Timing Game: A Conceptual and Methodological Framework for Temporal Processing Assessment in Digital Health

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Abstract. Introduction*: Deficits in temporal perception are sensitive transdiagnostic biomarkers for neurobiological conditions, including Parkinson's disease, ADHD, and Autism Spectrum Disorder. However, objective assessment of these deficits is currently confined to specialized laboratory settings, thereby limiting their scalable clinical application.* ***Objective****: To address this translational gap, this paper proposes a conceptual and methodological framework for applying the Timing Game, a previously developed mobile serious game platform that implements nine established psychophysical temporal paradigms as accessible behavioral assessments, as a potential digital phenotyping tool for clinical informatics.* ***Methodology****: The platform features a dual-mode architecture that balances scientific rigor with user engagement: (1) an Arcade Mode focused on Ecological Momentary Assessment (EMA) for high-precision psychophysical control, and (2) a Story Mode that integrates identical tasks within a cohesive time-travel narrative to enhance adherence in longitudinal protocols, a hypothesis to be empirically tested in future studies. Grounded in the Computational Phenotype Hypothesis, this work proposes that the platform's could produce high-granularity behavioral metrics, such as reaction time distributions and inter-response intervals, that could be use as scalable behavioral biomarkers and proxies for neural signatures of temporal processing errors relevant to clinical informatics and digital phenotyping.* ***Results****: This paper presents the application of the Timing Game within a digital phenotyping and clinical informatics framework, detailing its validation roadmap toward enabling scalable, ecologically valid temporal assessment for early detection and monitoring of neurobiological disorders.*

Keywords *Temporal Processing, Serious Games for Health, Ecological Momentary Assessment, Digital Health, Clinical Informatics, Digital Biomarkers.*

1. Introduction

Temporal processing, the ability to perceive and encode time intervals, is essential to cognition, supporting functions ranging from sensorimotor coordination to higher-order planning. While the clinical significance of temporal processing remains under investigation, deficits or distortions in temporal perception may be present across neurodevelopmental disorders, neurodegenerative conditions, attention disorders, and psychiatric diseases [Cravo et al. 2013].

However, despite its potential diagnostic relevance, objective assessment of temporal processing remains confined to controlled laboratory settings. Current protocols require specialized equipment, trained personnel, and 15–60 minutes per session. This creates a critical translational gap: while foundational neuroscience identifies the neural mechanisms underlying temporal coding, the practical integration of such knowledge into scalable clinical assessment remains unrealized [Fekonja et al. 2025]. To date, no standardized temporal assessment protocol has achieved consensus for routine diagnostic use.

Preliminary evidence links temporal processing abnormalities to multiple conditions. In Parkinson's Disease (PD), degeneration of basal ganglia circuits has been associated with altered "internal clock" mechanisms and negative asynchrony [Tokushige et al. 2018, Terao et al. 2021]. In Huntington's Disease (HD), progressive striatal degeneration produces marked impairments in interval timing, particularly in temporal bisection and discrimination [Lemoine et al. 2021, Agostino et al. 2017]. Children and adolescents with Attention Deficit Hyperactivity Disorder (ADHD) often show a faster subjective internal clock and impaired time reproduction, especially under dual-task conditions [Hwang-Gu e Gau 2015, Marx et al. 2017]. Autism Spectrum Disorder (ASD) has been linked to reduced precision in duration judgments and an enlarged temporal binding window [Chan et al. 2023, Falter et al. 2012], while in Tourette Syndrome (TS) timing task accuracy appears inversely related to tic severity [Martino et al. 2019].

These findings collectively indicate that temporal processing abnormalities span multiple conditions. However, a critical interpretive challenge remains: whether these deficits reflect true dissociations or merely sampling bias due to non-overlapping task batteries. This highlights the need for comprehensive, accessible assessment tools capable of profiling multiple temporal dimensions across diverse clinical populations. In this context, digital phenotyping, the moment-by-moment quantification of individual-level behavioral patterns using personal digital devices [Onnela e Rauch 2016], offers a promising framework for translating temporal processing assessments into scalable clinical informatics tools.

