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Virtual body ownership affects the processing of sensorimotor contingencies and goal-oriented information extraction, but not semantics

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ABSTRACT

Previous research has attempted to quantify presence in virtual environments using event-related potentials (ERPs). We contend, however, that previous efforts have fallen short of fully realizing this goal, failing to either (A) independently manipulate presence, (B) validate their measure of presence against traditional techniques, (C) adequately separate the constructs of presence and attention, and/or (D) implement a realistic and immersive environment and task. We address these shortcomings in an ERP experiment in which participants play an engaging target shooting game in virtual reality (VR). ERPs are time-locked to the release of a ball from a sling. We induce breaks in presence (BIPs) by freezing the ball's release on a minority of trials. Embodiment is manipulated by allowing manual manipulation of the sling with a realistic avatar in one condition (embodied condition) and passive manipulation with only controllers in another (non-embodied condition). We find, in line with our preregistered predictions, that the N2, the P3b, and the N400 are selectively sensitive towards embodied BIPs, information extraction, and BIPs regardless of embodiment, respectively. The pattern of findings carries significant implications for theories of presence, which have been seldom addressed in previous ERP investigations on this topic.

1. Introduction

Virtual reality (VR) often compels users to respond physiologically and consciously as if virtual events were real, otherwise known as the experience of being present. However, presence, the subjective sense of "being there" in a virtual environment, is notoriously difficult to measure. Electroencephalography (EEG) may offer a promising, unobtrusive means of assessing a user's momentary state of presence. Unlike traditional questionnaires, EEG does not interrupt the experience or rely on users' retrospective self-reports, thereby avoiding interference with the very state it aims to capture.

The experience of presence is thought to arise from two distinct illusions: Place Illusion (PI), the feeling of being located inside the virtual environment, and Plausibility Illusion (PsI), the feeling that the depicted events are actually occurring. Despite compelling theoretical accounts that PI is driven by bottom-up sensorimotor contingencies (SMCs) and PsI by top-down environmental "coherence," the field lacks moment-to-moment neural evidence to index and begin to dissociate these illusions. Standard post-experience questionnaires are too coarse and miss the transient "breaks in presence" (BIPs) that occur when either illusion collapses.

In this report, we asked whether specific event-related potentials (ERPs) could be used to identify PI-related and PsI-related processing during controlled BIPs in an immersive VR task. Our intention was not yet to directly separate PI and PsI, but to investigate whether particular ERPs are sensitive to different, known aspects of presence in a realistic and immersive setting while simultaneously utilizing a design that does not measure presence through attention.

To accomplish this task, we designed a VR slingshot game in which brief freezes of the virtual hand and/or slingshot were used to elicit BIPs under two conditions: with and without motion-based interactions and a tracked first-person virtual body. Analyzing event-related activity in the EEG signal, we focused on several established ERP components which we expected to capture distinct perceptual and cognitive aspects related to embodiment, task completion, and semantics. The results are discussed within the context of existing theories of presence, especially PI and PsI and their assumed contributing factors, to advance the neural quantification of presence-based illusions.

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2. Related work

Although the exact definition of presence sometimes varies within the VR literature, one of the more commonly accepted models is Slater's view that presence consists of two orthogonal illusions called Place Illusion (PI) and Plausibility Illusion (PsI) (Slater, 2009; Slater et al., 2022). According to this model, PI is the illusion of being in another location, yet having the sure knowledge one is not (this sensation is sometimes referred to as *Spatial Presence* in VR literature; Skarbez et al. 2017a). PsI, on the other hand, is the illusion that events in the VR experience are actually happening, even while maintaining the sure knowledge that they are not. It is argued that these two illusions are orthogonal; for example, one can experience PsI without PI by watching TV (Baños et al., 2000; Skarbez et al., 2017a), or by mistaking a physical mannequin for a real person (Slater et al., 2010), and that the user responds realistically to VR events specifically when both of these illusions are taking place (Slater, 2009). Disentangling these illusions through empirical behavioral studies has proven to be nontrivial (Slater et al., 2022). However, if these illusions are truly orthogonal, we should be able to identify dissociable brain processes related to each. We propose that neuroimaging techniques, such as EEG, could help to overcome earlier limitations of behavioral studies in this respect.

Multiple cognitive and neuroscientific models of presence have been discussed by the VR community, however, the amount of empirical evidence backing each model is so far limited. Perhaps the most well-known model is the so-called Slater/Skarbez model according to which PI is driven by SMCs provided by the VR system whereas PsI is enabled by *coherence* — the extent to which the high-level content of the virtual environment matches the user's predictions (Skarbez et al., 2017a). Although not specifically mentioned in the original (Skarbez et al., 2017a) article, this division also suggests that PI would be more driven by earlier perceptual processes whereas PsI would be the result of later cognitive ones. Hofer et al. (2020) specifically suggested that PI is a bottom-up process whereas PsI is a top-down one; if this is true, then neural signatures related to these illusions could be potentially found in earlier, and later stages of cognition, respectively. Although the dual-nature approach for presence is well-known in the VR research community, it has attracted relatively little empirical investigation from neuroscience. One of the exceptions is the article of Gonzalez-Franco and Lanier (2017), which proposed and discussed model for VR illusions based on previous (behavioral and neuroscientific) studies. According to this model, VR illusions are sustained by the interplay of bottom-up multisensory processing, sensorimotor self-awareness frameworks, and top-down predictions, especially when the stimuli can be reconciled without semantic violations, i.e., moments when the user tries to interact with the environment, but that interaction is not supported. Another example is radical *body-semantic violations*, in which the VR user's body behaves in an unexpected manner (Padrao et al., 2016; Gonzalez-Franco and Lanier, 2017). Unlike the proposal of Hofer et al. in which PI is considered a bottom-up process whereas PsI is a top down one, the model of Gonzalez-Franco and Lanier (2017) suggests that violations of SMCs (i.e., factors that contribute to PI in the Slater/Skarbez model) result in semantic errors, implying that they are processed in the later stages of cognition.

In this article, we seek to provide a starting point for discussing theories from the VR community against neuroscientific empirical evidence. We chose to discuss our findings specifically against the Slater/Skarbez model due its relative simplicity, and it being perhaps the most well-accepted model in the VR community, with the original (Slater and Wilbur, 1997) article being one of the most cited works in the field. Furthermore, we discuss our results in light of whether violations of SMCs result in prediction errors more related to perceptual processing or semantics.

2.1. Designing for PI and PsI

Much of presence research is devoted to understanding which factors contribute to presence or alternatively break it. Although in colloquial speech, *immersion* has a role similar to presence in media experiences (e.g., *"I was immersed in the story throughout the book"* or *"the weird behavior of the characters broke my immersion in this video game"*), in the context of VR research, immersion usually refers to the set of hardware and software factors that contribute to presence (Skarbez et al., 2017a; Slater and Wilbur, 1997). Interestingly, the aesthetic quality of graphics appears to have little effect on presence. For example, an early study by Zimmons and Panter (2003) found that even an untextured black-and-white grid representation of a virtual pit elicited a fear response in participants, and increases in graphics fidelity elicited no measurable increases in those responses. According to Slater, immersion equates to the extent of the *sensorimotor contingencies* (SMCs) that the VR system can support (Slater, 2009; Slater et al., 2022).

The predictive coding framework (Clark, 2013; Friston, 2010; Rao and Ballard, 1999; Seth, 2013) can explain why SMCs and coherence matter for the presence experience from a neuroscientific perspective. According to hierarchical predictive coding, the brain constructs models that continuously predict the sensory consequences of (top-down) self-generated action and minimize (bottom-up) precision-weighted prediction error. Here, SMCs constitute the learned mappings between actions and their predicted sensory effects which reflect the same core principles emphasized in theories of embodied cognition, which view perception and action as inseparably grounded in the body's capabilities to interact with its environment (in other words, an *affordance*; Gibson 2014, Noë 2004).

When a VR system correctly supports these contingencies, such as when a motor command reliably produces the predicted reafferent input, low-level prediction error remains small, and PI is sustained. For example, head turns or hand movements yield congruent visual and haptic feedback. Conversely, a sudden mismatch, such as a tracked hand freezing in mid-air, constitutes a spike in prediction error that the system cannot immediately explain away, manifesting phenomenologically as a BIP. At higher levels of the hierarchy, causal, narrative, and social regularities are encoded, i.e., *coherence*. If virtual agents behave implausibly or objects violate physics, prediction errors arise at these levels, jeopardizing PsI. Guided by this framework, our study deliberately perturbed SMCs, briefly freezing the user-controlled hand or slingshot, to induce BIPs and examine how PI and PsI are affected by violations of predictions under different levels of embodiment. Designing VR to minimize prediction error at the intended levels therefore aligns with both SMC-based and predictive coding explanations of presence.

In the context of VR specifically, SMCs refer to the extent to which the VR system can render stimuli according to natural sensorimotor actions such as turning one's head, moving one's arms, and so on. More specifically, if the set of *valid actions*, which is the union of natural sensorimotor actions, matches the effectual actions supported by the VR experience (Slater, 2009), PI will be sustained. A break in SMCs occurs when the display of the VR system fails to support these actions. For example, such a break might occur when a CAVE user looks outside of the display coverage, or when a user pushes their hand into an obstacle, but the system does not respond with the appropriate tactile or visual feedback. According to a meta-analysis by Cummings and Bailenson (2016), immersion factors such as tracking quality and display properties (i.e., FOV, stereoscopy) contribute specifically towards spatial presence (i.e., PI) more than, for example, graphics or audio fidelity.

In their articles, Skarbez (Skarbez, 2016; Skarbez et al., 2017a, 2020) revisits Slater's model and argues that if immersion is the set of factors contributing towards PI, there must be a similar set of factors contributing towards PsI, as well. Skarbez suggests the concept of *coherence*, which refers to the extent the VR experience behaves in a reasonable or expected way. Immersion and coherence differ, however, in that while the immersion of a VR system can be defined in an objective manner, coherence cannot, as expectations are always subjective. Skarbez argues that it is useful nevertheless to treat coherence as if it was objective, that is, that the programmed contents of the VR experience are geared towards matching users' expectations in a given context. Both Slater and Skarbez point out that PsI is not dependent on objective realism, but rather on what can be expected in a particular scenario (Skarbez et al., 2017a; Slater et al., 2022).

In the VR literature, *sense of embodiment* (SoE) is considered an illusion related to, but distinct from presence (Kilteni et al., 2012). According to Kilteni et al. (2012), SoE consists of three components which can be manipulated using contemporary VR systems: a sense of body ownership (the body that I see belongs to me), a sense of agency (I am in control of this body), and a sense of self-location (a sense of one's location in relation to one's own body, not to be confused with PI). When a VR user is equipped with body-tracking and a virtual representation of a body viewed from a first-person perspective (1PP), a sense of body ownership towards the virtual body often emerges (Maselli and Slater, 2013; Kilteni et al., 2012). Furthermore, a sense of body ownership towards physical stationary mannequin bodies have been elicited by synchronized visuo-tactile stimuli (Van Der Hoort et al., 2011; Van Der Hoort and Ehrsson, 2016). Although SoE is considered an illusion of its own and not presence exactly, having a tracked 1PP virtual body appears to contribute towards presence as shown by decades of studies (Arora et al., 2022; Slater et al., 2010; Skarbez et al., 2017b; Slater and Usoh, 1993; Slater et al., 1995, 1998). According to some studies, a 1PP virtual body contributes towards both PI and PsI (specifically, Slater 2009, Slater et al. 2010, Skarbez et al. 2017b), even if this finding contradicts the claim that PI is a result of SMCs and PsI is a result of coherence factors. Possibly due to the strong relationship between SoE and presence, they are sometimes referenced in scientific literature interchangeably (e.g., Suzuki et al. 2023).

2.2. Measuring presence

Although presence is a phenomenon that can be easily understood once experienced, its empirical quantification has proven to be anything but straightforward. A common method in the past has been to utilize post-experiment questionnaires. These, however, pose multiple problems. Firstly, questionnaires force participants to reflect on their experience after the experience itself, when the actual illusion is already lost (Slater et al., 2022). It has been argued that querying an abstract, and relatively uncommon (in day-to-day life) sensation such as presence in a virtual world in this way could even plant the sensation in the head of the participant even when it did not exist in the first place (Slater, 2004). Furthermore, there are great differences in how questionnaires quantify presence; some questionnaires focus solely on PI as in *the sense of being there* (Slater et al., 1994; Usoh et al., 2000), whereas others include related factors such as *attention* and *engagement* (Vasconcelos-Raposo et al., 2016), and others still focus not on merely the sensation itself, but also include aspects of the VR experience that are assumed to affect presence (e.g., Witmer and Singer 1998). Because of these discrepancies, comparing results between studies is difficult, and some questionnaires might not even be suitable for certain types of experiences like those that require relatively little interactivity (Skarbez et al., 2017a; Slater et al., 2022; Kober and Neuper, 2012). Questionnaires have also been criticized for their lack of sensitivity, especially when comparing systems of wildly different immersion levels; for example, researchers were not able to find a statistically significant difference in presence between a VR experience and physical reality in a between-group experiment (Usoh et al., 2000; Slater, 2009). Although PI has been the focus of many presence questionnaires, there are no equally established questionnaires specifically targeting PsI. For Slater's PsI, past experiments have utilized study-specific questionnaires in which PsI is targeted by gauging whether participants physically or emotionally reacted to events of the VR experience as if they were real (e.g., Pan et al. 2016, Neyret et al. 2020). Other examples targeting plausibility-related aspects of VR experiences include the *reality judgment* questionnaire by Banos et al. and the questionnaire used by recent studies focusing specifically on the Latoschik & Wienrich model of presence (e.g., Brübach et al. 2022, 2024, Baños et al. 2000). Finally, the Multimodal Presence Scale (MPS) by Makransky et al. (2017) contains factors that partially overlap, but does not fully match with Slater's PI and PsI.

