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Developing Frameworks to Translate Embodiment Metrics to Human-Machine Interactions

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Developing Frameworks to Translate Embodiment Metrics to Human-Machine Interactions

By

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THESIS

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Abstract:

Fear, mistrust, and unclear responsibility continue to impede the adoption of autonomous and collaborative technologies. Embodiment, the way people perceive their body and actions, provides a framework for understanding human–machine interaction, with potential to reduce fear, foster trust, and clarify responsibility between users and systems. However, translating embodiment theory into practical evaluation tools for human–machine interaction has proven challenging, as existing metrics often yield conflicting results. This thesis uses psychophysics to quantify embodiment metrics, investigating their relationships during whole limb movements and in prosthetic tasks. Chapter 2 systematically varies visual, auditory, and haptic feedback to examine how four common embodiment metrics covary, revealing inconsistencies with earlier findings and suggesting that these measures may capture distinct constructs. Chapter 3 focuses on the sense of agency, the experience of authoring one's actions and their outcomes, using a tightly controlled, forced-choice psychophysical paradigm. We test the validity of intentional binding and introduce a novel precision-based index, the temporal discrimination limen. Results show that intentional binding does not consistently reflect agency, whereas the temporal discrimination limen is selectively sensitive to volitional control. We conclude that the temporal discrimination limen is a promising implicit metric for agency and outline future work to validate its relationship with explicit measures and to examine the role of the supplementary motor area in volition and time perception.

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Chapter 1. Introduction and Background

1.1 Problem and background:

Despite the economic and societal benefits that autonomous and collaborative technologies promise [1], perceptions of fear, lack of trust, frustration, and ambiguous lines of social responsibility still plague their adoption [2], [3], [4], [5]. Embodiment theory defines how we perceive our body and its capabilities within our environment [6]. It offers a framework for evaluating human-machine interfaces (HMI) and an avenue to define the relationships users develop with technologies [4], [7]. It also plays a crucial role in reframing perceptions of fear, promoting forgiveness, and establishing limits of social responsibility during interactions with autonomous and collaborative agents [4], [8], [9], [10]. High abandonment rates in upper limb prostheses, associated with a poorly formed sense of embodiment [7], [11], [12], best exemplifies its importance for device adoption.

Originally developed to understand body schema and self-image within the field of cognitive neuroscience [13], embodiment has since seen numerous applications in HMIs: prosthetics, exoskeletons, autonomous vehicles, virtual reality, augmented reality, and brain-computer interfaces [7], [14], [15], [16], [17]. However, translation of embodiment theory has faced challenges. Many studies report inconsistent results across measurement paradigms, and there remains no unified framework to evaluate HMI interactions[18], [19], [20]. Without this comparability, it is difficult to assess which design approaches best foster embodiment. Developing unified frameworks and standardized metrics could enable such comparisons, provide insight into how embodiment mitigates fear and ambiguity in responsibility, and ultimately improve user acceptance of emerging technologies.

Embodiment is theorized to arise from a combination of three constituent components: (1) the sense of agency, (2) the sense of ownership, and (3) peripersonal space [4]. The sense of agency refers to the experience of initiating and controlling one's actions and their consequences, and it can be further subdivided into internal agency, or the experience of controlling one's own body, and external agency, which involves perceiving control over changes in the environment [6], [21], [22]. The sense of ownership describes the feeling that a body part or tool belongs to oneself, often shaped by congruent visual and tactile feedback [4]. Peripersonal space defines the boundary of the space around the body that is accessible for interaction [4]. Together, these components form the perceptual foundation of embodiment. They are malleable experiences that can be altered by the sensory feedback a user receives from their device and environment [4], [23]. By altering sensory feedback to users, we are able to alter their perceptions of embodiment [4], [23], and their relationships with technologies.

