systems that functionally integrate with the mind. With ongoing breakthroughs in immersive extended reality (XR) technologies engaging the full range of sensory and perceptual modalities, we now have an unprecedented opportunity to bring this theory into practice. To capitalize on XR's potential for realizing full brain–XR integration as *eXtended cognition*, this research introduces a three-pillar framework: measurement, modeling, and modulation of perception. My doctoral research is framed within the *ChronoPilot* project, which specifically investigates the modulation of time perception in XR. Within this framework, I have implemented two components: EEG-based *measurement* and XR-driven *modulation* of perceived time. The final phase of my work focuses on *modeling* time perception through deep learning applied to biosignals such as EEG and eye-tracking data. Together, these three components form the basis for an online loop in XR that modulates perception in real time, enabling extended cognition.

Index Terms: Extended cognition, extended reality, perception, biosignals, deep learning, time perception.

1 Introduction

The extended mind theory [2] attributes cognition to any external systems that functionally couple with the mind, such as notebooks, calculators, or digital devices, considering them integral parts of the cognitive process when they operate seamlessly with internal mental states. For example, when a person routinely uses a notebook to store information they cannot recall internally, the notebook becomes part of the overall cognitive system. In this case, the *human agent* and the *external system* are functionally integrated, forming a unified process of memory and reasoning.

Based on this view, extended reality (XR) is uniquely suited to enable the experience of extended cognition for several reasons. As XR technologies advance rapidly, we gain access to all sensory and perceptual modalities, allowing us to augment information flow or focus it selectively for directing attention within virtual environments. Secondly, our access to cognitive input channels is not only comprehensive but also customizable. This enables the selective amplification or suppression of specific modalities beyond the limits of natural experience (e.g., enhancing auditory cues over visual ones) to more efficiently meet the demands of a given setting. Finally, and most significantly, the immersive quality of XR blurs the boundaries between real and virtual environments, enabling a seamless and intuitive integration between mind and system.

Nevertheless, XR is more than merely a suitable platform for extended cognition. While the *extended mind* theory includes external systems as part of cognition, these systems are typically construed as epistemic tools whose integration depends on deliberate and sustained cognitive engagement by the human agent. However, in XR, real-time, fine-grained control over the environment enables the external system to initiate the engagement through the modulation of perception, even when the user is cognitively passive. This gives rise to a distributed form of agency that turns the system into an external *agent*. This, in turn, paves the way for delegating agency to various external entities, such as another person, a domain expert, an AI system, or even a collective mind.

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2 Background

Perception is a subjective and internally constructed experience that injects a personal narration of reality into cognition. For this reason, perception and its illusions across different modalities have long been intriguing subjects of scientific study. However, deliberately modulating perception to trigger specific cognitive processes or interpretations is a relatively new research trajectory.

With no dedicated sensory organ and a high plasticity under a wide range of internal and external influences, time perception has a greater subjectivity than other modalities, such as vision or hearing. Yet, distortions in time perception critically affect vital functions, ranging from speech recognition and motor control to higher cognitive processes such as decision making. ChronoPilot [1] is a pioneering project exploring time perception modulation in XR. Its goal is to utilize multiple sensory modalities, such as vision, audition, and haptics, within an XR platform to influence psychological states, in order to enhance well-being and facilitate collaboration.

My doctoral research builds on ChronoPilot's foundation by developing a pipeline for objective measurement, data-driven modeling, and XR-based modulation of time perception to establish a real-time loop for seamless integration between the brain and the virtual environment.

3 Research Approach

To translate the concept of extended cognition into a practical XR framework, I structured my research around three core components: the measurement, modeling, and modulation of perception.

Measurement. A basic requirement for such an XR framework is the ability to sense the user state. This state may be physical (e.g., posture and locomotion), physiological (e.g., heart rate and body temperature), or psychological (e.g., emotions and cognitive load). The first two types of user state can be quantitatively assessed using motion sensors and wearable biosensors. In contrast, the psychological state—such as perceptual experiences—is traditionally measured through self-report questionnaires, which are subjective, unreliable, and often inaccurate, but most importantly, incompatible with real-time feedback loops. Therefore, to integrate perception within a virtual environment, it must be mapped to one or more physiological signals that can be quantitatively sensed in real time. This mapping enables objective measurement, which in turn provides the basis for building data-driven models of perception.

