Beyond Entertainment:
Academic Approaches to Gamedev Industry
ISBN 978-83-969444-4-3, AVANT Anthologies

Embodied Pixels: A Neuroscientific Framework for Cognitive Research using Games

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Received 2025-06-09; accepted 2025-12-18; published Online First 2025-12-30.

Abstract

Purpose: Traditional cognitive tasks isolate cognitive parameters but miss how cognition naturally operates. I argue that games can be used to study cognition as it unfolds in ecological settings. **Methodology:** Drawing from predictive coding and embodied cognition, I show that the very embodiment in the brain also works with tools and virtual tools. An avatar in a game is treated by the brain as a body part, such as a hand. Given this insight, I derive five design principles for games to reinstate ecological settings in virtual worlds: autonomous goal pursuit, embodied avatar control, consistent rules, continuous temporal flow, and complex environments. **Results**: Commercial games unintentionally include classic cognitive paradigms: racing games demand continuous visuomotor control that can't be accomplished through discrete trials; FIFA leverages executive functions beyond traditional working memory assessments. **Main Contribution:** Given findings of body schema and peripersonal spaces, and embodied mind and predictive coding frameworks, I provide methodological guidance for behavioural, physiological, and neural measurements during gameplay, offering researchers tools to assess cognition while preserving experimental rigour. **Practical Implications:** Beyond novel experimental designs that allow for the exploration of unaddressed neural processes, adopting ecological games has the potential to aid neurodegenerative and neurodiverse conditions.

Keywords: predictive coding, embodied cognition, reinforcement learning, ecological validity, avatar embodiment

1. Introduction

A person sits quietly in a laboratory, pressing buttons as they watch colourful shapes move on the screen. Nearby, someone else is immersed in exploring a virtual world, making quick decisions, managing resources, and tweaking their strategies as they go. Both situations can measure executive function, yet they involve very different brain processes. The former is a discrete task, such as playing chess, whereas the latter is continuous, like driving. In chess, the entire system is known at a given moment, and the next moment depends solely on the current state. When driving, the ongoing dynamics are continuous, as a person navigates the trajectory of the car that depends on the previous state of the system, giving inertia to the car (Kingstone et al., 2008). The former can be tested easily and is widely used in cognitive science; the latter is difficult (Shamay-Tsoory & Mendelsohn, 2019). In this article, I show how to use games for testing the second way in the laboratory.

The field keeps stumbling forward with gaming research (Anguera et al., 2013; Kühn et al., 2014; Pallavicini et al., 2018), and some researchers look for virtual reality applications in research and diagnosis (Bohil et al., 2011; Parsons, 2015). However, these attempts are made without a sufficient theoretical backbone that would guide a standardised way of designing the games. Researchers select design elements based on intuition or by copying what has worked before. This lack of theoretical understanding limits the ability to predict which interventions might succeed or understand why they work.

I propose a framework grounded in neuroscience, drawing on predictive coding (Clark, 2013; Friston, 2010), and embodied cognition (Maravita & Iriki, 2004; Varela et al., 2017). The key findings are that a primate's body schema computed by the brain can be extended with tools and can be projected on a computer screen (Bassolino et al., 2010; Maravita & Iriki, 2004; Serino, 2019). This means that impractical virtual reality games could be an overkill relative to the video games presented on a computer screen. If the neural mechanisms are in fact there, as the evidence suggests, then we should use computer games broadly with all the possible measuring equipment.

To set a waypoint for future studies, I articulate five design principles that emerge from understanding how brains process embodied experience. Rather than claiming superiority over other approaches, I offer one theoretically motivated pathway among many possible routes to ecological validity. These are broad recommendations on what to watch for when designing games with research or clinical applications.

I highlight classical cognitive protocols and provide examples of games embodying these paradigms in continuous environments grounded in well-learned rules. I also review the methodological toolbox for cognitive research with gam-

es (Section 4), highlighting behavioural and neural imaging tools, their potential applications, and challenges with integrating the signal in environments constructed according to the previously outlined five principles.