To study embodiment in human-machine interfaces, researchers have developed both explicit and implicit methods for quantifying its components. Explicit measures, such as validated questionnaires, ask participants to consciously reflect on their experience of control, ownership, or spatial integration. These approaches have been widely adopted across experimental paradigms, but they are limited by susceptibility to response bias, including factors like social desirability, expectation effects, and subjective interpretation [15], [21], [22], [24]. In contrast, implicit measures aim to capture subconscious or automatic responses that reflect embodiment without requiring deliberate introspection. These include changes in time perception, physiological responses such as skin conductance, and sensorimotor illusions induced through multisensory feedback [18]. Implicit approaches offer greater resistance to cognitive bias and are often better suited for capturing subtle or dynamic changes in perception. Yet, their interpretation is often complicated by unresolved debates over their validity. For example, it remains unclear whether certain time-based illusions directly reflect agency or more general causal inference processes [16], [25], [26], [27], a topic further discussed in chapter three of this work. Despite these challenges, implicit methods continue to play a vital role in embodiment research, offering an additional layer of insight into how users form relationships with assistive and autonomous systems.

To address the limitations of existing measurement approaches, researchers have increasingly turned to psychophysics: a branch of perceptual science focused on quantifying the relationship between physical stimuli and subjective experience [18], [27]. Psychophysics provides a rigorous foundation for capturing both the bias and acuity of perceptual judgments [28], [29], offering a more precise alternative to current measurement techniques. One widely used tool in psychophysics is the psychometric function, often modeled using the cumulative normal function. These curves describe the probability of a particular perceptual judgment as a function of stimulus magnitude, allowing researchers to extract key parameters such as the point of subjective equality and just-noticeable difference [28], [30], [31]. In the context of embodiment, and in this work, this enables a novel and precise analysis of how users perceive action-outcome relationships, spatial displacement, or temporal delays, providing methods to validate implicit measures of agency and ownership.

Mixed effect models are another quantitative strategy widely applied in the fields of psychology and human factors research [32], [33]. Able to account for individual variability and repeated measures, researchers are able to model both fixed and random effects across participants, improving their statistical power and generalizability across paradigms [33]. Mixed effect models may help establish frameworks to measure embodiment during HMI interactions, informing designers on user experience. By combining the precision of psychometric modeling with the flexibility of mixed effect frameworks, psychophysics offers a reproducible and scalable method for developing validated, theory-grounded metrics to quantify embodiment in human-machine interaction.

1.2 Objective:

The objective of this thesis was to develop and validate quantitative psychophysics models for the sense of embodiment as it relates to human-machine interactions. This work aims to measure embodiment through experimental paradigms that manipulate sensory feedback and volitional control, and to quantify perceptual changes across agency, ownership, and peripersonal space. Specifically, we are going to use generalized mixed effect models to quantify how changes in interface design (haptic feedback, user control, anthropomorphic position) affects four widely used embodiment metrics (sense of agency questionnaire, sense of ownership questionnaire, intentional binding, and proprioceptive drift). The aim is to help contextualize findings across experimental paradigms using a quantifiable framework that can reframe contradictory evidence from different interface experimental designs. We also aim to use cumulative normal function analysis on intentional binding, an implicit measure for the sense of agency, to precisely quantify and further validate its use in embodiment. Together, these modeling approaches help relate findings in the field and establish a framework to evaluate the sense of agency, a component of embodiment, reliably. This thesis contributes to the broader goal of improving the design, acceptance, and societal integration of autonomous and collaborative systems by grounding user experience metrics in perceptual science.

1.3 Thesis Outline:

In this thesis, we conduct psychophysics analyses to quantitatively measure the sense of embodiment during human-machine interactions. The first chapter is meant to introduce the theory of embodiment, psychophysics, the challenges faced in the research field and present an outline of this thesis.

The second chapter presents how four embodiment metrics (sense of agency questionnaire, sense of ownership questionnaire, intentional binding, and proprioceptive drift) change with different upper limb prosthetic interface parameters (control via EMG, haptic feedback on fingertips, and anthropomorphic position of a robotic hand); quantified using generalized mixed effect models. We also examined the relationships between the embodiment measures and their implications with established literature; showing both conflicting and supporting results.