Breaks-in-presence (BIPs) relate to occurrences in which the participant becomes more aware of the surrounding physical reality instead of the VR experience (Skarbez et al., 2017a). Self-reported BIPs have been used to model the presence of VR users probabilistically through discrete time-steps (Slater and Steed, 2000) as well as a raw measure of presence (number of BIP occurrences correlating negatively with questionnaires; Brogni et al. 2003). Deliberate BIPs have also been utilized to experimentally manipulate presence for various research purposes, such as in order to investigate PI- and PsI-related aspects separately (Hofer et al., 2020; Brübach et al., 2022; Skarbez et al., 2020; Garau et al., 2008). Some studies have opted to utilize qualitative data instead of questionnaires. The studies of Garau et al. (2008) and Pouke et al. (2022) utilized thematic interviews to ask participants to describe their sense of presence and BIPs qualitatively, the latter also attempting to investigate PI and PsI separately. Furthermore, the studies of Beacco et al. (2021) and Slater et al. (2023) recruited participants to write about their experience in text and used sentiment analysis to investigate the results qualitatively. Finally, the so-called *metamer* approach has been used to manipulate and model aspects of the VR experience (i.e., immersion and coherence factors) probabilistically to investigate their contribution to PI and PsI (Slater et al., 2010; Bergström et al., 2017; Skarbez et al., 2017b).

2.3. Behavioral and biometric measures

Since presence is often understood as the participant responding to VR stimuli as if they were real (Sanchez-Vives and Slater, 2005; Slater, 2009), it is often suggested that visible behavioral reactions (e.g., participant trying to dodge virtual objects), and physiological signals (e.g., changes in heart rate or skin conductance) could be used to measure presence (Skarbez et al., 2017a). For example, Arora et al. (2022) found that when viewing a real-time 360° video experience through a head-mounted display (HMD), participants equipped with a tracked virtual body (and who considered the said body realistic enough) reacted to stimuli approaching the 360° camera more strongly than without the body. Heart rate has been used as a proxy for experienced fear of heights in a VR experience (Meehan et al., 2002) as well as a measure to identify BIPs (Garau et al., 2008; Skarbez et al., 2020). Skin conductance has been used to measure presence/body ownership (the terminology for these illusions sometimes appear interchangeably within VR literature) when causing an illusory threat to the virtual body (Slater et al., 2009; Suzuki et al., 2023).

The problem with the measures above is that they require specific and intense stimuli in order to be effective, whereas a VR user can experience strong presence even during mundane VR experiences that cause no measurable changes in visible behavior or stress-related physiological signals (Skarbez et al., 2017a). EEG offers a potential way to overcome these issues since it can also measure VR users' changes in cognition in real-time, while its sensitivity is not restricted to only overtly exciting or stress-inducing stimuli. Multiple studies have utilized the ERP technique with an auditory oddball paradigm based on the hypothesis that participants experiencing lower presence would allocate more attention toward the auditory stimuli compared to the VR experience (e.g., Kober and Neuper 2012, Grassini et al. 2021, Savalle et al. 2024). Although the results have been promising, many scholars argue that presence cannot be equated with attention, as one can experience a strong sense of being in a place while not paying any particular attention to one's surroundings (Skarbez et al., 2017a). Based on the results of these studies, attention might serve as a useful proxy for presence similar to how, for example, heart rate can target presence indirectly through fearful stimuli but does not directly measure the sensation itself. There are also promising measures of presence focusing on spectral EEG features (e.g., Kober et al. 2012, Clemente et al. 2014), or combinations of EEG and physiological measures (Ronca et al., 2025), though spectral measures lack the temporal precision of ERPs to track transient changes in presence, or to cleanly disambiguate earlier perceptual processes from later cognitive ones. Furthermore, similarly to physiological measures, changes in broad frequency bands often leave ambiguity in terms of their functional significance; for example, a change in alpha power could indicate changes in presence, or likewise, attention, creativity, and/or working memory, among other processes (Başar and Güntekin, 2012; Fink and Benedek, 2014).

2.4. ERPs in presence research

There are also ERP studies more directly targeting how contents of the experience itself cause changes in cognition. These studies commonly use some variation of BIPs and study their associated ERP signatures. The study of Gehrke et al. (2019) manipulated the timing congruency of feedback elicited when a participant was touching a virtual cube. They found that the amplitude of a negative going deflection around 200 ms after stimulus onset was modulated by the immersiveness of the feedback (visual only, haptic only, or visuo-haptic), which they dubbed the "prediction error negativity (PEN)." However, questionnaire results (IPQ; Vasconcelos-Raposo et al. 2016) indicated no significant differences in presence between the conditions (Gehrke et al., 2019). The study of Padrao et al. (2016) manipulated body ownership by embodying participants an 1PP tracked virtual body that mimicked their movements in real-time in one condition and performed pre-recorded movements on some trials in another condition. In both conditions, participants were engaged in an error-prone fast-reaction task while the system sometimes gave erroneous feedback to participants' responses. They found an early frontocentral negativity to be sensitive to true self-generated errors and a late parietal negativity to be sensitive to non self-generated errors (the virtual body hand performing an incorrect response on its own; Padrao et al. 2016). The study of Porssut et al. (2023) focused on breaks in embodiment, specifically, and manipulated body ownership on the trial-level by causing unexpected hand movements in a virtual tracked body. They found the error-related negativity (ERN), Pe and N400 components to be sensitive to the manipulation (Porssut et al., 2023). The recent study of Lehser et al. (2024) also targeted BIPs caused by visuo-tactile mismatches. Participants observed a virtual hand corresponding to their real hand, and were instructed to press a button whenever a paintbrush touched their index finger. On a subset of trials, the paint brush was visually depicted to touch one finger while it touched another in the real world. They found a positive component at 120 ms to be sensitive to the mismatches, and similar to studies by Porssut et al. (2023) and Padrao et al. (2016), an N400-like component as well, which was interpreted as a visuo-tactile correlate of the N400 commonly observed in response to semantic violations.

A common limitation of the aforementioned studies is that none of the experiments made strong attempts to simulate a meaningful experience, but opted, instead, for utilizing visually minimal settings with little resemblance to commercial VR experiences, VR experiences commonly used in presence studies, or the real world. For example, Gehrke et al. (2019) speculate that their inability to detect an effect using questionnaire-based measures in their study could have been caused by the minimalistic experience failing to elicit presence in the first place. Furthermore, implications for theories of presence have been only sparsely discussed in these studies.

In this paper, we present the results of our study investigating presence-related ERP signatures during a virtual arcade game experience. Our participants were given a task to achieve a high score in a slingshot game. They could perform the task embodied with a 1PP virtual body (embodied condition) or passively with game controllers and a static avatar (non-embodied condition). Although, strictly speaking, SoE (Kilteni et al., 2012) is considered an illusion distinct from presence, we chose *embodiment* as our block-level manipulation due to the well-known effect of embodiment increasing various behavioral and biometric measures of presence (Arora et al., 2022; Slater et al., 2010; Skarbez et al., 2017b; Slater and Usoh, 1993; Slater et al., 1995, 1998). 1PP virtual body and motion control input modality provided a way to manipulate SMCs with relatively few visual differences, which is necessary for ERP designs; this would have been more difficult by manipulating SMCs through display types (e.g., a 2D screen vs. a HMD.) Finally, by manipulating immersion through embodiment, we could replicate whether SMC violations are semantic in nature, as proposed by Gonzalez-Franco and Lanier (2017), or processed only in earlier stages of cognition.

On most trials, the ball would fly from the sling and obey the regular physics of the game engine (normal trials), whereas on a minority of trials, we elicited SMC-related BIPs by freezing the ball and virtual slingshot (and, in the embodied condition, the avatar's hand) used to play the game (BIP trials). These manipulations resulted in a two-by-two within-subjects design. Based on previous findings and our own pilot data (Nardi 2024; see also Supplement A), we focused on three main components in our preregistration: the N2, the P3b, and the N400.

2.5. Theoretical background of relevant ERPs

The family of early fronto-central negativities includes the mismatch negativity (MMN), associated with auditory sensory memory (Näätänen et al., 1978; Näätänen, 2001), the error-related negativity (ERN/Ne), elicited in response to the noticing of self-generated errors (Falkenstein, 1990; Gehring et al., 1993, 2007), and the feedback-related negativity (FRN), elicited in response to performance error feedback (Miltner et al., 1997; Nieuwenhuis et al., 2004). There are a host of other N2 components associated with novelty (Courchesne et al., 1975), perceptual mismatch (Kimura et al., 2006), or error monitoring/cognitive control (Bartholow et al., 2005), and much debate over whether these and the aforementioned components reflect similar or different underlying processes (Folstein and Van Petten, 2008). Early fronto-central negativities have been observed in response to SMC violations in some VR paradigms (Padrao et al., 2016; Gehrke et al., 2019), but not others (Porssut et al., 2023; Lehser et al., 2024). If there is an electrophysiological signature of a mismatch between predicted and observed body movements, we would have good reason to expect it to manifest from the N2 family as a form of error-monitoring or perceptual mismatch. Further, the component should only be prevalent when violations occur in the presence of strong priors, such as controlling a body in a way that closely resembles our everyday experience. Such a component would thus make a strong candidate for an index of PI.

Although canonically observed in the oddball paradigm and at times oversimplified as a sign of surprise (Donchin, 1981), the P300 has been demonstrated to arise in a variety of contexts beyond basic probability manipulations, supporting an interpretation that it reflects broader attentive processes. These processes have alternately been described as attentional resource allocation (Wickens et al., 1983), context updating (Donchin and Coles, 1988), information extraction (Gratton et al., 1990), and/or neural inhibition (Polich, 2007), as well as evidence accumulation (Twomey et al., 2015). A further distinction is made between attentional reorienting responses deriving from truly unexpected stimuli, as indexed by the P3a, and the integration of information deriving from behaviorally relevant stimuli, as indexed by the P3b (Polich, 2007). In embodiment research, Lehser et al. (2024) observed a P3b in response to infrequent visuo-tactile mismatch events. Previously, González-Franco et al. (2014) reported a somewhat later but topographically consistent positivity in response to instances when a virtual knife passed through the participant's co-located virtual hand as opposed to passing through the table on which the hand rested (note that the events were equiprobable in this case). Despite the fact that a minority of the trials in our procedure contain BIP events and we expect these events to generate a P3b response, we additionally expect, based on our pilot data (Supplement A), that the response will be present on all trials and that embodiment will be a stronger determinant of P3b amplitude than BIP probability. We reason that relative to trials in the more passive non-embodied condition, trials in the embodied condition will offer richer behaviorally relevant information regarding body position and slingshot manipulation that can contribute to the goal of achieving a high score (Begleiter et al., 1983). As the P3b has been characterized as the process of noticing behaviorally relevant information and integrating that information into working memory (i.e., context updating; Donchin and Coles 1988), we question whether the component could represent a kind of bridge for information transfer between the representations maintaining a perceptually based PI and a cognitively based PsI, or whether it is better characterized as representing more general attentional processes that carry no specific relation to presence.

The N400 is classically associated with semantic violations in language (Kutas and Hillyard, 1980; Kutas and Federmeier, 2011). Extensions of this paradigm have found N400-like effects in response to semantically incongruent line drawings (Nigam et al., 1992; Ganis et al., 1996), comic panels (Cohn and Kutas, 2015), and images (Ganis and Kutas, 2003; Võ and Wolfe, 2013). Tromp et al. (2018) demonstrated an N400 effect in VR by creating mismatches between virtual objects in an environment and the spoken discourse regarding those objects by virtual agents. Meanwhile, others have reported N400-like components in response to embodiment manipulations (Padrao et al., 2016; Porssut et al., 2023; Lehser et al., 2024), which have often been interpreted as violations of “bodily semantics.” We expect to see a similar type of N400 effect here, but we predict that the effect will extend beyond the body to violations of the semantics of physical laws (e.g., the freezing of a sling), appearing just as strongly to BIPs in the non-embodied condition as in the embodied condition. As the N400 has been described as reflecting semantic access (Kutas and Federmeier, 2011), a large N400 amplitude might be associated with disruptions of *coherence,* which Skarbez defines as the extent to which the virtual scenario behaves reasonably and expectedly (Skarbez et al., 2017a, 2020). Coherence depends on the internal logic and consistency of the virtual experience, and Skarbez argues that it enables PsI to take place similarly as *immersion* enables PI (Skarbez et al., 2017a). Therefore, we are hopeful that the N400 would allow us to detect breaks in PsI through the predictive processing of coherence disruptions.

In our experiment, we could not only replicate and extend multiple findings of previous studies within a single experiment, but we also did so by utilizing an immersive VR experience which, we argue, provides greater external validity for investigating a concept such as presence. Finally, we discuss our findings in light of existing theories of presence, which we consider an interesting aspect overlooked by previous articles.

3. Hypotheses

Confirmatory hypotheses and associated data collection and analysis protocols were preregistered at the Open Science Framework (osf.io). We predicted the following:

- Manipulation Check: Embodiment questionnaire overall scores will be greater in the embodied condition than in the non-embodied condition.
- H1: The N2 component will be significantly more negative for trials with breaks in presence compared to normal trials only in the embodied condition but not in the non-embodied condition (interaction effect).
- H2: The P3b component will be significantly more positive in the embodied condition than the non-embodied condition, regardless of trial type (main effect).
- H3: The N400 component will be significantly more negative for break in presence trials than normal trials, regardless of embodiment condition (main effect).

This set of predictions thus sets up the idea that each highlighted component could reflect its own specific aspect of presence. Here, the manipulation check seeks to provide evidence that our embodiment manipulation increases the participant’s sense of embodiment, using an established method. This evidence is necessary to ensure meaningful interpretations of the subsequent hypotheses. H1 then predicts that breaks in SMCs will be evident in the early N2 component, but only in the embodied condition where SMCs closely resemble real-life conditions, which would implicate the N2 as a functional marker of SMC breaks. H2 then predicts that the P3b will be larger in the embodied condition regardless of trial type, which could indicate that faithful embodiment leads to increased information extraction in the service of hitting targets. Finally, H3 predicts that the N400 will be larger for BIP trials independent of embodiment condition, suggesting a sensitivity to semantic violations that extends beyond language, images, and the body.