2. Literature review

2.1. The embodied brain in action

The brain is a prediction machine constantly generating expectations about the future information (Bubic et al., 2010; Clark, 2013; Friston, 2010). Neural circuits anticipate incoming flow, compare these predictions against the expectations and update them when surprised by prediction errors. The details of the neuroscientific and philosophical understanding of how the brain adjusts computations are intensively debated. Some argue that the brain is ecological-enactive (Bruineberg et al., 2018), others defend the position that it is mainly representational (Constant et al., 2021). Here, I incorporate the idea about predicting future information and analyse how the brain predicts the position of the body.

Recognition that the body is essential for cognitive processes has been articulated as an extended mind thesis in the late 90s (Clark & Chalmers, 1998). We use external artefacts as a means to extend the mind by shaping decisions and metaphors (Chemero, 2009; Wilson, 2002). However, this embodied cognition isn't only philosophical speculation. The brain predicting the position of the body relies on continuous streams of information, navigating multiple trajectories at once (Adams et al., 2013; Chiel et al., 2009; Cisek, 2007). I demonstrate how it is measurable in neural architecture, based on experiments involving body and space computation in the brain.

The brain's map of the visual space near the body is called peripersonal space (Serino, 2019). Objects near hands, arms, trunk, head, eyes, or body are coded by the brain in a privileged way. This visual space around body parts is attached to them and allows for grasping and defensive actions (Bufacchi & Iannetti, 2018; Canzoneri et al., 2012; Di Pellegrino & Làdavas, 2015). For example, Maravita & Iriki's (2004) rake-using monkeys remain the canonical demonstration of the plasticity of peripersonal space. Monkeys trained in rake use extend the peripersonal space from around the hand to the rake tip. The tool becomes part of the body schema.

Crucially, this worked even when the monkey's hand was displayed on the computer screen (Maravita & Iriki, 2004). The findings have been replicated in humans using virtual tools. Consistent visual feedback from cursor movements, robotic arms, or game avatars triggers the same incorporation (Bassolino et al., 2010; Holmes, 2012; Serino, 2019). Pixels become extensions of self, measurable in neural activation, reaction times, and behavioural responses (Kilteni et al., 2012). Virtual embodiment isn't cyber-fantasy. It's neurologically real.

These neuroscientific observations show that computer games can be neurobiologically immersive and, hence, can be used in cognitive science experiments. Surprisingly, this has been rarely done. The majority of experiments used in the laboratory are discrete tasks akin to slideshows (Dolan & Dayan, 2013; Janacsek et al., 2020; Keele et al., 2003). On the one hand, it is understandable as the sterile experimental paradigms allow for clear data collection and analysis. On the other hand, however, real life is continuous. I argue that to understand the brain in its natural context, we must be brave in implementing paradigms that resemble these conditions. In the next section, I present guidelines on how to use computer games as such measures.

3. Theoretical framework

3.1. Defining ecological validity through the five principles

What makes a cognitive task ecologically valid? How to capture the real-life conditions? I understand that real life is pursuing meaningful goals within continuous, consistent environments. Actions and their consequences are bound during classical and instrumental conditioning through midbrain dopaminergic circuits tracking rewards and punishments (Beier et al., 2015; Schultz, 2017). This ancient system drives behavioural adaptation across species (Loonen & Ivanova, 2015), from worms to humans.

Games have cracked the code on these circuits. Achievements and progression systems all hijack dopaminergic learning, but that's not the real story (Koepp et al., 1998). Players experiment, fail, adapt, and improve through exactly the iterative process reinforcement learning evolved to support (Howard-Jones et al., 2016). Below, I propose five principles that are, in my opinion, needed for the ecological validity of a game:

1. **Autonomous Goal Pursuit:** Players need to pursue goals with their own paths by engaging in self-determination (Ryan et al., 2006). Brain dopaminergic circuits activate when exercising genuine choice, transforming mundane tasks into an intrinsically rewarding experience (Przybylski et al., 2010). Each crossroads decision (sneak through shadows or charge directly? Gather resources or race against time?) sparks cascading neural activity. This transformation from puppet to puppeteer activates the brain networks deeply rooted in our evolution when one has agency over the direction that is pursued.
2. **Embodied Avatar Control:** The other factor is agency over the game's avatar or a perspective in the case of first-person games. As the example with the body schema and peripersonal spaces shown, avatars on the computer screen transcend external object status to become genuine body schema extensions through consistent sensorimotor correspondence and immediate feedback (Bassolino et al., 2010; Maravi-

ta & Iriki, 2004). This embodiment operates regardless of perspective or avatar visibility; whether controlling humanoid characters, piloting spacecraft, or experiencing worlds through implied first-person presence, systematic **intention-action-consequence** mapping matters most (Gonzalez-Franco & Peck, 2018; Kilteni et al., 2012). Predictive coding mechanisms generate sensory consequence predictions that strengthen the avatar's neural representation (Apps & Tsakiris, 2014; Seth, 2013). A player interacts through the embodied avatar as if this virtual perspective were his own.

3. **Consistent Rules:** The intentions-actions-consequences mapping requires learnable patterns for world model construction, making consistent rules essential regardless of realism or complexity (Friston, 2010; Rao & Ballard, 1999). When mechanics follow reliable patterns (realistic physics or fantastical magic), players form hypotheses and test strategies, experiencing dopamine-mediated prediction success rewards (Schultz, 2017). Predictability paradoxically enables creativity; internalising rules allows novel combinations, discovering emergent solutions, which engage prefrontal and striatal circuits supporting real-world problem-solving (Botvinick et al., 2019). Keys lie in consistency, not realism: fireballs always damage enemies, and momentum or icy tires predictably affect driving. These relationships create generative models allowing mental outcome simulation before acting (Clark, 2013).

4. **Continuous Temporal Flow:** In contrast to discrete tasks akin to chess puzzles, real cognition unfolds as unbroken perception-action streams. The continuous temporal flow principle is crucial for maintaining the embodiment in the game (Csikszentmihalyi, 1990). Flow emerges when players remain cognitively engaged across transitions, preserving the activity of attention and control networks (Klasen et al., 2012; Ulrich et al., 2016). The continuous ongoing flow is crucial for ecological validity as the everyday experience consists of continuous episodes (Ben-Yakov & Henson, 2018).

5. **Complex Environments:** The final principle is scalable as environmental complexity operates spectrally: minimalist Tetris to sprawling open worlds, each engaging different cognitive architecture aspects (Gee, 2003; Wasserman & Banks, 2017). Complex environments simultaneously activate multiple networks (Mathiak & Weber, 2006), revealing cognitive system coordination under realistic information demands (Pallavicini et al., 2018). Yet simpler environments enable deeper focus on specific operations like spatial reasoning or pattern recognition (Li et al., 2016). Researchers should match complexity to research questions; focused attention benefits from minimal environments while cognitive flexibility leverages dynamic worlds.

These principles synergise into the definition of ecological context. The task is ecologically valid when a participant controls an **embodied avatar** within **continuous**, **complex environments** with **consistent rules,** while **pursuing goals autonomously**. These conditions create cognitive engagement that mirrors real-world complexity while maintaining experimental rigour.

3.2. Classical tasks in ecological environments

The five principles serve as both a lens and a compass: they reveal the sophisticated cognitive experiments already hidden within existing games. Researchers can reuse games refined through decades of player engagement to run cognitive tests. Games that survived the brutal selection pressure of the marketplace often did so because they successfully tapped into fundamental cognitive operations. The outlined principles help to recognise these accidental experiments and understand why they work.