The present study leverages the Timing Game, a serious game platform previously developed for temporal perception research [Teixeira et al. 2025b, Teixeira et al. 2025a], to propose a theoretical and methodological framework for its application as a digital phenotyping instrument, outlining a roadmap for future empirical evaluation. The previous publications [Teixeira et al. 2025b, Teixeira et al. 2025a] focused on the design, development, and human–computer interaction evaluation of the Timing Game. The present manuscript adds three main contributions: (i) a clinical informatics and digital phenotyping framing of the platform; (ii) the formulation and elaboration of the Computational Phenotype Hypothesis linking temporal neural signatures to behavioral motor "echoes"; and (iii) a multi-phase validation roadmap toward clinical deployment. While the design and development of the Timing Game have been described in prior work focusing on human–computer interaction (HCI), this manuscript redirects the focus toward the platform's clinical informatics potential, specifically, its capacity to generate behavioral biomarkers of temporal processing that may inform digital phenotyping pipelines for neurobiological conditions.

2. Theoretical Foundations

Temporal processing has been modeled either as a centralized internal clock or as an emergent property of distributed neural dynamics. Pacemaker–accumulator frameworks, such as Scalar Expectancy Theory, posit that pulses are accumulated and compared against reference memories, yielding scalar variability in duration judgments [Buhusi e Meck 2005]. Conversely, "population clock" and state-dependent network models propose that time is encoded in evolving activity patterns across cortico-striatal, cerebellar, and cortical circuits [Merchant et al. 2013, Paton e Buonomano 2018]. Interval timing in the sub- and supra-second range recruits partially dissociable mechanisms, with the cerebellum more critical for duration-based timing of isolated intervals and basal ganglia circuits supporting beat- and rhythm-based timing [Grube et al. 2010, Breska e Ivry 2018].

This duality maps directly onto several Timing Game modules, which span single-interval discrimination (e.g., Duration Discrimination, Ready–Set–Go) and rhythm-based tasks (e.g., Isochrony Judgment, Rhythm-Induced Attention). Bayesian and predictive-processing accounts further emphasize temporal priors and contextual calibration [Jazayeri e Shadlen 2010], while transdiagnostic frameworks highlight convergent disturbances in duration processing, simultaneity and temporal order, and subjective time across conditions [Hinault et al. 2023, Kent et al. 2023]. Together, these perspectives motivate a multidimensional assessment of temporal computations that can be deployed beyond laboratory environments.

3. Related Work

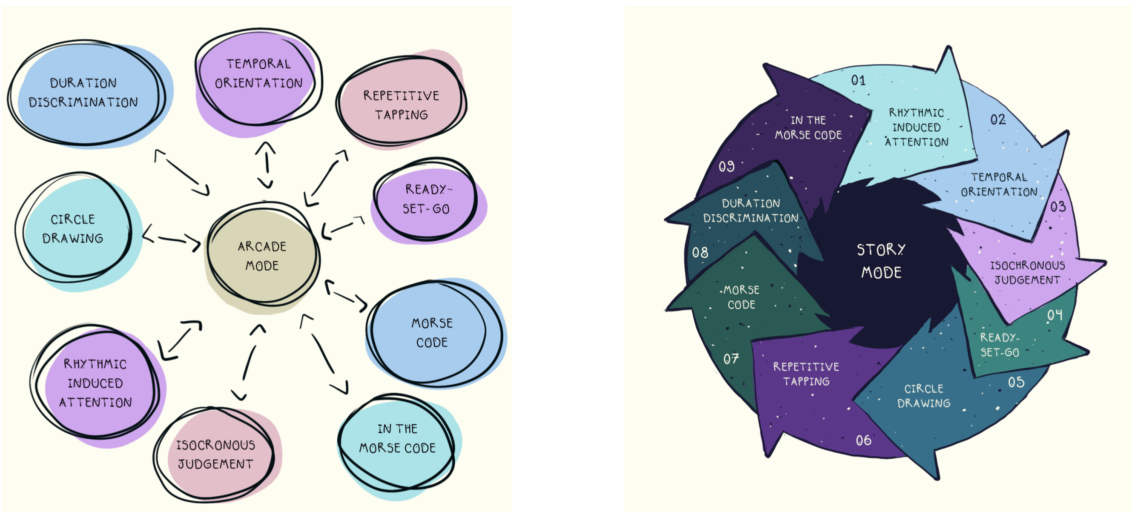
Laboratory studies have characterized timing abnormalities in specific neurological and psychiatric conditions using interval- and rhythm-based paradigms, showing that cerebellar and basal ganglia pathologies differentially impair duration-based and beat-based timing [Grube et al. 2010, Breska e Ivry 2018]. Review articles synthesize evidence for distributed timing networks spanning cortico-striatal, cerebellar, and cortical circuits [Merchant et al. 2013, Paton e Buonomano 2018], while recent taxonomies frame temporal processing as a transdiagnostic dimension that cuts across diagnostic categories [Hinault et al. 2023, Kent et al. 2023]. However, these studies typically rely on heterogeneous, non-gamified task batteries administered in controlled laboratory environments, with limited ecological validity and scalability.