4. Methods

4.1. Participants

Participants were recruited from the university and broader community using an online recruitment tool, which prevented participants who took part in pilot versions of the study from signing up. Effects sizes for H1:H3 were estimated in a pilot sample ($n = 12$; see Supplement A) from a practically identical experiment to be very large (all Cohen’s $dz > 1$) and thus *a priori* power analysis was used to ensure greater than 95% power to detect large ($dz >= 0.7$) effect sizes, resulting in a sample size of 30 participants (assuming within-subjects two-tailed t-tests with $\alpha = .05$). Our preregistered exclusion criteria stated that participants who failed to complete the whole experiment for any reason, such as their own withdrawal or irreparable equipment malfunction, and that participants for whom more than 40% of epochs are flagged as containing artifacts, would be excluded and replaced prior to further analyses. Two participants were lost due to software malfunctions that interrupted their session and prevented them from completing the entire experiment, and one participant’s data were found to be corrupted such that they could not be read for analysis. These three participants were replaced, resulting in a total of 33 participants of whom 30 passed exclusion criteria and were thus included in subsequent analyses.

Of the 30 participants, 23 identified as male and seven identified as female when asked to self-identify their gender. All reported to be right-handed, to have normal or corrected-to-normal vision, and to have no history of traumatic brain injury. The sample had a mean age of 26.7 years (range: 18 to 37). When asked about their previous experience using VR technology, six reported to have never used it before, 13 reported to have used it only once or twice before, eight reported using it once or twice per year, and three reported using it once or twice per week.

4.2. VR experience

The VR experience was developed in Unreal Engine 5.2 to act as our stimulus apparatus. The experience simulated a scenario in which participants were seated in front of an imaginary arcade game system in a furnished room. Playing this game system, the participants launched virtual balls with a slingshot while trying to hit targets placed in front of them (see Fig. 1). The targets were assigned different colors, indicating

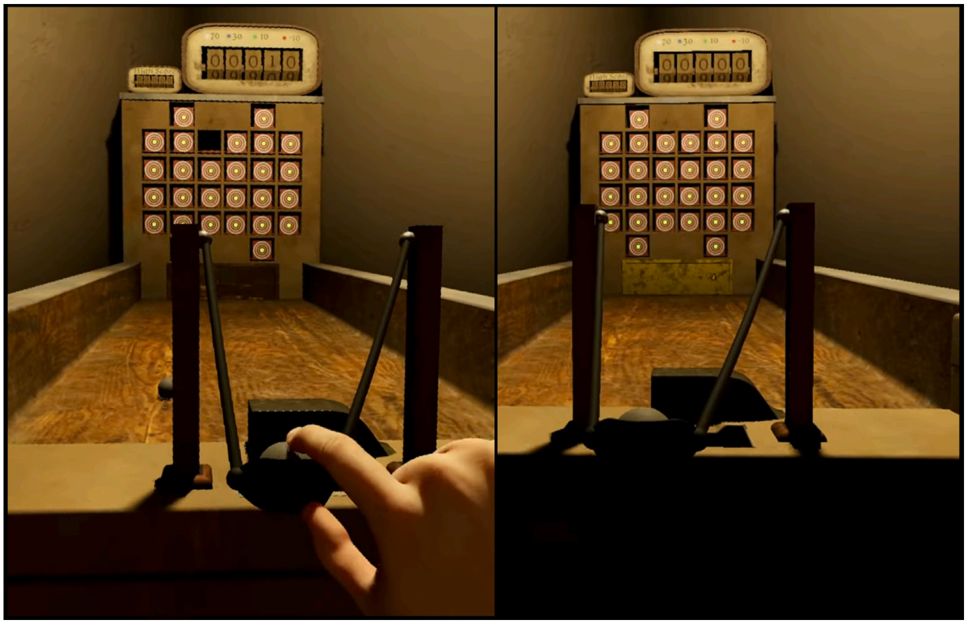

Fig. 1. The participants' task was to acquire as high a score as possible while playing a virtual arcade game. In the embodied condition (left), a virtual body was matched to participants' upper body movements and the participants could grab the slingshot naturally whereas in the non-embodied condition (right) the virtual body was stationary and the participants controlled the slingshot using game controllers.

different scores upon being hit. The scores were assigned as −10 for red, +10 for green, +30 for blue, and +70 for white. The participants were instructed to try to get as high of a score as possible. In the beginning of each round, all targets were colored green, and a new color was assigned every time a ball struck a target. The frequencies for the colors were assigned as 30% for red, 40% for green, 20% for blue, and 10% for white. To prevent the game from becoming too challenging, red targets were reshuffled after 30 s.

The experiment itself was divided into 10 rounds consisting of 200 trials, with the participant's score resetting between rounds. The first five trials of each condition (embodied or non-embodied) were considered practice trials separate from the primary 200. These trials were not included in analyses and the game board and score were reset after completion.

The participants viewed the VR experience with a Varjo Aero HMD and performed interactions using Valve Index controllers. The experience was rendered at 90 frames per second, and the HMD provided 102° and 73° horizontal and vertical fields of view, respectively. In addition, the participants were wearing VIVE trackers strapped to their chests and elbows to establish full upper-body tracking together with the controllers and the HMD. Three Valve Index base stations were used for tracking the headset, controllers, and the trackers. We manipulated two key factors, embodiment and breaks-in-presence (BIPs), resulting in a two-by-two within-subjects design. Fig. 2 provides a visual summary of the block and trial structure of the experiment. Please also see supplementary material to view a video of the VR experience.

	normal (both blocks)	BIP (both blocks)
embodied (block 1 or 2)	80 trials	20 trials
non-embodied (block 2 or 1)	80 trials	20 trials

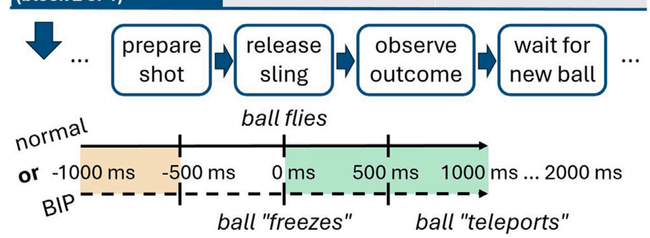

Fig. 2. A figure summarizing the block and trial structure of the experiment. The top table depicts the experiment's two-by-two within subjects manipulation of embodiment, at the block level, and breaks in presence, at the trial level. Blocks are counterbalanced among subjects and trial type is randomly permuted within each block for each subject. The middle flow chart depicts the progression of a trial, which is roughly aligned with the bottom timeline depicting the extracted epoch for normal trials (top, solid line) and BIP trials (bottom, dashed line), where the baseline period is shaded in tan and the post-stimulus window is shaded in green.

4.2.1. *Embodiment manipulation*

Throughout the experiment, the participants were given a 1PP of a gender-matched virtual avatar developed with the Unreal Engine *metahuman* tool. The participants were asked to match the avatar's skin tone as closely as possible to their own skin tone from five predefined options. Finally, the avatar's height was roughly matched to the participant's height from two alternatives (corresponding to "average" or "tall"). Only the avatar's upper and lower bodies were modeled; their heads were not included in order to reduce the performance overhead of the application and to prevent visual artifacts in the field of vision. The virtual chair in which the participants were sitting was modeled to match the visual appearance, dimensions, and location of the physical chair in which they were sitting during the experiment.

In the *embodied* condition, the avatar's upper body tilt and hand and elbow transformations were matched to the participant's corresponding physical body movements. Furthermore, the avatar's hands and fingers were animated using a set of predefined skeletal animations responding to the participant pressing the trigger button of the controller, allowing the participant to grab the virtual ball and the slingshot from different angles. Besides indicating the grabbing visually, the motion controller also elicited a subtle vibration effect at the moment of grabbing. After grabbing the ball, the participant could then use his/her hand to pull the sling and adjust the ball's launch velocity (strength and direction), initiating the launch by releasing the trigger. The participants could, therefore, play the virtual game using a mechanism mimicking natural sensorimotor actions. Only right-handed participants were recruited and participants were instructed to use their right hand throughout the embodied condition, taking breaks as needed. Finally, the brass sign of the arcade game system was modeled to be slightly reflective to enhance body ownership (Gonzalez-Franco et al., 2010). The sign did not produce a perfect mirror reflection of the avatar body, but the participants could observe their movements to cause visible, synchronized reflections in the sign (See Fig. 1 left).

In the *non-embodied* condition, we reduced the SMCs of the experience, aiming for reduced PI. In this condition, the virtual body was stationary; the upper body was leaning to the back of the chair, and its hands and arms were resting on the arms of the chair. Furthermore, instead of grabbing and controlling the slingshot with their hands, the participants used the thumbsticks of the Valve Index controllers to control the angle and the magnitude of the launch. The launch was initiated by pressing and releasing the trigger button of the Valve Index controller. The brass sign in this condition was non-reflective, so the participants could not even observe the reflections of the slingshot movement in the sign (See Fig. 1 right). The order of the *embodied* and *non-embodied* conditions was counterbalanced among participants.

4.2.2. BIP manipulation

We manipulated the experience in a randomly distributed 20% of the trials, attempting to cause deliberate BIPs. These BIP-events were time-locked to the ball launch and lasted 1000 ms. In the *embodied* condition, the Valve Index controller's transformation updates were frozen for the duration of the BIP event, causing the avatar's hand to temporarily freeze in place. Similarly, the slingshot was visually frozen in place with the ball remaining in its nest instead of exhibiting the usual animation coupled with the ball launch. The overall experience did not freeze, however, in terms of physics simulation updates; only the hand, the slingshot, and the ball were visually frozen in place. Instead, an invisible ball was launched according to the velocity specified at the time of the release, playing sounds and interacting with the rest of the game objects in an otherwise identical manner to the regular trials. After 1000 ms, the visibility of the balls was flipped: the active ball became visible, whereas the "prop" ball in the slingshot nest became invisible.

In the *non-embodied* condition, the behavior of the BIP events was similar except for the freezing of the avatar's hands, since the avatar's hands were resting in place throughout the condition. See Fig. 2 for a visual summary of the trial structure and trial events.

4.3. EEG recording

EEG signals were measured using a 24 bit Brain Products actiCHamp amplifier (Brain Products GmbH, 2024), sampling continuous EEG data at 1000 Hz using 32 active wet electrodes embedded in an elastic cap and placed according to the extended 10 percent system (Chatrian et al., 1985). The ground electrode was placed at position Fpz. The actiChamp system delivers a "reference free" stream at the time of recording, with raw voltages recorded relative to the amplifier's internal ground. Impedances were kept below 10 $k\Omega$ before data was recorded inside an electrically shielded chamber. No filtering was applied during online recording beyond a 260 Hz low-pass hardware filter. For synchronization of different data streams, the Lab Streaming Layer (LSL; Kothe et al. 2025) was used, integrating event markers from Unreal Engine with the EEG data stream. Systems were connected via an offline local area network (LAN).

EEG data was processed using EEGLAB (Delorme and Makeig, 2004) and ERPLAB (Lopez-Calderon and Luck, 2014). Event markers were shifted 36 ms forward to account for photodiode-measured system latency, and data was downsampled to 250 Hz and rereferenced to the arithmetic average of the left and right mastoids. Ocular artifacts were removed from the continuous data via Independent Component Analysis (ICA; Makeig et al. 1997). The data was first prepared for ICA by high-pass filtering using a fourth-order Butterworth filter with 12 db/oct rolloff with a 1.5 Hz half-amplitude cutoff, and data segments from channels (excluding frontal channels FP1, FP2, Fz, F3, F4, F7, and F8, so as to retain information specific to eye movements that would allow the ICA algorithm to accurately characterize them) exceeding +/- 250 microvolts were removed using the continuous artifact detection function from ERPLAB with a 500 ms moving window and 250 ms step size, joining artifactual segments separated by less than 100 ms. ICA was performed on the prepared data using a compute unit device architecture (CUDA) implementation of Infomax ICA (CUDAICA; Raimondo et al. 2012) on all channels excluding the mastoid reference channels.

Subsequently, ICA weights were transferred to the unfiltered data and any components identified as deriving from ocular sources with greater than 0.8 probability by ICLabel (Pion-Tonachini et al., 2019) were automatically removed. This ICA-cleaned data was then filtered using a fourth-order Butterworth filter with 12 db/oct rolloff with a 0.5 Hz half-amplitude cutoff. Because our primary measure of ERP components was a mean amplitude derived across prespecified latencies and electrode locations, no low-pass filter was applied (Zhang et al., 2024).

ERPs were time-locked to the release of the slingshot, marking a "trial." The experiment was self-paced. The time required for a new ball to reset after a launch was a minimum of three seconds and it normally took participants several additional seconds to line up a subsequent shot. This allowed us to select long epoch windows. The data was binned into epochs beginning 1000 ms prior to event onset and lasting 1000 ms after event onset, and baseline corrected using a baseline period from −1000 to −500 ms to help account for the response-locked (in our case, the release of a ball) nature of the time-locking event. Epochs containing voltage changes greater than ± 100 microvolts (after applying a 30 Hz low pass filter, used only for the purposes of this artifact detection step) were flagged using a 200 ms moving window with a 100 ms step size across the −1000 to 1000 ms interval. Clean epochs were averaged within conditions, within subjects.

ERP regions of interest (ROIs) and latencies were selected based on pilot data (Nardi 2024 and a subsequent unpublished pilot dataset of 12 participants which used an identical paradigm to the one reported here; see Supplement A for cluster-based permutation analysis results from this pilot sample). N2 amplitude was quantified as the mean voltage from a fronto-central ROI composed of electrodes Fz, FC1, FC2, and Cz across the mean of the 220 to 300 ms latency window. P3b amplitude was quantified as the mean voltage from a central ROI composed of electrodes FC1, FC2, Cz, CP1, and CP2 across the mean of the 300 to 380 ms latency window. N400 amplitude was quantified as the mean voltage from the same central ROI composed of electrodes FC1, FC2, Cz, CP1, and CP2 across the mean of the 380 to 580 ms latency window.

4.4. Procedure

All procedures were in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Human Sciences of the University of Oulu. Participants gave written informed consent prior to participating and were aware that they could withdraw at any time without consequence. Participants were given an oral overview of the complete procedure of the experiment, and then were shown to a restroom where they were asked to self-apply heart rate sensors according to a diagram on the wall (heart rate data was recorded for exploratory purposes and not processed in the current set of analyses). When the participant returned, they filled out a demographics questionnaire and we measured their head to fit an appropriately sized cap and start preparing the EEG recording system. Once impedances were brought to below 10 $k\Omega$, we presented participants with a live stream of their EEG data, highlighting their blinks, saccades, and jaw-clenching signals. Participants were instructed that they should behave normally other than to try to keep their face and neck muscles relaxed during the experiment.