Consider how classic games unknowingly recreated textbook cognitive paradigms (Table 1). Pac-Man's power pellet mechanic brilliantly implements the Stroop effect: players must override their deeply learned "flee from ghosts" response to suddenly chase them, creating cognitive conflict under intense time pressure. While Pac-Man has attracted significant research attention, it has primarily been a testbed for artificial intelligence and reinforcement learning algorithms (Bom et al., 2013; Schrum & Miikkulainen, 2016). Next, the Serial Reaction Time Task can be implemented in Mike Tyson's Punch-Out!!, as players unconsciously learn each opponent's attack patterns, decreasing the response time with practice. Alternatively, games in the sport, and music genres offer fantastic measures of the automatisation of sensorimotor sequences. Furthermore, studying players who are exceptional in classic games can reveal mechanisms behind automated navigation through the game's environment. The degree of variation in games remains predictable enough to enable model building yet variable enough to prevent habituation (Gee, 2003). These environments maintain sustained engagement of predictive circuits that standard tasks only briefly activate.

Traditional Task	Original Task Description	Core Cognitive Function	Classic Game Implementation	Why It Works?
Stroop Task	Name the color of ink while ignoring the written color word (e.g., "RED" printed in blue ink)	Inhibitory control, conflict resolution	**Pac-Man (Power Pellet sequences)**: When eating a power pellet, ghosts turn blue and player must override	Reversal of learned contingencies. Time pressure from pellet duration. Clear visual conflict between threat and target.

			the learned "flee" response to chase them instead.	
Serial Reaction Time	Respond to stimuli appearing in repeating sequences.	Implicit learning, procedural memory	**Mike Tyson's Punch-Out!! (opponent patterns)**: Each boxer has specific attack sequences; players learn patterns and respond faster with practice.	Hidden sequential patterns in opponent behavior. Measurable speed improvement with exposure.
Task Switching	Alternate between two different tasks (e.g., odd/even vs. high/low number judgments)	Executive control, set shifting	**Super Mario Bros (pipe/water transitions)**: Switch between land controls (running/jumping) and water controls (swimming/floating) when entering pipes.	Distinct control schemes require set shifting signalled by environmental cues. Switching costs evident in player errors.
Go/No-Go Task	Press button for certain stimuli (Go), withhold response for others (No-Go)	Response inhibition	**Duck Hunt (Don't Shoot the Dog)**: Shoot flying ducks but must not shoot the dog who retrieves them.	Clear go/no-go distinction. Response inhibition under time pressure. Natural consequences for inhibition failure.

Table 1. Classical Tasks in Ecological Environments. Examples of existing games that implement the same mechanics as cognitive tests.

Besides the replications of the classical games listed in the table, at least two areas worth intensive studies emerge. One area covers racing games. They provide unparalleled windows into continuous visuomotor control, particularly for controlling car trajectories in different conditions and inputs. These studies are already being conducted. Some lines of research use virtual driving simulators like Autobahnraser II (Walter et al., 2001) and Need for Speed II (Calhoun et al., 2002), demonstrating how racing games can be used in cognitive studies. Some simulators using immersive physical rigs inside the fMRI scanner allow measuring brain activity of the players (Choi et al., 2017; Chung et al., 2014; Kan et al., 2013; Schweizer et al., 2013). This direction promises a wide array of applications in testing ecologically valid tasks.

A second promising direction involves games like FIFA, which add an interpersonal component to sensorimotor coordination. Recent research has shown that soccer players' tactical decision-making under time pressure engages working memory capacity across all expertise levels, with professional players demonstrating superior performance but still showing sensitivity to cognitive

load (Glavaš et al., 2023). The possibility of simultaneous recording of competing and/or cooperating players opens a totally novel window to observe the mutual predictive dynamics of the brains in ecological settings.

The profound implication for researchers is that ecological validity and experimental control need not be enemies. Traditional cognitive paradigms are like testing a supercomputer's capabilities using only a calculator app: you can verify basic arithmetic, but you miss a lot. The human brain evolved to navigate dynamic environments, not pressing buttons in response to colored shapes. With games, we are finally giving the supercomputer problems worthy of its architecture.

4. Methodological toolbox for cognitive research with games

Implementing ecologically valid gaming research requires specialised measurement approaches. Here, I outline key methodological tools for capturing behavioural and neural signatures during continuous gameplay.