The third chapter builds on the findings of the second, exploring the validity of intentional binding; utilizing cumulative normal function regression to explore how time perception changes after coordinated whole-limb motor actions. We make a claim on the validity of intentional binding, put forth a new metric for the sense of agency, and develop a new framework for measuring the sense of agency during HMI interactions.

This thesis finally concludes by proposing future directions for establishing, validating, and applying psychophysics paradigms that quantify the embodiment in HMI interactions.

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Chapter 2. Quantifying Prosthetic Embodiment: Interactions Between Agency, Ownership, and Peripersonal Space in a Closed-Loop Sensorimotor Task

The majority of this chapter has been submitted for publication in the Journal of Neuroengineering and Rehabilitation as:

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2.1 Preface

This chapter reports generalized linear mixed-effects models of embodiment metrics recorded during an actively controlled rubber-hand-illusion study that manipulated sensorimotor feedback. This is a multiauthor publication that involved contributions from several graduate students and faculty members. Prior to my involvement, the experimental paradigm was published as a conference paper [55] that demonstrated the feasibility of the experimental setup in successfully manipulating the sense of ownership (SoO), sense of agency (SoA), and peripersonal space (PPS) using seven healthy, able-bodied participants. My specific contribution to this newly submitted work included repairing the apparatus, adding fourteen new participants, aggregating the data, and building the statistical models. With guidance from Kihun Hong and Richard Whittle, I quantified how sensorimotor conditions alter ownership, agency, intentional binding, and peripersonal space, and I prepared the initial introduction and discussion. Kihun Hong refined the figures and drafted the results, and together with Suniyya Waraich and Jonathon Schofield polished the final manuscript. This chapter clarifies the current limits of generalising embodiment metrics and informs future HMI research.

Prosthesis use provides a uniquely rich model for investigating embodiment because it requires the user to control and cooperate with a mechatronic appendage as if it were part of their own body. The integration of an artificial limb into the body schema is influenced by sensorimotor feedback, trust, and perceived agency, mirroring many of the challenges discussed in the introduction for autonomous and collaborative systems. By studying embodiment in this context, we can better understand the factors that promote seamless human–machine integration, develop standardized tools to evaluate these factors, and identify design approaches that mitigate barriers to adoption. In doing so, this chapter directly supports the thesis objective of translating embodiment theory into practical frameworks for improving user acceptance and performance across diverse HMI applications.

2.2 Introduction

Advancements in mechatronic upper-limb prostheses now offer sophisticated control, dexterity, and sensory feedback, with significant potential to improve independence and quality of life for individuals with limb amputation [1–4]. Despite these recent technological strides, users often continue to experience frustration when interacting with these devices, which can hinder both acceptance and sustained use of emerging prosthetic technologies [5, 6]. As upper-limb prostheses continue to evolve, the goals of modern mechatronic designs are shifting; not only to improve functional outcomes but also to promote seamless integration with the user, enabling the prosthesis to respond naturally and precisely to their intentions. In parallel, there is growing recognition that evaluating these systems requires more than assessing technical or functional performance; it also calls for a deeper understanding of how users perceive and relate to their devices. Increasingly, prosthetic embodiment is emerging as a goal for users to experience the device and its actions as part of their own body [1, 3, 7].

The sense of embodiment, the perceptual experience of owning and controlling a body or non-corporeal objects in space, has been understood to arise from three key perceptual components: sense of ownership (SoO), sense of agency (SoA), and peripersonal space (PPS), alternatively termed self-location [8]. SoO refers to the feeling that a body part belongs to oneself and is believed to be modulated by congruent visual and, most often, tactile sensory feedback [9–12]. SoA is the experience of controlling one's actions and their consequences, shaped by the congruence between motor intentions, internal predictions of their outcomes, and the actual sensory consequences of those actions (e.g., feeling the movement of a limb in response to one's intention to move it) [11, 13–16]. Lastly, PPS is defined as the dynamic envelope of space to which the body occupies and can interact with the external environment [9, 17–20].