Participants were moved into the experimental room and the HMD was placed onto the participants head over the EEG cap. The HMD was modified with 3-D printed contact points which were padded with yoga mat cutouts in an effort to make the HMD more comfortable and compatible when used in conjunction with EEG electrodes. Participants were asked to adjust the HMD until the image was clear. Afterwards we performed another impedance check and returned any disturbed electrodes to below 10 $k\Omega$. SteamVR calibration was carried out for each participant separately to ensure their viewpoint was correctly registered to the virtual body.

4.5. Analyses

Embodiment overall scores were calculated for each condition according to the method specified by Peck and Gonzalez-Franco (2021) and compared using a Wilcoxon signed-rank test due to the bounded, non-continuous nature of the data (manipulation check). Within-subjects ANOVAs (and pairwise follow-up tests, where appropriate) were used to test for the main effects and interactions for the breaks in presence and embodiment manipulations for each component (H1:H3). Alpha levels were set to .05.

Cluster-based permutation and peak-to-peak amplitude analyses were used as follow-up measures to better quantify overlapping components. For cluster-based permutation analyses, a period from 200 to 600 ms, encompassing the entire latency period of all predicted components, was tested using 10,000 permutations. Channels within approximately six cm from one another were considered to be neighbors (neighbors per channel $min = 2$, $max = 7$, $median = 4$) and the family-wise error rate was held to $\alpha = .05$ (two-tailed). For peak-to-peak amplitude analyses, ERPs were low-pass filtered using a 20 Hz cut-off, fourth-order filter with a 24 dB per octave roll-off to assist in peak identification. P3b and N400 peak amplitudes were algorithmically extracted from each subject as the largest positive and subsequent negative peaks in the same latency periods and channel ROIs as used for those components in confirmatory analyses, respectively.

Exploratory analyses included the extended Slater-Usoh Steed (SUS) questionnaire (Slater et al., 1994; Pan et al., 2016) as a measure of PI, single-item post-experiment probes to gauge participants' conscious awareness of the BIP manipulation, as well as the application of mixed-effect models to determine whether questionnaire items or demographic information contribute to the successful prediction of ERP component amplitudes. It should be noted that we could have utilized the SUS questionnaire as our manipulation check as well. However, since presence questionnaires have been criticized heavily in the past (indeed, the motivation of this study is to improve presence quantification because of these deficiencies) we chose to target the functionality of our embodiment manipulation directly, inspired by Padrao et al. (2016), and leave SUS as an exploratory measure.

For modeling purposes, the effect of BIPs was collapsed by subtracting mean BIP trial ERP responses from mean normal trials to account for the fact that questionnaire items were recorded at either the condition or experiment level rather than the trial level. Given the varied nature of predictor variables (some categorical, some numeric), we used linear mixed-effect models to predict this difference in ERP responses for various components. We used the 'buildmer' package in R (Voeten and Voeten, 2021) for model selection. The algorithm was set to start with the maximal provided model, progressively remove terms, and compare competing models using likelihood ratio tests until a best-fitting model was found. Predictors included embodiment condition, embodiment score, SUS score, age, VR experience, condition preference, perceived difficulty, counterbalancing order, and responses to the aforementioned probes regarding participants' awareness of the BIP events. However, the question regarding items freezing was omitted due to probable misinterpretation (see Supplement D), and gender was omitted due to only 7 of the 30 participants identifying as female. Interaction terms were prohibited due to the large number of predictors and limited number of instances at each level of interaction. A random intercept was provided to group responses within participants, and the algorithm was free to select random slopes and intercepts for all predictors.

5. Results

5.1. Confirmatory results

Embodiment overall scores were higher in the embodied condition, $Mdn = .73$, than in the non-embodied condition, $Mdn = .50$, $Z = 4.21$, $p = 2.76 \times 10^{-6}$, $r = .77$, providing support for the effectiveness of our embodiment manipulation.

N2 mean amplitudes indicated a main effect of embodiment, $F(1,29) = 7.69$, $p = .010$, $\eta_p^2 = .21$, and a significant trial type by embodiment interaction, $F(1,29) = 5.42$, $p = .027$, $\eta_p^2 = .16$, but no main effect of trial type, $F(1,29) = 2.57$, $p = .12$, $\eta_p^2 = .08$ (Fig. 3). Post-hoc tests revealed a more negative N2 in response to the BIP trials than to normal trials in the embodied condition, $m_{diff} = -1.57$, $t(29) = -2.43$, $p = .021$, $g = -0.43$, which was not apparent in the non-embodied condition, $m_{diff} = -0.31$, $t(29) = -0.47$, $p = .64$, $g = -0.08$ (Fig. 4), thus supporting our hypothesis that the N2 response to a BIP largely depends on embodiment (H1). However, it is notable that the N2 amplitude is least negative in the embodied normal condition and relatively similar across the other conditions, suggesting that some amount of error-related processing is present in all conditions except the one in which the users are able to smoothly operate their avatars.

P3b mean amplitudes showed a significant main effect of trial type, $F(1,29) = 5.68$, $p = .024$, $\eta_p^2 = .16$, a significant main effect of embodiment, $F(1,29) = 25.22$, $p = 2.38 \times 10^{-5}$, $\eta_p^2 = .47$, and a significant trial type by embodiment interaction, $F(1,29) = 12.44$, $p = .001$, $\eta_p^2 = .30$ (Fig. 5). Post-hoc tests revealed that P3b amplitudes were significantly larger in the embodied than non-embodied conditions for both BIP trials, $m_{diff} = 4.07$, $t(29) = 5.06$, $p = 2.14 \times 10^{-5}$, $g = 0.90$, and normal trials, $m_{diff} = 1.36$, $t(29) = 2.81$, $p = .009$, $g = 0.50$. Furthermore, there was in general a *smaller* P3b in response to BIP trials compared to normal trials, however this effect was only significant in the non-embodied condition, $m_{diff} = -2.93$, $t(29) = -4.02$, $p = 3.76 \times 10^{-4}$, $g = -0.72$, and not in the embodied condition, $m_{diff} = -0.22$, $t(29) = -0.27$, $p = .78$, $g = -0.05$ (Fig. 6). Thus, while the P3b response was primarily driven by embodiment (H2), a particular lack of a response for BIP trials in the non-embodied condition produced a significant interaction (see Fig. 5), giving us only partial support for H2.

For N400 mean amplitudes, we observed a significant main effect of trial type, $F(1,29) = 91.22$, $p = 1.85 \times 10^{-10}$, $\eta_p^2 = .76$, and a significant trial type by embodiment interaction, $F(1,29) = 5.43$, $p = .027$, $\eta_p^2 = .16$, but no main effect of embodiment, $F(1,29) = 0.71$, $p = .41$, $\eta_p^2 = .02$ (Fig. 5). Post-hoc tests indicated more negative N400 responses to the BIP trials than normal trials in both the embodied condition, $m_{diff} = -4.54$, $t(29) = -7.03$, $p = 9.78 \times 10^{-8}$, $g = -1.25$, and the non-embodied condition, $m_{diff} = -5.94$, $t(29) = -9.84$, $p = 9.51 \times 10^{-11}$, $g = -1.75$ (Fig. 6). Further contrasts revealed that BIP trials produced slightly more negative responses in the non-embodied condition than in the embodied condition, $m_{diff} = -0.92$, $t(29) = -2.06$, $p = .048$, $g = -0.37$, whereas this difference was not observed for normal trials, $m_{diff} = 0.48$, $t(29) = 1.41$, $p = .17$, $g = 0.25$. Similarly to our P3b effects, we find that this pattern of results supports our hypothesis that the N400 is overwhelmingly driven by BIP events (H3), while conceding that embodiment appears to make a modest yet statistically significant contribution.

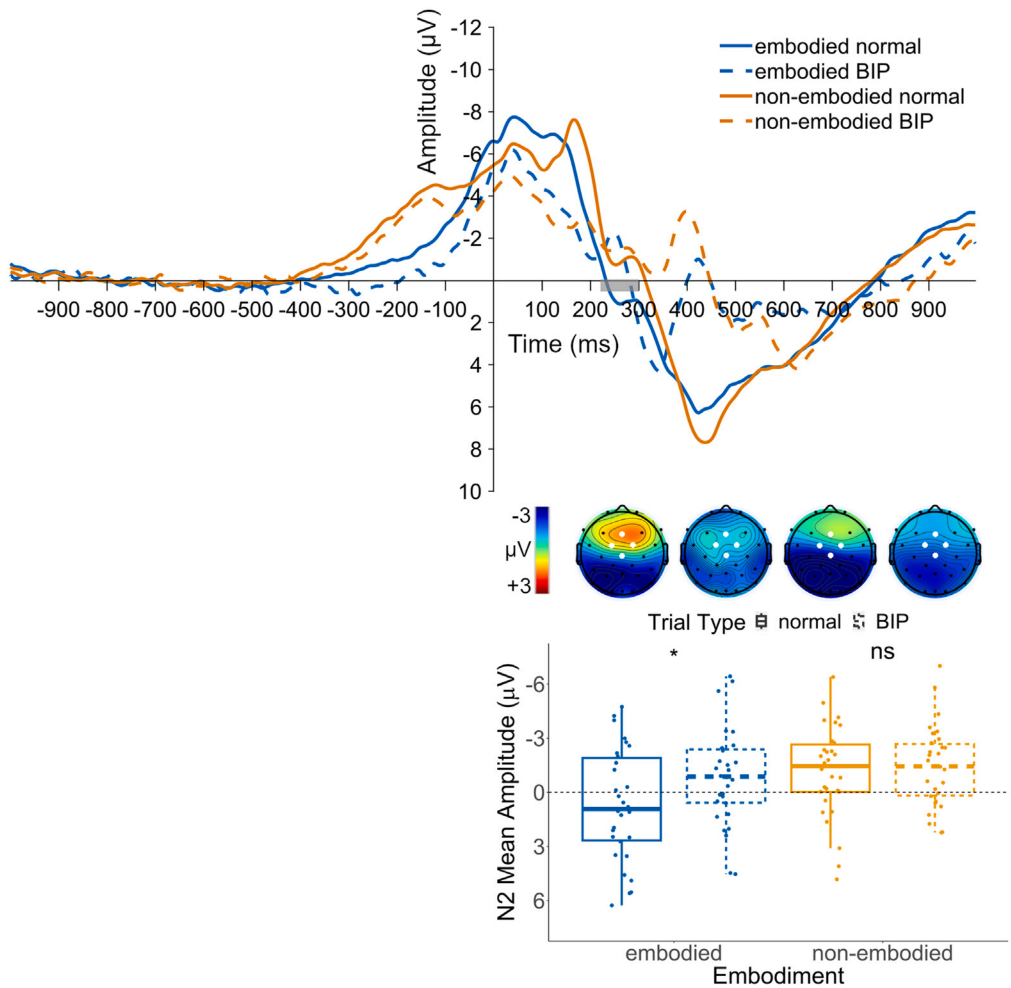

Fig. 3. Top: Grand average ERPs with embodied trials in blue, non-embodied trials in orange, normal trials in solid lines, and BIP trials in dashed lines. Time zero represents the moment that the ball is released. The latency window used in N2 component analyses is highlighted in gray across the *x*-axis (the same used to create the topographic and boxplots). Middle: Topographic plots displaying the mean voltage across the scalp for each condition within the latency window. Electrode locations forming the ROI for N2 component analyses (the same used to create the ERP and boxplots) are highlighted as white dots. Bottom: Boxplots depicting N2 distributions where dots represent individual subjects.

5.2. Exploratory findings

Given the temporal and topographic overlap of our P3b and N400 components, we performed additional analyses to confirm the existence of an independent N400 effect. We first performed a cluster-based permutation analysis (Maris and Oostenveld, 2007) on individual conditions against their own baselines to observe whether a negative-going cluster consistent with N400 timing and topography would be observed for BIP trials independent of contrasts with activity in the normal trials. For visual depictions of cluster-based permutation analyses for all conditions (and interactions), see Supplement B. Analysis of the embodied BIP trials revealed a widespread negative cluster ranging from 200 to 292 ms, $p = 4.00 \times 10^{-4}$, a central positive cluster ranging from 296 to 376 ms, $p = .034$, and a widespread positive cluster ranging from 464 to 600 ms, $p = .001$, but there were no significant clusters consistent with N400 activity. However, analysis of the non-embodied BIP trials revealed a widespread negative cluster ranging from 200 to 460 ms, $p < 1.00 \times 10^{-7}$, followed by a positive cluster that started frontal and moved widespread from 444 to 600 ms, $p = .002$. The negative cluster clearly seemed to lump together N2 and N400 activity, which was linked only by sparse lingering activations at electrodes Oz and O2, despite appearing to be distinct components across the rest of the head. A subsequent test was ran on only the second wave negative activity from the dividing point at 356 ms to the end of the negative cluster at 460 ms to examine whether it would survive on its own without reliance on earlier activity to boost the cluster size. A widespread cluster remained across the entirety of the window, $p < 1.00 \times 10^{-7}$. Thus the cluster-based permutation analysis finds support for an independent N400 component in the non-embodied condition but not for the embodied condition, potentially lending credence to the trial type by embodiment interaction observed in the confirmatory analyses.