A second strand involves smartphone-based EMA and digital phenotyping platforms that capture dynamic behavioral and affective data in daily life. EMA studies have shown that mobile apps can feasibly collect momentary reports of affect and stress multiple times per day, with acceptable adherence [Yang et al. 2018, de Vries et al. 2021]. Digital phenotyping extends these approaches to active and passive data streams, proposing "moment-by-moment quantification of the individual-level human phenotype in situ" as a scalable behavioral biomarker framework [Onnela e Rauch 2016], but most systems still rely on relatively coarse behavioral features and do not directly probe mechanistically interpretable temporal computations.

The third strand focuses on serious games and gamified interventions in health, rehabilitation, and professional education. Systematic reviews indicate that serious gaming and gamification can improve knowledge and, in some cases, skills and satisfaction among health professionals [Gentry et al. 2019], while meta-analyses in neurorehabilitation report moderate effect sizes for serious-game-based interventions after stroke [Doumas et al. 2021]. Additional work ranges from tangible-object-based rehabilitation systems [Pouplin et al. 2023] to mobile and VR games such as *Sea Hero Quest*, which has demonstrated ecological validity as a scalable spatial navigation biomarker [Coutrot et al. 2019], and sensor-controlled digital games for heart failure self-care [Radhakrishnan et al. 2022]. Despite this progress, few serious games target temporal processing itself, and even fewer integrate theory-driven psychophysical tasks within EMA-compatible, longitudinal designs.

4. The Timing Game: A Serious Game for Time Perception

The Timing Game is a serious game platform originally developed to support research on temporal perception by transforming traditional laboratory timing tasks into engaging, mobile-friendly minigames [Teixeira et al. 2025b, Teixeira et al. 2025a]. Implemented as a mobile-native application deployable on Android smartphones and tablets, the platform comprises two complementary operational modes, each supporting specific research use cases while maintaining identical underlying psychophysical structures and task parameters [Teixeira et al. 2025b, Teixeira et al. 2025a]. As the implementation and user interface details of the platform have been extensively reported elsewhere [Teixeira et al. 2025b, Teixeira et al. 2025a], we summarize here only the aspects most relevant to clinical informatics and digital phenotyping. At present, the platform targets Android devices only, which constrains its reach in populations where iOS is prevalent; a cross-platform deployment, including iOS, is part of our planned roadmap to strengthen scalability claims.



(a) Diagram of Arcade Mode (b) Diagram of Story Mode

Figura 1. Differences between Arcade and Story Mode

The *Arcade mode* — operationalized as Ecological Momentary Assessment (EMA) — foregrounds specific temporal tasks with concise, repeatable trials, prioritizing task purity and parametric control. In this mode, participants engage in isolated digital-biomarker tasks (60–180 seconds per task) that are standardized psychophysical procedures adapted from classical temporal-perception research, enabling systematic manipulation of temporal intervals, stimulus modalities, and response demands while maintaining minimal ecological burden. In this mode, users can select any of the 9 available tasks (Fig. 1a), returning to the menu after finishing it.

Conversely, the *Story mode* — operationalized as Narrative-Integrated Assessment — embeds these identical temporal processing tasks within a cohesive narrative context. Participants progress through a structured scenario in which they play a time-traveling scientist who created a time machine and is now trapped in intertemporal space, needing to overcome problems arising in the machine, where success requires accurate temporal judgments (Fig. 1b). The narrative framing, in which the time machine resembles a spaceship with episodic challenges (Fig. 2), is hypothesized to enhance perceived meaningfulness and reduce perceived burden, aiming to improve adherence to longitudinal sampling protocols to be tested in Phase II of the validation roadmap.