Experimental paradigms have demonstrated that these perceptual components over artificial limbs or objects can be altered through the manipulation of multisensory cues. One well-known paradigm is the rubber hand illusion (RHI), which provided empirical evidence that individuals can develop a sense of body ownership over a rubber hand when synchronous visuotactile stimulation is applied to both the real and rubber hands [9]. Later adaptations of the paradigm incorporated voluntary movements, demonstrating that the perception of authorship over intended movements can also emerge through congruent sensorimotor engagement [13, 21, 22].

Embodiment may play a key role in supporting the psychological and physiological integration of a prosthesis, with the potential to shape both the user’s propensity to adopt and effectively use the device [7, 23]. Perceptually, the sense of embodiment describes the experience of recognizing oneself as an autonomous agent, controlling a physical body while interacting within an external environment [6]. Importantly, this experience is highly malleable and can extend beyond the biological body [9, 10, 24–29], laying the groundwork for prosthesis embodiment [30, 31]. In turn, this may allow prosthetic devices not only to restore motor function, but also to meaningfully substitute for the user’s sense of bodily presence and agency.

Understanding how these components of the sense of embodiment interact, and how they can be modulated through a device’s motor behaviors and sensory feedback, may offer a critical pathway for assistive systems to promote a seamless and coherent sense of integration within users’ sensorimotor control loops [6, 23, 24, 32–34]. While it is recognized that the sense of embodiment can be essential for fostering this integration with upper-limb prostheses, there remains a lack of consistency in how it is measured, with a variety of disparate techniques employed to quantify its effects [1, 3, 7]. Among the most common measurement approaches are explicit methods, which typically use validated questionnaires to assess the conscious perception of an artificial limb, and implicit methods, which evaluate behavioral, autonomic, or perceptual changes that occur behind conscious perception when a limb is embodied. Two prominent examples of implicit measurements include the assessment of SoA through intentional binding, distortions in time perception between self-generated actions and their sensory outcome; and PPS through proprioceptive drift, a non-conscious change in which one's sense of body part position shifts toward an embodied inanimate object [28, 35–39].

In various domains, including advanced prostheses, explicit and implicit measures are not applied consistently across studies, and there is ongoing debate about whether they capture the same underlying constructs or reflect distinct aspects of embodiment [1, 7, 40]. This lack of conceptual clarity complicates the interpretation and comparison of findings [1, 3]. Further amplifying these challenges, it is well recognized that there are relationships between SoO, SoA, and PPS; however, how they influence one another remains poorly understood and inconsistently defined. For example, ownership and agency often emerge together when individuals engage with non-biological objects using congruent multisensory feedback [13, 21, 36]. On the other hand, these experiences appear dissociable, with one present in the absence of the other [13, 41, 42]. Proprioceptive drift is often interpreted as an implicit measure of SoO. However, recent studies have questioned the reliability of this association, suggesting that proprioceptive drift may instead reflect changes in peripersonal space (PPS) rather than ownership [9, 18, 19, 37, 38, 43]. Similarly, the relationship between explicit SoA and intentional binding as an implicit behavioral marker of SoA, remains contentious [35, 44–48].

These ambiguities are further complicated by the fact that our understanding of the sense of embodiment and its assessment paradigms has been primarily developed through studies involving healthy individuals with intact limbs and no sensorimotor impairments. Thus, studies that systematically investigate the psychometric validity of these measures in affected populations, such as individuals using modern prosthetic limbs, remain sparse. For example, it has been shown that prosthetic systems delivering sensory feedback that closely matches the stimulation of missing hands in sensory modality, somatotopy, and temporality can readily promote a strong sense of ownership over the prosthetic limb [49]. Yet, despite advances in upper-limb prosthetic control systems, most commercially available devices still do not fully achieve this fidelity and replicate the seamless and intuitive control and feedback found in biological limbs. Users often encounter delays in system response that can interfere with natural movement timing [50], control inaccuracies that can compromise the execution of intended movements [51], and a reliance on predefined grasping movements that limit functional flexibility [52], all of which may directly influence the SoA over the prosthesis.