Still, one reason why the cluster-based permutation analysis might have failed to detect an independent N400 component against baseline in the embodied BIP trials is contamination from the preceding P3b component, which was much larger for embodied BIP trials than for non-embodied BIP trials. We sought to account for this difference in preceding activity using a peak-to-peak amplitude analysis. The peak-to-peak amplitude difference (N400 minus P3b; see Supplement C) revealed a significant main effect of trial type, $F(1, 29) = 16.57$, $p = 3.30 \times 10^{-4}$, $\eta_p^2 = .36$, a significant main effect of embodiment, $F(1, 29) = 9.32$, $p = .005$, $\eta_p^2 = .24$, and no trial type by embodiment interaction, $F(1, 29) = 2.41$, $p = .13$, $\eta_p^2 = .08$. Post-hoc tests showed that the peak-to-peak amplitude difference in the embodied condition was significantly larger for BIP trials, $m_{diff} = -7.06$, than normal trials $m_{diff} = -1.90$, $t(29) = 4.28$, $p = 1.84 \times 10^{-4}$, $g = 0.76$, and the same was true for the non-embodied condition where again the

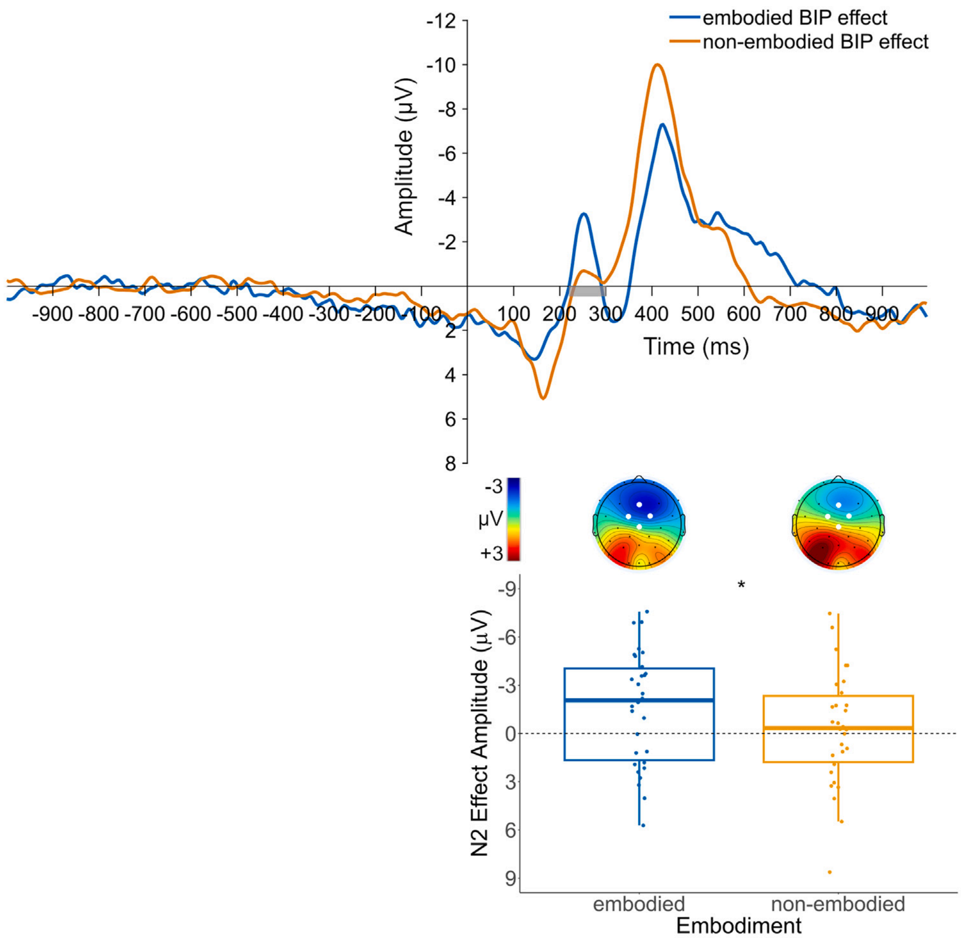

Fig. 4. Top: Difference waves (BIP trials minus normal trials) with embodied trials in blue and non-embodied trials in orange. Time zero represents the moment that the ball is released. The latency window used in N2 component analyses is highlighted in gray across the x-axis (the same used to create the topographic and boxplots). Middle: Topographic difference plots displaying the mean voltage across the scalp for each condition effect within the latency window. Electrode locations forming the ROI for N2 component analyses (the same used to create the ERP and boxplots) are highlighted as white dots. Bottom: Boxplots depicting N2 effect distributions where dots represent individual subjects.

difference was significantly larger for BIP trials, $m_{diff} = -4.10$, than normal trials, $m_{diff} = -0.74$, $t(29) = 2.83$, $p = .008$, $g = 0.50$. The pattern thus indicates a larger positive-to-negative shift in both sets of BIP trials than in corresponding normal trials, consistent with the presence of a genuine negative component in BIP trials that cannot be accounted for by changes in P3b activity. Furthermore, in contrast to primary analyses relying on normal trial subtractions, peak-to-peak amplitude differences were significantly larger for *embodied* BIP trials than non-embodied BIP trials, $t(29) = 2.63$, $p = .013$, $g = 0.47$. This result argues against the notion that N400 activity is truly greater in the non-embodied condition, suggesting it might even be greater in the embodied condition instead.

Though they were not planned components of interest in our preregistration, there were two visually striking earlier components that can be observed in both Figs. 3 and 5 which are thus worth mentioning. Leading up to the release of the ball, one can see a slow-going negative buildup that is maximal over central electrode sites indicative of a readiness potential, which is visually larger for the non-embodied condition. Such potentials are common in situations when participants are preparing a response or anticipating a stimulus (see Brunia et al. 2011). Then, prior to the N2 window, an early negative potential appeared between 120 to 220 ms that was maximal over parietal and occipital electrode sites and prominent only in normal trials. We interpret this component as a visually-evoked potential (VEP) attributable to the visual difference between what the participant sees when a trial is frozen versus when the trial proceeds normally with motion of the ball, sling, and hand.

SUS mean scores were significantly higher in the embodied condition ($Mdn = 5.33$) than in the non-embodied condition ($Mdn = 4.58$), $Z = 3.47$, $p = 2.46 \times 10^{-4}$, $r = .63$, indicating that operating an embodied avatar boosted participants' sense of place illusion. When asked about their preference on interaction methods, 24 participants preferred playing the game while controlling the virtual body, while 6 preferred playing using just the thumbsticks. For those who preferred controlling the virtual body, many open responses cited greater control or engagement, whereas those who preferred thumbstick control tended to cite greater fatigue controlling the virtual body as their main motivator. There was no significant difference in perceived difficulty between the embodied ($Mdn = 4$) and non-embodied ($Mdn = 4.5$) conditions, $Z = -0.83$, $p = .42$, $r = .15$.

For the P3b and N400 responses, the best-fitting model was simply the embodiment condition predictor with a random intercept for participants, similar to the analyses already presented in the confirmatory results section. This was true for both the mean amplitude and the peak-to-peak measure (collapsed across trial type) of the N400. However, for the N2 response, the best fitting model included VR experience ($\beta = -1.18$; 95% $CI = [-2.14, -.23]$), embodiment ($\beta = -1.27$; 95% $CI = [-2.35, -.18]$) and a random intercept for participants ($\sigma^2 = 6.62$). This model was a significantly better fit in comparison to the null model, $\chi^2(2, N = 30) = 10.84$, $p = .004$, and the embodiment

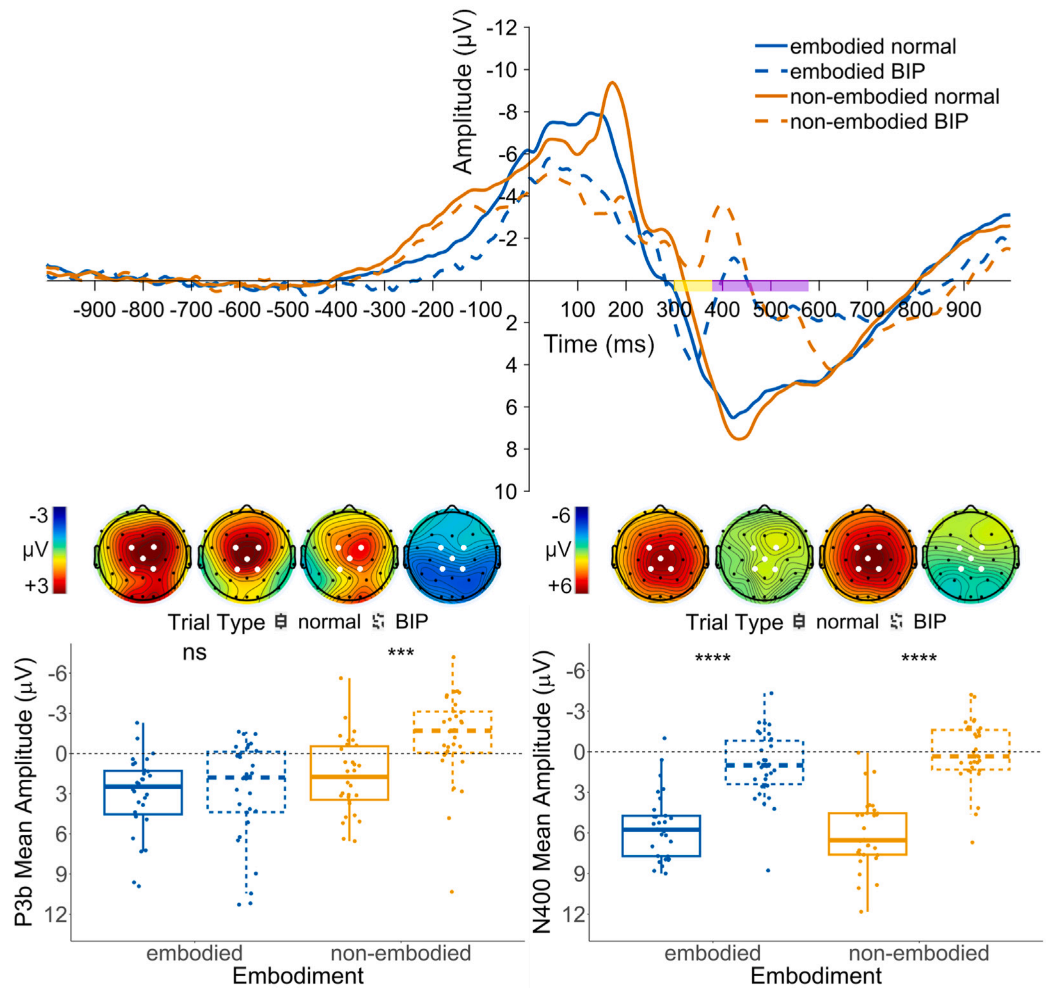

Fig. 5. Top: Grand average ERPs with embodied trials in blue, non-embodied trials in orange, normal trials in solid lines, and BIP trials in dashed lines. Time zero represents the moment that the ball is released. The latency window used in component analyses is highlighted across x-axis in yellow for the P3b and purple for the N400 (the same as those used to create the topographic and boxplots). Middle: Topographic plots displaying the mean voltage across the scalp for each condition within the latency window for the P3b (left) and N400 (right). Electrode locations forming the ROI for P3b and N400 component analyses (the same used to create the ERP and boxplots) are highlighted as white dots. Bottom: Boxplots depicting P3b (left) and N400 (right) distributions where dots represent individual subjects.

condition-only model, $\chi^2(1, N = 30) = 5.70$, $p = .017$. The slope of the VR experience predictor would indicate that the N2 effect increases with increasing experience using VR systems. This trend can be clearly observed in Fig. 7 which plots N2 effects by VR experience. Note that despite greater SUS scores in the embodied condition, SUS score itself was not a reliable predictor of amplitudes in any model.

6. Discussion

Our results mostly supported our hypotheses H1-H3. Support for the manipulation check validated that our body ownership manipulation was successful, and that the tracked virtual body elicited a larger body ownership than the non-tracked one (embodied vs non-embodied conditions). This allows us to interpret the main results meaningfully. Our SMC manipulation did not only depend on the visual representation of body movements, but also on how the participants controlled the slingshot. Most participants reported the embodied condition being more enjoyable while there was no significant difference in perceived difficulty. Our exploratory SUS results indicate that the participants experienced greater PI during the embodied condition, specifically. Although presence questionnaires have been criticized in the past (Usoh et al., 2000; Slater et al., 2022; Slater, 2004), this result is overall in line with multiple previous studies according to which a visual representation of a body and the utilization of natural sensorimotor actions in VR increase presence (e.g., Slater et al. 1995, Slater and Usoh 1993, Arora et al. 2022). Interestingly, however, SUS scores did not predict N2 amplitudes even if both SUS and N2 responded to embodiment at block-level.

Regarding H1, our results showed a larger BIP N2 response during the embodied condition than the non-embodied one, supporting this hypothesis. A similar finding was also made by Gehrke et al. (2022) in which N2 BIP-effect magnitude was dependent on the fidelity of sensory feedback during a VR motor task. Furthermore, a BIP-like effect within the N2 region was also found in studies by Padrao et al. (2016), Lehser et al. (2024), and Porssut et al. (2023). These results are consistent with a functional interpretation of the N2 as an early error catching system which stays quiet as long as natural SMCs remain intact. Given the theoretical implication that PI would depend on the SMCs supported by the system, these findings support the idea that N2 could serve as an index for breaks in PI. It could be taken as somewhat of a surprise that SUS scores, one traditional measure of PI, did not provide utility in mixed effect models predicting N2 amplitudes. In fact, the two measures did not even correlate (Spearman's $\rho = -.10$, $p = .59$, for the correlation of N2 and SUS differences between embodiment conditions). Graphical inspection indicated that this lack of a relationship was not a matter of little inter-participant variability in either measure, nor was it a lack of