4.1. Behavioural and physiological measures

Eye tracking is one of the simplest behavioural measures, allowing for the collection of rich data on eye movements and pupil dilation. Pupil diameter is a reliable indicator of mental effort and task difficulty (Beatty & Lucero-Wagoner, 2000; Klingner et al., 2008; Van der Wel & Van Steenbergen, 2018). Eye trackers can automatically provide hundreds of pupil size measurements per second (Chen & Epps, 2014), while pupil diameter changes and microsaccade patterns effectively discriminate cognitive load levels (Duchowski et al., 2018; Krejtz et al., 2018). This measure is extensively used in racing simulators with a great amount of data on occulomotor coordination already being collected (Lappi, 2016, 2022).

Game telemetry provides unprecedented access to player behaviour with millisecond-precision recordings of all commands issued in games (Thompson et al., 2013). This approach enables analyses of motor chunking, action latencies, and complex cognitive-motor skill learning impossible with traditional tasks (Thompson et al., 2017). Large-scale telemetry datasets, sometimes including thousands of players across multiple skill levels, offer unique insights into expertise development and behavioural patterns (Thompson et al., 2014). Recent advances show that telemetry from racing simulators can be leveraged with machine learning to predict driving performance and distinguish fast from slow drivers based on the telemetric data (Hojaji et al., 2024). Game telemetry, combined with advances in artificial intelligence, enables the extraction of structure from large datasets in ecological tasks, thereby facilitating data analysis.

Motion capture of the participant's body parts provides information about the degrees of freedom that a body has and forces generated by the body (Di Domenico, 2020; Humphrey & Delange, 2004; Keogh & Hume, 2012). Research using Kinect sensors has demonstrated how gross body gestures can manipulate on-screen content while measuring learning gains (Johnson-Glenberg et al., 2014; Johnson-Glenberg & Megowan-Romanowicz, 2017). Modern biomechanical markerless systems allow natural movement tracking without the constraints of traditional markers, making them particularly suitable for gaming contexts where real-time transmission of natural human movement to virtual avatars enhances immersion (Lam et al., 2023; Wade et al., 2022). This approach enables the recording of players with ultra-sensitive cameras, collecting data to millisecond precision, and thus measuring the exact movements as they engage in ecological play.

Physiological measures complement behavioural data. For example, galvanic skin response (GSR) provides unfiltered insights into emotional arousal and stress levels through changes in skin conductivity (Affanni et al., 2018). GSR measurements are particularly effective when combined with other sensors, as they indicate arousal intensity but not valence (Sánchez-Reolid et al., 2022). Additional measures include heart rate variability (Mandrick et al., 2016) and synchronised event markers, ensuring millisecond-precision temporal alignment across all data streams (Whitford & Klimley, 2019). This stream of data provides an additional channel that can be used for enriching our understanding of the brain in the wild.

4.2. Neuroimaging approaches

EEG is the most common neuroimaging tool used in cognitive science research. It's cheap, easy to use and offers the possibility to measure electrical brain activity with millisecond temporal resolution, which is ideal for tracking rapid cognitive events during gameplay. Studies have captured increased cortical complexity and prefrontal activation patterns during gaming tasks (Amjad et al., 2019; Palaus et al., 2017). While portable and allowing natural postures, EEG requires careful artefact removal and provides limited spatial resolution compared to other neuroimaging methods.

fNIRS complements EEG as it is also portable, but allows for better spatial resolution by measuring cortical blood flow through wearable optical sensors. Research demonstrates fNIRS sensitivity to cognitive load and state, with activation scaling linearly with working memory demands (Fishburn et al., 2014; Pinti et al., 2020). This technology is particularly suited for sustained cognitive state monitoring during active gameplay and executive function assessment (Causse et al., 2017), though coverage is limited to cortical surface regions.

fMRI is the standard tool for measuring brain activity with excellent spatial but poor temporal resolution, albeit supine positioning and movement restrictions limit natural gameplay. Nevertheless, some laboratories modify the equipment to fit into the fMRI scanner (Choi et al., 2017; Chung et al., 2014; Kan et al., 2013; Schweizer et al., 2013). Note that these studies put a fully functional steering wheel with pedals into the scanner, projected the video through glasses and enabled participants to play the game while lying in the scanner. Now combine this with the progress in prospective motion correction using real-time tracking systems (Maziero et al., 2020). The technology is ready to test continuous tasks even in the fMRI scanner.