Task structure, stimulus parameters, cognitive demands, and logging routines remain identical across both modes, ensuring full comparability and scientific validity. This dual-mode design could be used to balance methodological control with ecological engagement, aligning with SBGames's health track, which focuses on serious games that simultaneously respect methodological rigor and user-centered design in health-related serious games. For the purposes of this study, the dual-mode architecture is particularly relevant as a digital phenotyping instrument, as it enables both controlled psychophysical assessment (Arcade mode) and ecologically valid longitudinal behavioral data collection (Story mode).

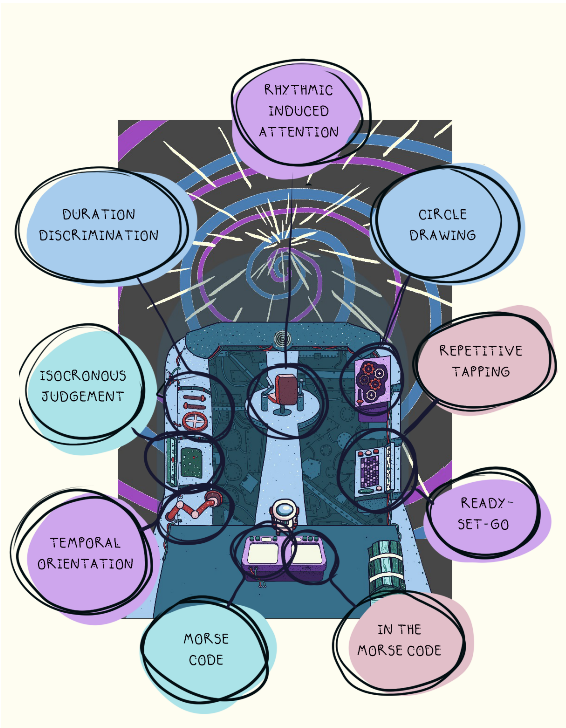


Figura 2. The Time Machine

4.1. Core mechanics and temporal processing skills

At its core, the Timing Game instantiates classical temporal perception paradigms as interactive mini-games that probe a range of temporal processing skills [Teixeira et al. 2025b, Teixeira et al. 2025a]. The platform implements nine core task modules:

- *Duration Discrimination*: participants compare a standard and a comparison interval adapted from Merchant [Merchant et al. 2008], assessing the ability to discriminate different durations.
- *Temporal Orientation*: based on Coull [Coull e Nobre 1998], central and peripheral cues direct attention to upcoming targets, probing temporal attention.
- *Repetitive Tapping*: participants synchronize taps with a pacing stimulus and continue after it stops [Merchant et al. 2008], evaluating sensorimotor synchronization.
- *Ready-Set-Go*: participants observe and reproduce intervals marked by flashes [Jazayeri e Shadlen 2010], measuring temporal accuracy and variability.
- *Morse Code* and *In The Morse Code*: reproduction and match-to-sample tasks based on Laje et al. [Laje et al. 2011] that probe learning and discrimination of temporal patterns.
- *Isochrony Judgement*: participants detect deviations within sequences of evenly spaced tones [Grube et al. 2010], indexing rhythmic processing.
- *Rhythm-Induced Attention*: visual targets appear on predictable or random schedules [Breska e Ivry 2018], testing the impact of temporal predictability on detection.
- *Circle Drawing*: circular movements paced by auditory cues [Zelaznik et al. 2002, Merchant et al. 2008] assess synchronization of motor actions with sensory stimuli.

4.2. Design rationale: ecological validity and engagement

Traditional timing tasks often involve monotonous, repetitive stimuli (e.g., tones, flashes, simple button presses) that can lead to fatigue and reduced adherence, especially in longitudinal studies [Paton e Buonomano 2018]. The Timing Game addresses this limitation by embedding tasks in an engaging 2D mobile game environment, with visually distinct mini-games, narrative progression, and game-like feedback elements that maintain user motivation without compromising psychophysical control [Teixeira et al. 2025b, Teixeira et al. 2025a].

The Story mode, in particular, frames temporal tasks as challenges within a time-travel narrative in which the participant serves as a time-traveling scientist piloting a time machine (resembling a spaceship) through intertemporal space. This narrative framing can be especially helpful for younger participants or individuals who might otherwise disengage from abstract laboratory tasks [Teixeira et al. 2025b].