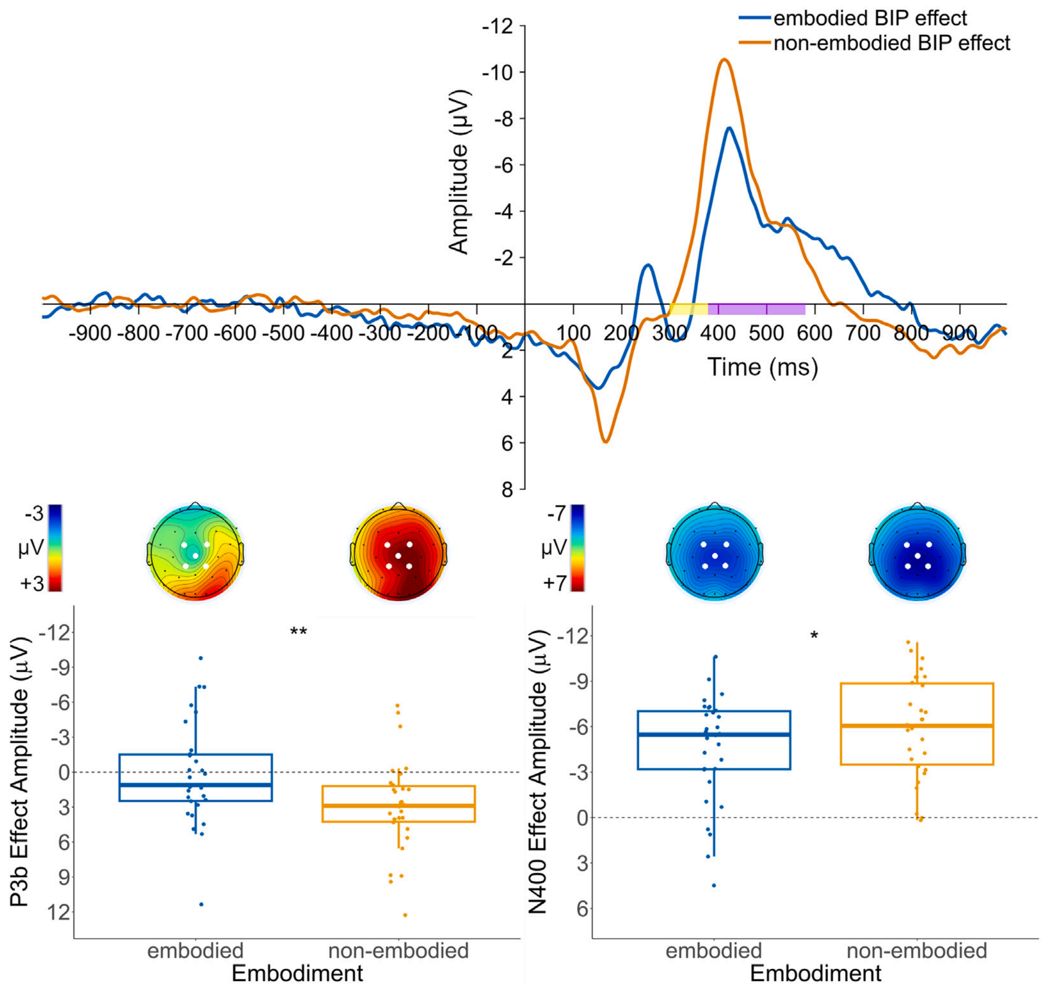

Fig. 6. Top: Difference waves (BIP trials minus normal trials) with embodied trials in blue and non-embodied trials in orange. Time zero represents the moment that the ball is released. The latency window used in component analyses is highlighted across *x*-axis in yellow for the P3b and purple for the N400 (the same as those used to create the topographic and boxplots). Middle: Topographic difference plots displaying the mean voltage across the scalp for each condition effect within the latency window for the P3b (left; exceptionally depicted as normal trials minus BIP trials) and N400 (right). Electrode locations forming the ROI for P3b and N400 component analyses (the same used to create the ERP and boxplots) are highlighted as white dots. Bottom: Boxplots depicting P3b (left; exceptionally depicted as normal trials minus BIP trials) and N400 (right) effect distributions where dots represent individual subjects.

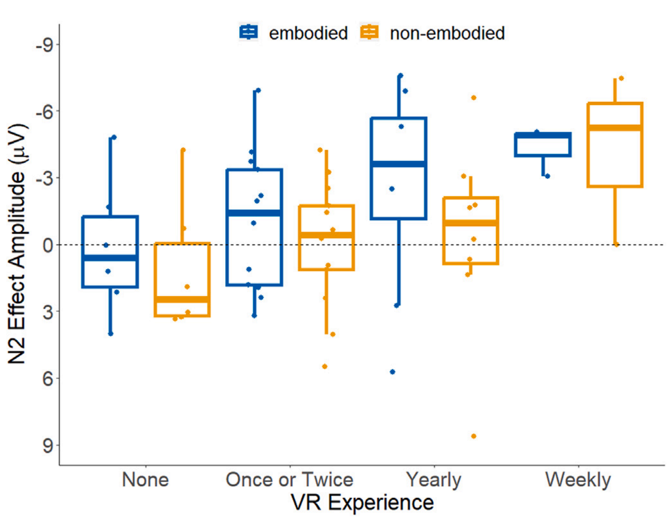

Fig. 7. Boxplots depicting N2 effect distributions according to VR experience, where dots represent individual subjects. Embodied responses are depicted in blue whereas non-embodied responses are depicted in orange.

measurement reliability as according to additional analyses reliability estimates were high for both measures; Chronbach's α of our sample's SUS responses was estimated at .80 for the embodied condition and 0.85 for the non-embodied condition, and split-half reliability of the N2 BIP effect was estimated using Monte Carlo sampling with 1000 stratified samples, yielding an average Spearman-Brown corrected reliability of .82 for the embodied condition and .86 for the non-embodied condition. Provided that both the N2 and SUS were sensitive to our block-level embodiment manipulation, we are inclined to believe that these metrics are simply capturing different aspects of PI, in which one is based on perception in the moment, and the other is based on subjective recollection. However, if PI truly depends on SMCs, an ERP-component that directly reflects the error-monitoring of SMCs should theoretically be the more accurate measure of the two.

We also partially supported H2, according to which the P3b component was more positive in the embodied condition compared to the non-embodied condition. Contrary to our predictions, however, there was also a main effect of trial type and an interaction effect according to which P3b amplitude was smallest for BIP trials in the non-embodied condition. In classic ERP studies, the P3b has been associated with information extraction and attention. Previous presence studies have utilized the P3b as a proxy for presence through attention using auditory oddball tasks (e.g., Savalle et al. 2024); even if VR literature cautions against coupling attention directly with presence (Skarbez et al., 2017a; Slater et al., 2022). In these paradigms, the increased P3b effect for oddballs indicates the shift of attention towards an external stimulus. In this experiment, however, we did not utilize a classical oddball task or attempt to explicitly manipulate attention. Though there was a frequency manipulation in terms of BIP trials occupying only 20% of all trials, our P3b was either not sensitive at all to less frequent trials, or elicited a smaller amplitude in these trials, which is not what is observed in typical P3b oddball designs. In fact, the largest P3b effect size by a considerable margin was at the block-level in which the P3b magnitude was greater for embodied trials. This overall pattern is not difficult to interpret if viewed from the standpoint of information extraction. The participant's goal in our task was only to achieve a high score, for which they needed to focus on their manipulation of the sling and then take into account the immediate consequences of that manipulation regarding whether it led to a hit or a miss. The manual manipulation required by the embodied condition offered more sensitive strategies and therefore more information to encode than the relatively coarse manipulation offered by the thumbsticks in the non-embodied condition. The BIP trials then cut that information extraction process short with a nonsensical event that requires additional conscious interpretation and interrupts the player's progress. It could have been the case that the freezes (BIP events) in the embodied condition were interpreted as something the players did themselves, prompting them to put more effort (consciously or unconsciously) into encoding the preceding events, whereas the freezes in the non-embodied condition could have been more easily externalized as a glitch in the game that was independent of the player, and thus not worthy of incorporating into their game strategy. We thus contend that a general information extraction account is the most parsimonious explanation of our P3b results; increased immersion (i.e., richer SMCs) and coherence (i.e., the slingshot working as it should) conferred a greater amount of task-relevant information to the participant, and therefore, a larger P3b was generated.

Regarding H3, we found, as predicted, that the N400 component was significantly more negative for the BIP trials. However, we also found a comparatively modest but statistically significant interaction effect, according to which the N400 BIP effect was greater for the non-embodied trials. This result did not precisely match our predictions, according to which N400 would not have been sensitive to body ownership at all. It is also surprising that the N400 effect was greater for the non-embodied condition, specifically. To further investigate whether there was an embodiment effect related to the N400, we carried out two additional exploratory analyses; the results of these analyses, however, were found to be contradictory. The cluster-based permutation analysis indicated that there was an independent N400 effect in the non-embodied condition but not in the embodied condition, potentially supporting the interaction found in our confirmatory analysis. The peak-to-peak analysis, however, suggested the opposite results; the N400 activity was statistically greater for the *embodied* trials rather than the non-embodied trials, after taking into account preceding P3b activity. This sets up a situation in which all analyses indicate an N400 BIP effect, whereas the existence and the direction of the embodiment effect is dependent on the analysis type, each which have their own benefits and caveats. We are therefore inclined to favor our original prediction that the N400 is more sensitive to BIPs than embodiment.

The N400 effect observed here likely reflects the semantic processing of the prediction error initially flagged by the N2 component. As the N400 is commonly associated with language incongruencies and disruptions of visual semantics, we are hopeful that the N400 would react to coherence violations, events within the VR environment which go against the user's expectations, therefore potentially serving as an index for breaks in PsI. If this is true, the N400 effect could have been elicited by the freezing of the slingshot as well as the disappearing ball, instead of the freezing hand, which would indeed match Skarbez's definition of coherence (Skarbez et al., 2017a). Another possibility for the effect is that disrupting SMCs in VR sends a cascade of prediction errors across various levels of cognition even without coherence-specific manipulations. This would imply that PI and PsI are not truly orthogonal, and a break in PI would always result in a break in PsI, as suggested by some behavioral studies (Pouke et al., 2022; Brübach et al., 2024). If either of the above explanations are true, then the missing N400 effect in the study of Gehrke et al. (2022) could be the result of a visually minimal environment, such that there was simply no PsI that could be broken in that setting.

A third alternative is that, although PI should depend on SMCs, specifically, the existence of a 1PP virtual body affects both PI and PsI, as suggested by Slater (2009). Therefore, disrupting SMCs through the freezing of the virtual body could elicit both a break in PI and a break in PsI. Furthermore, the model of Gonzalez-Franco and Lanier (2017) suggests that SMC violations are processed as semantic errors, referencing the study of Padrao et al. (2016) in which an N400 was observed when a user's virtual body performed an action that was opposite to the user's physical action. Similar effects were also found by Porssut et al. (2023) and Lehser et al. (2024), but not by Gehrke et al. (2019). According to the results of this study, however, we do not have compelling evidence that the N400 was sensitive to embodiment at the block level — increased SMCs did not result in a greater N400 magnitude.

6.1. Implications for presence

Taken at face value, the results of this study would support the (Hofer et al., 2020) suggestion that PI is a lower-order process and that PsI is a higher-order one. Therefore, breaks in PI could be detected by ERPs in the earlier stages of cognition that are sensitive towards disruptions in SMCs; according to our results, the N2 was sensitive towards both embodiment and BIPs. Furthermore, breaks in PsI could be detected by later ERPs sensitive towards disruptions in semantics; according to our results, the N400 was sensitive towards BIPs, but less so towards embodiment. We also concluded that although the P3b was sensitive towards embodiment, the effect was not because of presence, but because of increased SMCs being relevant to the task in the game.

Our results support the core idea of the Slater/Skarbez (Skarbez et al., 2017a; Slater, 2009) model, according to which PI is driven by SMCs, whereas PsI is driven by *coherence* (i.e. the extent the VE supports the expectations of the user, and general credibility of the environment). However, our experimental design was too limited to study the orthogonality of these two illusions; we cannot be certain whether the implied break in PsI (the N400 effect) was caused by coherence factors (the slingshot and the ball behaving unexpectedly), or whether a break in PI resulted in a break in PsI as well.

Our results do not support the suggestion that 1PP virtual body would benefit PI and PsI equally (Slater, 2009). Furthermore, our results do not entirely support the (Gonzalez-Franco and Lanier, 2017) model of illusions, specifically the claim according to which SMC disruptions are processed as semantic violations.

Interestingly, our exploratory analysis found that the N2 effect was larger for participants with more experience in VR. It could be that experience with VR controllers and hardware allowed participants to immerse themselves into the experience without consciously thinking about the controllers, or similarly that more experience in virtual environments allowed predictive coding processes to fine-tune expectations regarding SMCs in VR, leading to larger responses when they were violated. This finding further suggests that the capability of VR to elicit PI would not diminish through increased exposure to VR, though future work is required to draw firm conclusions.

6.2. Limitations and suggestions for future work

Despite the above, further investigation is still needed before we can make strong conclusions about presence or the correctness of each model. We queried whether the participants consciously registered our BIP manipulations, and whether they caused phenomenological losses in presence. Although 25 participants reported bugs that appeared to relate to our BIP manipulations, most of the participants attributed losses in the *"sense of being there"* to fatigue or discomfort related to the EEG and VR equipment. Interestingly, 11 participants reported not noticing any instances of items freezing in place, which contradicts their other reports related to bugs and glitches (see Supplement D). We suspect that this discrepancy could be related to language. Based on the responses above, although our EEG results are quite robust and sensitive to our manipulations, we cannot state with perfect certainty whether our N2 and N400 effects are strictly associated with conscious losses in presence. Instead, these effects could also index the perception of glitches in the VR experience which the brain processes either unconsciously, or which the VR user immediately forgets. We should also note that the relative lack of women in our sample limits the generalizability of our findings and should be better balanced in future experiments.

This study is also limited by the fact that our experimental paradigm was not designed to cause distinct breaks in PI and breaks in PsI, specifically, and we, therefore, cannot fully isolate the neural signatures of either. Although it is tempting, based on existing literature, to infer that the N2 response is specific to breaks in PI, and that the N400 response is specific to breaks in PsI, a manipulation that generates and breaks each illusion independently would be required to draw this conclusion with certainty. However, empirical separation of PI and PsI appears to be a nontrivial task (Slater et al., 2022), and it is occasionally disputed whether PsI can even exist without PI in a VR experience (e.g. Pouke et al. 2022, Brübach et al. 2024). A potential pathway for stronger a presence manipulation could be found by comparing experiences utilizing traditional displays to ones using HMDs (i.e. non-immersive and immersive displays, respectively), however, as stated earlier, this is difficult to achieve in the ERP paradigm where one typically wants to minimize visual differences between conditions. That said, future studies should look for novel ways to target either PI-related or PsI-related aspects of the virtual experience to advance the separation of their neural signatures. Finally, we suggest that future work also focus on the P3b-related finding in this study, investigating the relationship between information extraction and presence. A design that would separately manipulate SMCs and informativeness could illuminate whether this component is sensitive to presence, or whether the sensitivity towards embodiment, observed in this study, was related to the embodiment condition being more helpful in the task at hand.

7. Conclusion

In this paper, we reported the results of our preregistered ERP experiment focusing on neural signatures indicating either existence or loss of presence in VR. Participants were engaged in a virtual arcade game in which their task was to get as high a score as possible shooting balls towards targets using a slingshot while EEG data was collected during the gameplay. We caused deliberate BIPs in 20% of the trials by freezing the slingshot and the participant's hand in the embodied condition, and only the slingshot in the non-embodied one.