4.3. Integration challenges

The greatest challenge in cognitive research on ecological games with multimodal recordings is the amount of data from multiple sources. Time synchronisation between recording systems is essential, with modern solutions achieving median errors of 40ms between devices (Whitford & Klimley, 2019). Fortunately, progress in data management strategies handles the potentially massive datasets generated by continuous telemetry recording (Drachen et al., 2012). Close collaboration with game developers enables proper instrumentation while maintaining engaging gameplay (El-Nasr et al., 2016). The design of the experimental setup requires careful consideration of the game and the tools to be used, as well as a technical approach to collecting and analysing data.

This is a difficult task, as continuous paradigms provide an enormous amount of data amplified by the number of potential imaging methods. Despite this complexity, these integrated approaches offer a chance to reveal how cognition unfolds during naturalistic interaction. If our goal is to understand the brain as it works in natural conditions, the difficulty of the task should not limit our attempts.

5. Discussion

Obviously, this opportunity brings complexity. Traditional paradigms offer simplicity: one variable, one measure, clear causation. Gaming environments present rich data streams where multiple brain systems interact dynamically (Cardoso-Leite & Bavelier, 2014). A single racing game simultaneously engages visuomotor control, spatial prediction, risk assessment, and strategic planning. Disentangling these threads requires sophisticated analytical approaches that require interdisciplinary teams (Yannakakis & Togelius, 2018). The curse of ecological validity is its complexity (Holleman et al., 2020). The framework complements the traditional approaches, offering a path to study cognition as it naturally operates while maintaining scientific rigour (Washburn, 2003).

The framework also challenges the conception of experimental control as the systematic variation is unavoidable (Powers et al., 2013). Individual differences in gaming experience become valuable data about skill acquisition and transfer (Bediou et al., 2018). It's time to acknowledge that every person is different and investigate how these differences are distributed statistically. For example, varied participant expertise becomes a strength by modelling cognitive adaptation across expertise gradients (Colzato et al., 2013).

Consider the implications for clinical assessment. Traditional neuropsychological batteries feel artificial to patients, reducing compliance and ecological relevance (Burgess et al., 2006). Assessments with games could revolutionise diagnosis by embedding cognitive measurement within engaging experiences (Lumsden et al., 2016). Imagine detecting early Parkinson's through subtle changes in racing game performance (Garcia-Agundez et al., 2019), or monitoring ADHD medication effectiveness through sustained attention metrics in strategy games (Mishra et al., 2016). The ecological principles outlined in this article allow for immersive experience and potentially provide a tool for investigating the neurodegenerative and neurodiversive conditions as never before.

6. Conclusion

This paper began with a simple observation: cognitive science faces a persistent tension between experimental control and ecological validity. Understanding that the brain extends into its environment is philosophically grounded in the cognitive sciences. I pushed this further, recognising how *exactly* the brain processes the body and tools in areas of computing body schema and peripersonal spaces. This line of research shows that the extension takes place also when body/tools are displayed on the computer screen, creating the rationale for virtual extension encoded in the brain. For the brain, an avatar on the screen is as much part of the body as a real hand.

This observation justifies that games can be used as an ecological environment to study cognition as it appears in the real world. I conceptualise this further by providing five principles describing ecological tasks. **Autonomous goals**, achieved while controlling an **embodied avatar** within **continuous**, **complex** environments built upon **consistent rules**, are pinnacles for replicating real-life conditions in the laboratory.

Ecological games are challenging to implement due to the vast amount of data and potential tools required for their collection. But this should not prevent us from trying. Physicists embark on nearly impossible tasks to understand the nature of the universe. It's time for cognitive scientists to be brave and try to understand the human brain as it really is in everyday life. I believe that games are tools that finally make it possible.

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