From a translational health perspective, this dual-mode design could increase ecological validity in two ways. First, it approximates the cognitive demands and attentional fluctuations of everyday interactive media use, which is relevant for digital health interventions that aim to integrate into daily life. Second, by reducing perceived burden and enhancing intrinsic motivation, it is designed to support higher adherence in ecological momentary assessment protocols and decentralized clinical trials, where repeated measurements over extended periods are necessary.

5. From Neural Signatures to Behavioral Phenotypes: The Translational Bridge

Recent work by Niknam et al. [Niknam et al. 2025b, Niknam et al. 2025a] suggests that errors in time perception may produce detectable neural signatures, specifically, measurable distortions in cortical activity patterns that appear to correlate with perceptual timing errors in immersive virtual environments. These preliminary studies suggest a neurobiological basis for distortions in temporal processing. However, applying virtual reality coupled with neuroimaging for routine clinical assessment faces significant barriers: (1) prohibitively high costs, (2) limited accessibility outside laboratories, (3) technical complexity requiring specialized personnel, and (4) a fundamental lack of scalability for longitudinal population-level monitoring.

5.1. Conceptual Rationale: The Computational Phenotype Hypothesis

To overcome this barrier, the application of the Timing Game in this study is grounded in the *Computational Phenotype Hypothesis*. We posit that timing distortions identified by Niknam et al. [Niknam et al. 2025b, Niknam et al. 2025a] (via EEG) produce distinct, measurable echoes in behavioral motor outputs. Specifically, we propose that neural noise “leaks” into measurable behavioral domains, which the platform captures as high-granularity phenotypes:

1. **Reaction Time Distributions:** Beyond mean reaction time, we analyze the full statistical distribution (skewness, kurtosis, tail behavior) to proxy decision variability and neural temporal certainty.
2. **Inter-Response Timing Precision:** The coefficient of variation and autocorrelation structure of tapped intervals serve as markers for internal clock stability.
3. **Directional Production Biases:** Systematic underestimation or overestimation of target intervals indicates specific distortions in clock speed mechanisms.
4. **Motor Execution Dynamics:** Pressure curves and keystroke dwell times may reflect differential dysfunction in cerebellar vs. basal ganglia circuits.

By validating that these behavioral metrics correlate with the established EEG signatures [Niknam et al. 2025b, Niknam et al. 2025a], the goal is to provide a device-agnostic proxy for neural dysfunction. Within this framework, we can formulate specific, testable predictions for different clinical populations based on existing timing literature. Although this remains a hypothesis until empirically tested, it renders the Computational Phenotype framework falsifiable by tying qualitative neural differences to quantitative behavioral metrics. This approach removes laboratory barriers, specialized equipment and controlled environments, democratizing access to neuroscience-informed temporal assessment and, in the future, enabling decentralized clinical trials on commodity smartphones.

6. Validation Roadmap and Future Directions

To bridge software architecture and clinical utility, we propose a multi-phase validation protocol. Phases 0–II address short- to medium-term objectives; Phases III–V outline a multi-year research program.

All phases involving human participants will be conducted only after approval by the local Research Ethics Committee (Comitê de Ética em Pesquisa – CEP) and will follow the Declaration of Helsinki. Informed consent will be obtained from every participant (or legal guardians, when applicable), and data will be anonymized prior to analysis.

6.1. Short-Term: Technical and Clinical Validation

Phase 0: Technical Precision Verification (ongoing). Android devices show heterogeneous input latencies, so an embedded *Hardware Latency Benchmark* will estimate audiovisual latency and variability on first launch and compute a device-specific Clinical Readiness Score [Roussel et al. 2025]. Devices with high or unstable latency will be excluded from primary endpoints in timing-sensitive tasks (e.g., Duration Discrimination, Isochrony Judgment), while more tolerant tasks (e.g., Ready–Set–Go, Circle Drawing) may be analyzed with appropriate caution.

Phase I: Normative Data & Construct Validity. Healthy adults will perform the battery in a traditional laboratory setup and in the mobile app. Intraclass Correlation Coefficients will quantify agreement, with the expectation that duration discrimination and related measures show strong concordance between settings.

6.2. Phase II: Clinical Feasibility (Pilot)

ASD and ADHD participants will use both mode , Arcade and Story Mode, over several days (e.g., 3–7). Primary outcomes are retention after Day 1 and System Usability Scale scores; we hypothesize that the narrative framing will sustain engagement better than non-gamified tasks.