We found several ERP components to be sensitive to our manipulations, partially confirming our hypotheses. We found that the N2 component was sensitive to BIP trials, and also that the effect was significantly stronger during the embodied condition. We also found that the P3b was more positive for all trial types during the embodied condition. However, the P3b was also less positive in the BIP trials, specifically within the non-embodied cognition. We also found that the N400 component was sensitive to BIP trials, and although we predicted that the N400 would not be sensitive to embodiment, we found an effect according to which the N400 was slightly more negative during the non-embodied condition. Further exploratory analyses yielded contradictory results concerning this embodiment effect, which led us to conclude that the N400 was mostly sensitive towards BIPs, but not towards embodiment.

We suggest that the N2 component could serve as an index for breaks in SMCs, and therefore PI. We also suggest that P3b does not relate specifically to presence, but rather serves as a separate but related index of, in our case, information extraction, or in other paradigms, attentional reorienting. Whereas previous studies have reported that the N400 is sensitive to virtual body visuomotor violations, here we show that the N400 also extends to violations of physics that are independent of bodily sensations. Although we propose that the N400 could be potentially used to index coherence in virtual environments, there are multiple interpretations for our findings. We recommend that future research focuses on decoupling the role of the N400 component in relation to body movement violations and the coherence of the virtual environment.

Despite the acknowledged limitations, this work advances existing ERP presence research in multiple ways. In our experimental paradigm, we manipulated presence independently through embodiment, allowing a cause-and-effect investigation of presence-related ERPs. We were also able, in some cases, to validate the effectiveness of our manipulation through traditional questionnaires. Our trial-level manipulation targeted SMCs and coherence, indexing presence through ERPs coupled with BIPs instead of measuring presence indirectly through attention. We also utilized a realistic, aesthetically pleasing virtual environment with a meaningful task to minimize confounds due to the experiment itself failing to elicit presence. Finally, we reflected our findings against theories of presence, which has been uncommon in previous neuroscientific presence investigations.

CRediT authorship contribution statement

Evan G. Center: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matti Pouke:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandro Nardi:** Writing – original draft, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Lukas Gehrke:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Klaus Gramann:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Timo Ojala:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Steven M. LaValle:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors have nothing to declare.

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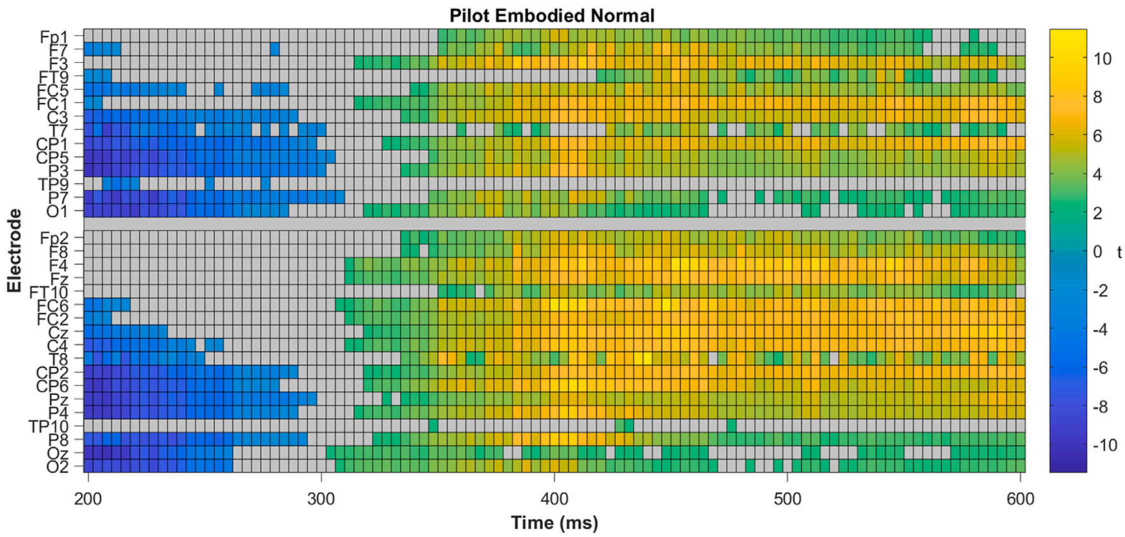
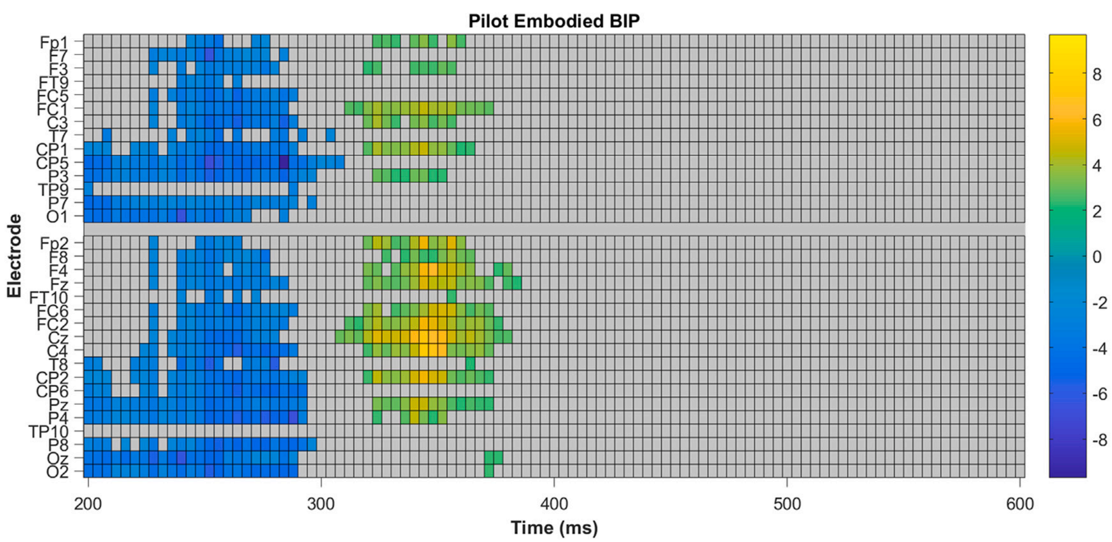
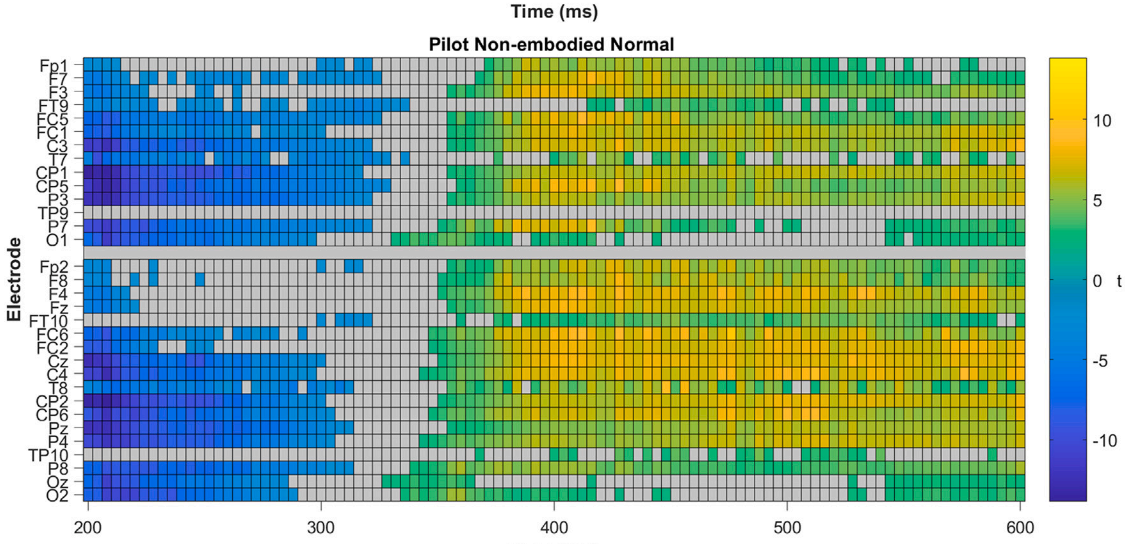
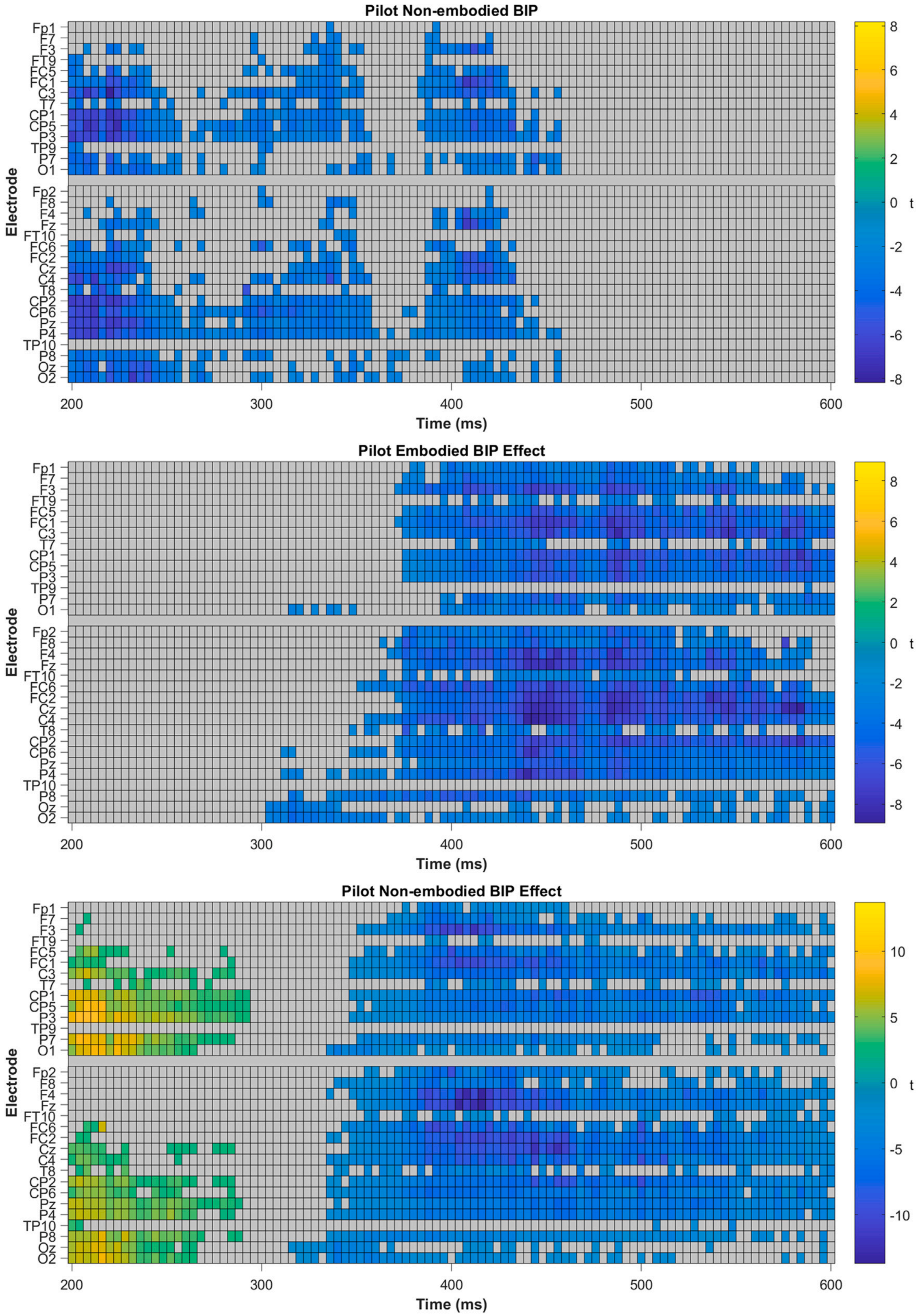
Supplement A