Furthermore, sensory feedback in prosthetic systems remains largely experimental, and many systems rely on sensory substitution techniques, such as vibrotactile stimulation applied to the residual limb, that do not align with the natural somatotopy or sensory modalities of the missing limb [53]. While direct electrical stimulation of residual peripheral nerves can evoke somatotopically appropriate sensations, these are often described as buzzing, tingling, or other sensations that are not perceptually congruent with naturalistic modalities such as touch or associated contact forces [54]. The mismatch between the type and location of sensory feedback and the natural sensory experience anticipated from an intact limb can result in an artificial feeling, which can impede the development of SoO over the device. Thus, without validation efforts, it remains difficult to understand how embodiment emerges and presents in modern prosthetic systems, given these current differences from the biological control and sensory experience of a biological limb.

In our previous work [55], we developed and validated a prosthetic-like system and methodology capable of strategically manipulating sensory and motor variables that support the formation of the SoO, SoA, and PPS. By leveraging our previous work, the goal of the current study was to develop a more complete understanding of the dynamic nature of the sense of embodiment under factors reflective of advanced upper-limb prosthesis use. Specifically, we aimed to characterize the relationships between explicit agency and ownership questionnaires alongside implicit measures, including intentional binding and proprioceptive drift.

We hypothesize that: H1. Congruent sensory feedback (i.e., spatial alignment and tactile feedback) combined with voluntary control will increase implicit and explicit measures of ownership and agency, H2. Relationships between explicit SoO and PPS will show no correlation, supporting the idea that PPS and self-location represent a distinct component, adding to the greater sense of embodiment, H3. Intentional binding and explicit SoA will emerge together under congruent sensory and motor conditions, but dissociate under incongruent conditions, H4. Explicit and implicit measures of SoO and SoA will show positive correlations, indicating partial overlap between conscious and non-conscious dimensions of embodiment.

2.3 Methods

2.3.1 Participants

We recruited a cohort of able-bodied participants (N= 23) aged 18-30 years (mean age: 21.3 years; 53% male). All participants provided written informed consent prior to participation, and protocols were approved by the UC Davis Institutional Review Board. All participants were right-handed as verified by the Edinburgh Handedness Inventory [56]. Exclusion criteria included cognitive deficits, limited hand movement due to acute or chronic injury or disease, and neurological or musculoskeletal conditions affecting biological motor control and/or sensory perception.

2.3.2 Experimental setup

Participants were seated at a dual-layered table, where a robotic right hand positioned on the upper surface of the table while their own right hand remained hidden under the table [55]. Following the classic rubber hand illusion paradigm [9], a cloth was draped over the participants' shoulders to enhance the visual impression that the robotic hand was part of their body, replacing their real hand. Participants were instructed to keep their left hand resting on the upper layer of the table while maintaining their right hand in a fixed position on the lower layer of the table throughout the experiment.

The experimental setup was designed to manipulate three key sensorimotor variables, including the position of the robotic hand, the level of control that participants had over the hand, and the presence of tactile feedback they received. The setup included the following components, as illustrated in 1a: (1) A custom-built robotic hand capable of open-close grasping movements, covered with a black nitrile glove to match the participant's hand and enhance the visual illusion (2) Capacitive force sensors (SingelTact, Glasogow, UK) embedded in the robotic hand's digits (index, middle, and thumb) to detect object contact during grasping, (3) A wearable electromyography (EMG) armband (Thalmic Labs, Waterloo, Canada) used to read participants' muscle activity and translated it into a single degree of freedom (grip open/close) for robotic control, (4) A sensory feedback system comprising: a custom-built tactile vibration feedback glove delivering to relevant fingertips [9, 18, 57], an LED light indicating voluntary grasping actions as a visual feedback, and a piezoelectric speaker to emit auditory feedback corresponding to the subsequent sensory event, (5) Headphones to dampen background noise and present an auditory tone, as well as (6) A 'light box' placed on the upper layer, geometrically identical to a 'blank box' on the lower layer, allowing participants to perform grasping tasks with both the robotic and their actual hand respectively.

This setup ensured precise control over sensory and motor conditions and was previously validated as capable of perturbing SoO, SoA, and PPS [55].