Modeling. Data-driven modeling with deep learning translates sensed biosignals into perceptual states in real time. In this process, the most immediate issue is data scarcity for training models, due to the difficulties of collecting biosignals. To address this, deep

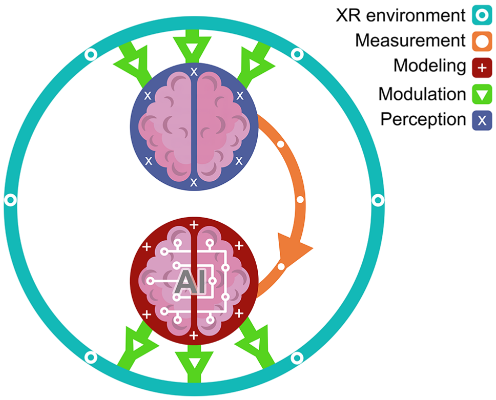

Figure 1: Schematic of the extended cognition loop in XR.

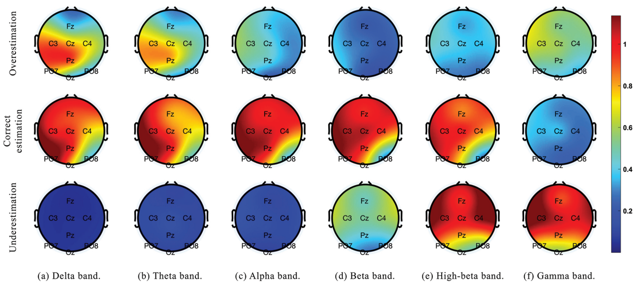

Figure 2: Brain activity in time perception states (adapted from [3]).

generative models can be used to synthesize additional samples and augment bio-datasets. However, unlike AI-generated visual or textual samples, whose plausibility can be evaluated intuitively, synthesized biosignal samples demand novel, expert-driven validation methods.

Modulation. This component transforms a basic adaptive XR environment into an *external agent*. With knowledge of the user's perceptual state and based on expert-defined prescriptions, the external agent adjusts the environment to influence the human agent's perception and elicit a desired cognitive state.

4 Progress and Results

Measurement. For an objective measure of time perception, we investigated electroencephalography (EEG) as the intermediate biosignal, selected for its affordability, portability, and high temporal resolution. We developed a dataset of 1,386 EEG recordings across eight channels. Each sample was collected while participants were exposed to time perception modulation in different modalities and performed a timing task [3]. Samples were sorted based on participants' performance on the timing task into three groups: overestimation, correct estimation, and underestimation. After processing the EEG signals with different analysis methods, we observed a clear mapping between brain activity pattern and the perception of time (Fig. 2).

Modulation. Numerous recent studies have tested traditional time perception modulators in virtual environments, showing that they influence our sense of time similarly across virtual and physical environments [4]. However, the effect of XR-native features such as embodiment on time perception remains understudied. To take advantage of XR's potential as a toolbox of time perception modulators, we conducted a study to test the effects of user engagement and environmental dynamics.

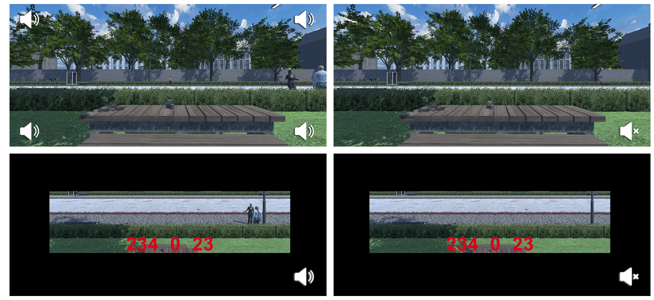

Figure 3: Four conditions, formed by permuting two features: user engagement and environmental dynamics (adapted from [4]).

The study's findings indicate that users who are actively engaged in the virtual environment tend to experience time compression, whereas passive observers in dynamic environments report a sense of time expansion.

5 Future Work

Modeling. Using two studies [3, 4], we created two datasets of biosignals, including EEG and eye-tracking. The signals were recorded over varying durations, ranging from two to 70 seconds, and labeled with duration estimation error. While fundamental signal processing analyses established EEG as a reliable metric for time perception, the next step is to apply deep learning techniques to develop classification and regression models that predict perceived duration in real time.

Furthermore, we have collected eye-tracking data and a range of other biosignals, including heart rate and skin conductivity. These can be further explored to augment EEG-based measurement, identify complementary markers for time perception, and support the development of more accurate and stable predictive models.

6 Conclusion

Advances in XR technologies and data-driven modeling have made the concept of extended cognition an achievable goal. My research contributes to realizing this vision by structuring around the measurement, modeling, and modulation of perception within an XR framework. At this stage, we have successfully defined an objective measure of time perception, modulated it in virtual reality, and created biosignal datasets to support the development of predictive models as the next step.

Acknowledgments

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