Pilot Non-embodied BIP
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Fp2
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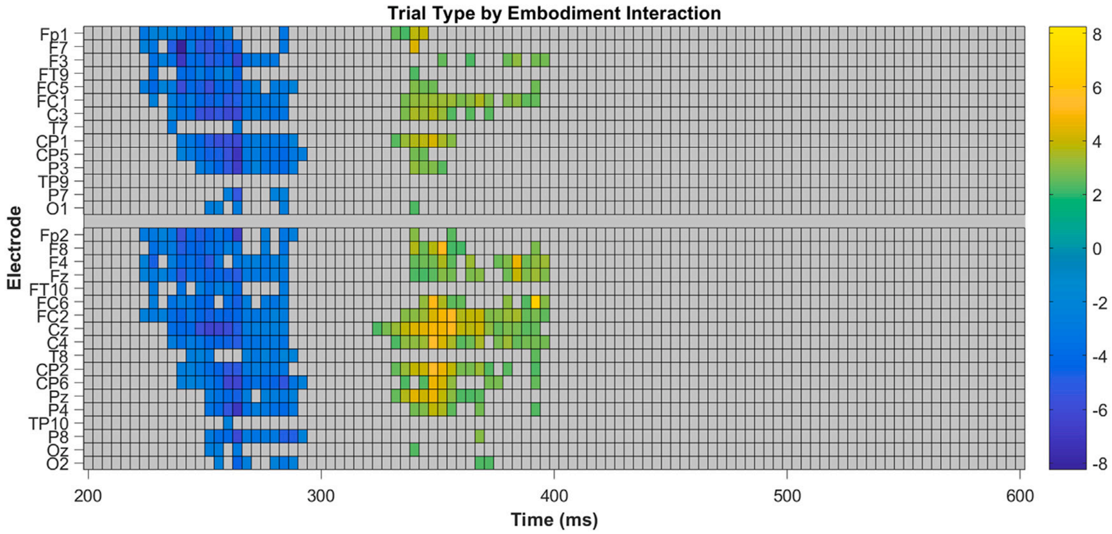
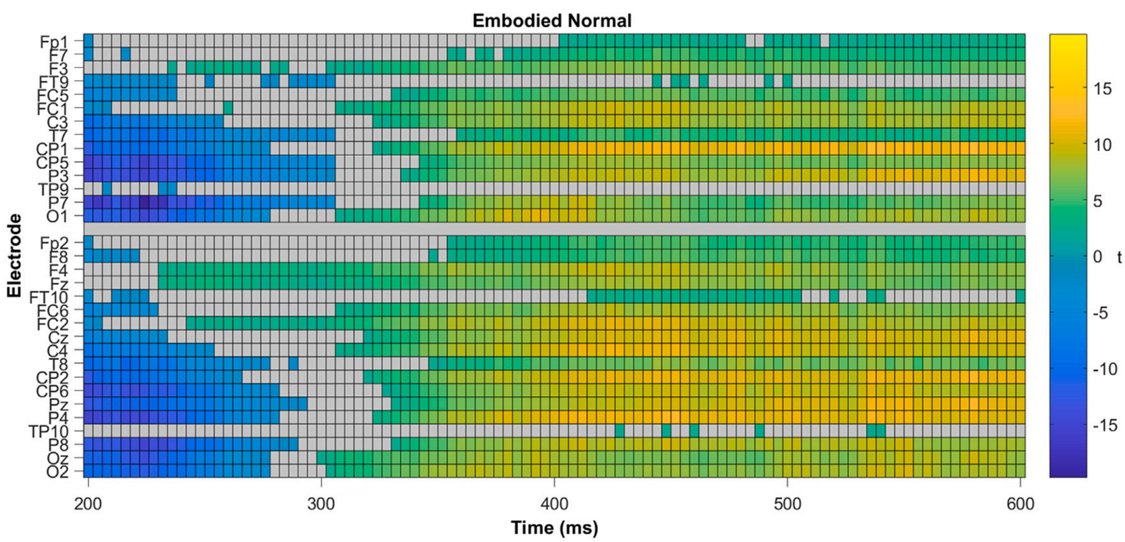
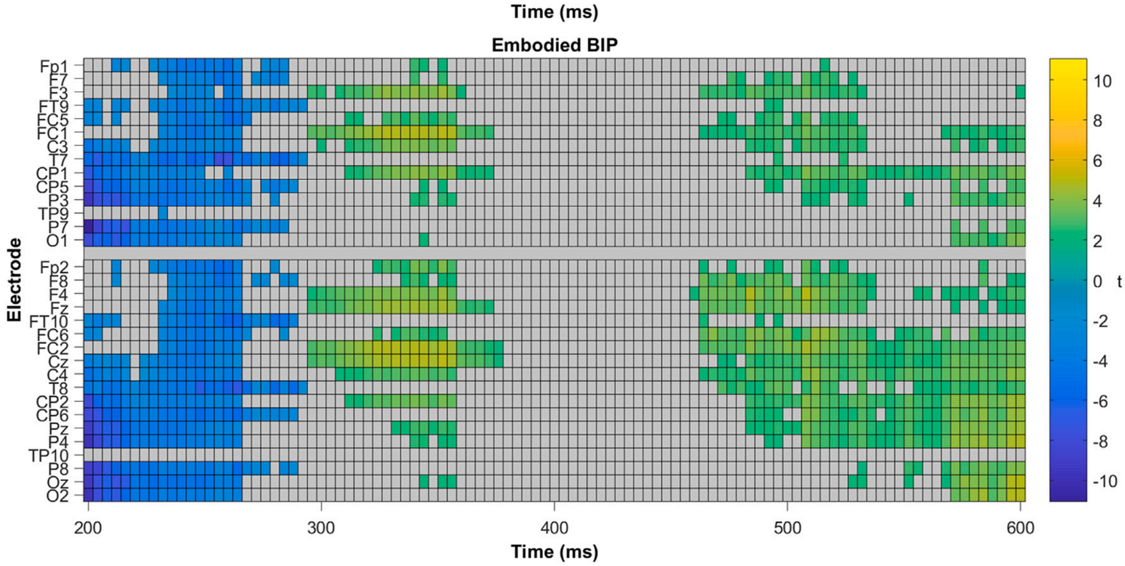
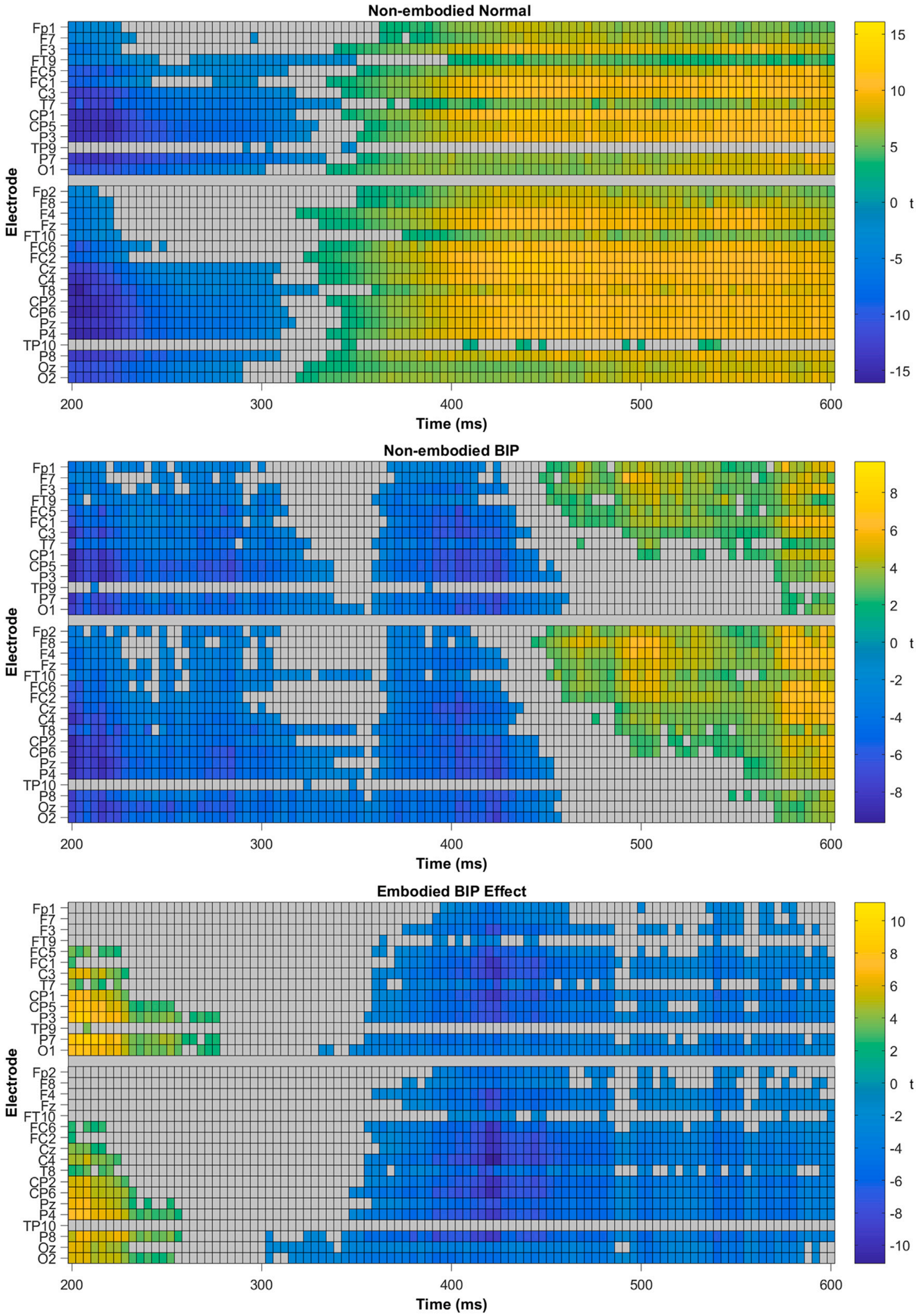


Supplement B






Non-embodied Normal
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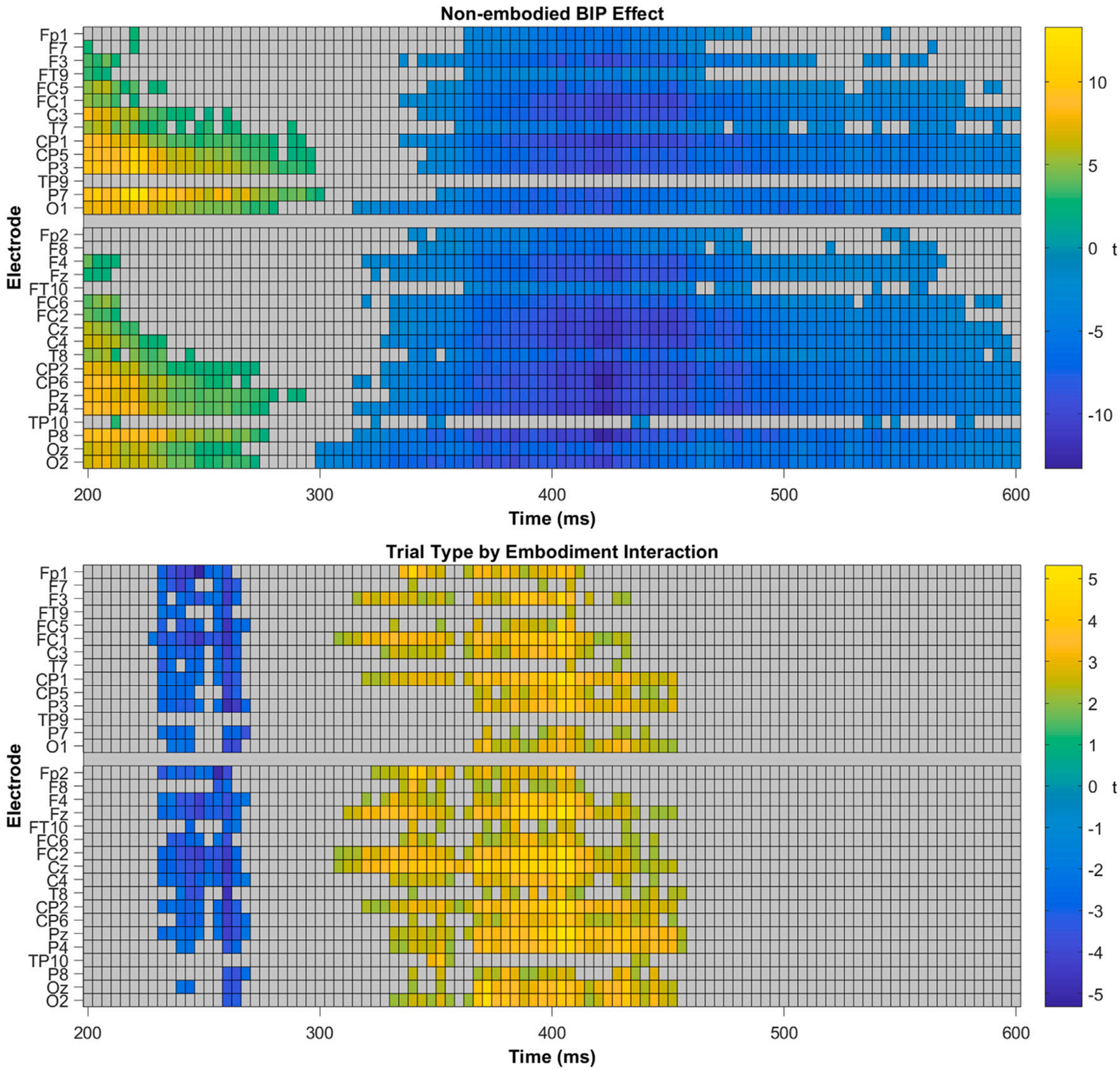

Supplement C

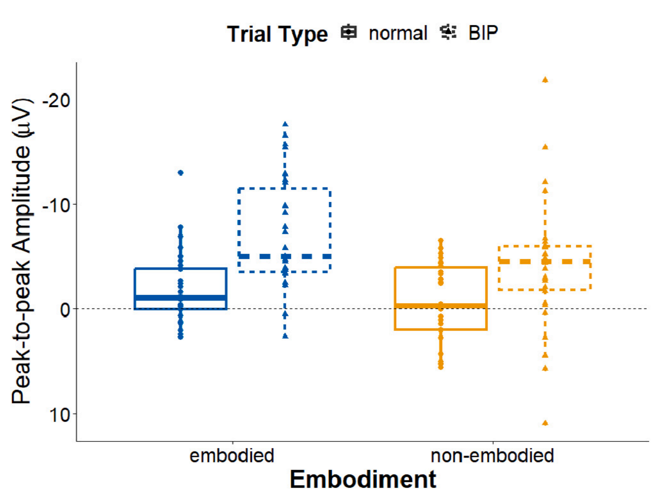

Fig. 8. Peak-to-peak amplitude measures to disentangle the P3b from the N400, computed as the N400 ROI latency window peak minus the P300 ROI latency window peak.

Supplement D

We were curious to what degree participants would consciously register the BIP events. When asked whether there were any moments when par- ticipants became suddenly aware of the real-world laboratory, eight affirmed this never happened, nine only without the virtual body, two only with the virtual body, and 11 affirmed it happened in both cases. The 15 provided open responses to what triggered these moments varied greatly in content, however the modal response (from four participants) concerned the discom- fort of the equipment and/or fatigue. When asked whether they noticed any bugs or errors, two claimed to have not noticed any, zero only without the virtual body, six only with the virtual body, and 22 affirmed to have noticed in both cases. Twenty-five of the 30 accompanying free responses described bugs that could plausibly relate to the BIP manipulation. Finally, when explicitly asked whether they noticed any instances of items freezing, 13 (!) claimed to have not noticed any such instances, one only without the virtual body, four only with the virtual body, and 12 affirmed to have noticed such instances in both cases. Given the pattern of open responses to the previous question, we suspect that the large number of negative responses to this item might stem from a misunderstanding of the question phrasing as none of the participants were native English speakers.

Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.neuroimage.2026.121715.

Data and code availability statement

De-identified ERP data and analysis code are available at: https://osf.io/s9hyk/files/osfstorage

Unreal project files are available at: https://github.com/ucc-general/PresenceEEGFollowup.

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