2.3.3 Experimental protocol

In each trial, participants either actively grasped the 'blank box' on the lower layer of the table using their right hand while the EMG armband detected muscle activity to actuate the robotic hand to synchronously grasp the "light box" on the upper layer or passively observed the robotic hand's movement. As illustrated in Fig. 1a, the LED on the 'light box' illuminated immediately upon grasping, followed by an auditory tone presented after a variable time delay ranging from 0 to 1 second. This LED-auditory tone sequence was designed to facilitate measurement of the SoA through intentional binding (see outcome measurements below). Together, this setup enabled perturbation of the SoO, SoA, and PPS by manipulating the following factors (also shown in Table 1):

Table 1 Overview of manipulated sensorimotor conditions and time delays.

		Levels	Description
Manipulated sensorimotor conditions (9 conditions)	Sensorimotor feedback conditions	BUZ	VIB[1] on + Active control
		NB	VIB[1] off + Active control
		WAT	VIB[1] off + Passive control
	Robotic hand positions	C	No offset from the actual hand
		M	200mm
		F	400mm
Time delay of auditory tone (ms)		300	Randomized and evenly distributed across experimental blocks
		500	
		700	

[1]VIB: Tactile vibration feedback.

The experiment comprised 9 blocks, each corresponding to one of the 9 combinations of sensorimotor feedback (3 levels) and robotic hand position (3 levels). Within each block, participants completed 18 trials: 6 repetitions of each of the three time-delay conditions presented in a randomized order to prevent biased interval estimation. Block order was randomized across participants (totaling 18 trials per block and 162 trials per participant), as illustrated in Fig. 1b and Table 1.