6.3. Long-Term: Multimodal Integration & AI

Phase III couples Timing Game metrics with portable EEG, peripheral biomarkers, and structural MRI to map temporal deficits onto neural and biological markers.

Phase IV develops machine learning models using high-dimensional temporal features (reaction-time distributions, inter-response intervals) to derive transdiagnostic clusters.

Phase V explores adaptive, closed-loop training for cognitive rehabilitation, testing whether improvements in temporal processing generalize to clinical outcomes such as functional status and quality of life.

7. Discussion

The Timing Game platform sits at the intersection of temporal neuroscience, digital phenotyping, and serious games. By operationalizing canonical timing paradigms as mobile mini-games, it translates constructs such as scalar variability, population clocks, and Bayesian calibration of temporal priors into high-throughput behavioral assessments deployable in everyday contexts [Merchant et al. 2013, Paton e Buonomano 2018, Jazayeri e Shadlen 2010].

Within this framework, the Computational Phenotype Hypothesis becomes empirically testable: if temporal distortions observed in EEG and virtual reality paradigms [Niknam et al. 2025b, Niknam et al. 2025a] have reliable behavioral echoes, they should emerge in reaction time distributions, interval reproductions, and motor dynamics harvested by the platform once appropriate validation studies are completed. This may help reframe digital phenotyping through a more mechanistic lens by grounding behavioral markers in explicit models of internal clocks, predictive coding, and distributed timing networks [Onnela e Rauch 2016, de Vries et al. 2021].

Several limitations constrain current conclusions. Empirical validation of the Computational Phenotype Hypothesis and of task equivalence between mobile and laboratory implementations is still pending, EMA deployments must address adherence and missingness [de Vries et al. 2021, Onnela e Rauch 2016], and smartphone-based timing assessments remain vulnerable to hardware and operating-system-dependent latencies. These constraints motivate the validation roadmap outlined above, including norming across demographics and multimodal studies that integrate Timing Game metrics with passive sensing, physiological indices, and neural measures, as well as future work on closed-loop training and rehabilitation.

8. Conclusion

This work presented the application of the *Timing Game*, a serious game platform previously developed for temporal perception research, within a digital phenotyping and clinical informatics framework and proposes a validation roadmap for it. By leveraging its translation of established psychophysical paradigms into a mobile-native environment, the study addresses the critical translational gap between controlled-laboratory neuroscience and scalable clinical applications for digital phenotyping of neurobiological conditions.

The platform's dual-mode architecture balances the strict parametric control required for Ecological Momentary Assessment (Arcade Mode) with the narrative engagement necessary for longitudinal adherence (Story Mode), making it suitable for sustained digital phenotyping protocols. This design offers a potential solution to the historic trade-off between scientific rigor and user retention in clinical informatics applications, a proposition that will be empirically evaluated in the planned clinical feasibility phase.

As outlined in the proposed validation protocol, the immediate next steps are to verify hardware latency and establish normative data. Subsequent phases will aim to validate the *Computational Phenotype Hypothesis*, determining the extent to which mobile behavioral metrics can serve as proxies for the neural signatures of temporal error documented in literature [Niknam et al. 2025b].

Ultimately, applying the Timing Game as a digital phenotyping tool represents a step toward high-frequency neurocognitive monitoring within clinical informatics. In an era of increasing digitalization of healthcare, assessing temporal processing with gamified, accessible tools offers a scalable approach to generating behavioral biomarkers for early detection and personalized monitoring of neurobiological disorders, provided that the hypothesized relationships between temporal phenotypes, neural signatures, and clinical outcomes are rigorously validated in future empirical studies.

AI Assistance

In compliance with scientific integrity guidelines, the authors declare the use of Grammarly Pro and Google Gemini during the preparation of this manuscript. These AI tools were employed exclusively to assist with language refinement and LaTeX formatting. The authors reviewed, edited, and validated all AI-generated text and assume full responsibility for the accuracy, originality, and final content of this publication.

Funding

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001 and Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq (proc. nº 302259/2026-0, JPG). This work was also funded by the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), grant no. 2026/01540-9, linked to the project "Instituto Nacional de Ciência e Tecnologia sobre Comportamento, Cognição e Ensino: Ciências comportamentais aplicadas à função simbólica - implicações para a equidade e a inclusão social - INCT-ECCE".

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