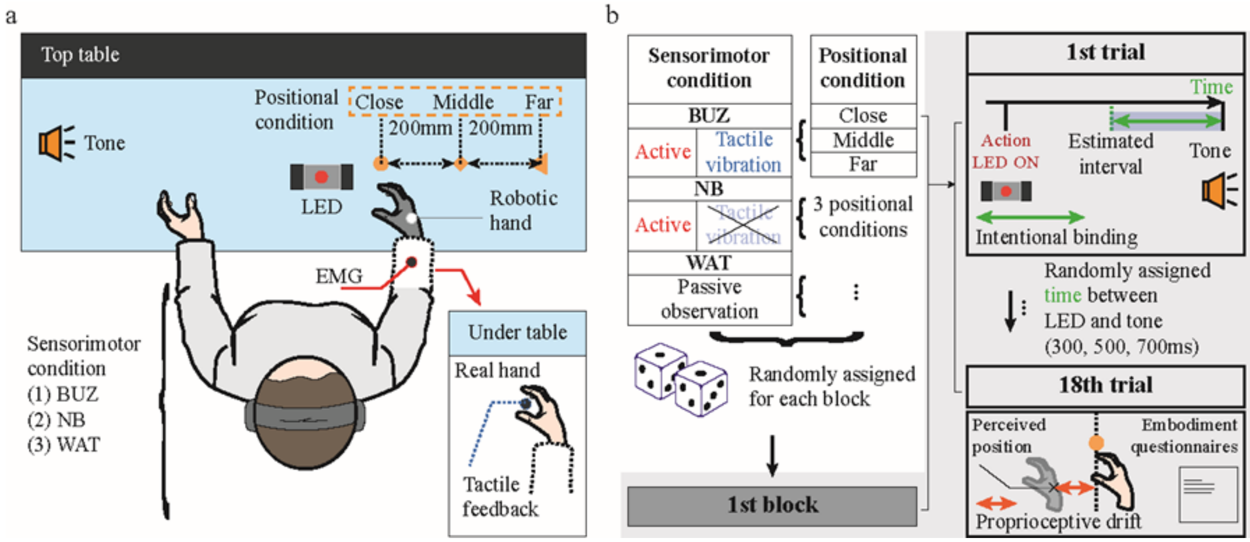

Fig.1 Schematic design of experimental setup and process. a. Description of experimental setup to systematically investigate how visual, tactile, and motor cues shape the sense of embodiment through sensorimotor integration. Participants interacted with a robotic hand positioned at one of three positions (close, middle, far) on the upper layer of the table. The experiment included three sensorimotor conditions: BUZ (active control with tactile feedback), NB (active control without tactile feedback), and WAT (passive observation without control) b. Participants experienced nine conditions, combining three sensorimotor conditions (BUZ, NB, WAT) with three hand positions (close, middle, far). These conditions were randomly assigned to blocks. Within each block, trials involved random assignment of time intervals (300ms, 500ms, 700ms), each repeated six times. Participants reported intentional binding by estimating the perceived time interval between LED activation and the auditory tone per trial. At the end of each block, they completed embodiment questionnaires and proprioceptive drift measurements by indicating the perceived location of their right hand to assess changes in the perceived position of their hand.

2.3.4 Outcome measurements

Fig. 1b illustrates the procedure used to measure each component of the sense of embodiment, including explicit SoA, SoO, intentional binding, and peripersonal space. As an evaluation of the subjective sense of embodiment, we implemented a 16-statement ownership and agency questionnaire (Supplementary Information, Table1), which included questionnaires to control for task compliance, suggestibility, and expectancy effects. These statements were adapted from established questionnaires used in traditional rubber hand illusion experiments [8, 9]. At the end of each block, participants rated the statements on a Likert-scale ranging from -3 (totally disagree) to +3 (totally agree), with randomized question order.

The formation of SoA was also implicitly assessed using verbal estimation of the temporal interval between LED illumination (representing the active action) and the auditory feedback (the subsequent sensory outcome). Participants reported their perceived interval in milliseconds from 0 to 1 second per trial, a method validated in previous studies on intentional binding [46, 58–61]. A shorter perceived duration of this interval is associated with a stronger sense of agency [44, 62, 63].

Finally, PPS was assessed through proprioceptive drift. However, it is also important to note that this phenomenon is often also used as an implicit measure of SoO [9], and agreement on which construct proprioceptive drift most closely measures remains debated [37, 38, 43, 64]. At the end of each block, participants closed their eyes and used their left index finger to indicate the perceived position of their right hand. This perceived position was then marked on the upper layer. Proprioceptive drift was quantified as the distance between the indicated and actual hand positions [65]. Thus, proprioceptive drift relative to the actual position of the hand was measured as a change in the perceived location of the hand in the direction of the robotic hand.

2.3.5 Statistical analysis

The goals of our analysis were to investigate how sensorimotor information, including spatial alignment, tactile vibration feedback, and active control, contributes to forming a cohesive sense of embodiment, and to examine how implicit and explicit SoO, SoA, and PPS relate to one another. This multi-metric approach allowed us to disentangle their respective contributions, assess how they are modulated by experimental conditions, and explore their potential interrelationships within participants.

Data for each component of the sense of embodiment (SoO, SoA, and PPS) were collected using repeated measures across multiple conditions, with observations nested within participants. Given this hierarchical structure, all response models assessing the effects of possible positions, the presence of tactile feedback, and the presence of active control were constructed with generalized linear mixed-effects models (GLMMs). Three-factor GLMMs were fitted using maximum likelihood estimation with adaptive Gauss-Hermite quadrature [66] to assess the effects of categorical independent variables (position, feedback, and active control). To account for within-subject correlations across repeated measurements, participant was included as a random intercept in all models. Intentional binding data followed an approximately normal distribution, justifying the use of a Gaussian family with an identity link function (i.e., the expected value of the outcome variable μ is given by $\mu = \eta$, where η represents the linear predictor). Distributions of agency and ownership scores, as well as proprioceptive drift, showed deviations from normality, exhibiting heavy tails with potential outliers. To accommodate these distributional properties, models for these outcomes were specified using a t-family distribution with an identity link function. The t-distribution was chosen for its robustness to non-normality and its ability to accommodate extreme values without disproportionately influencing parameter estimates.

Model comparisons were then conducted using an information-theoretic approach with Akaike Information Criterion (AIC) [67], to identify the best-fitting models. For the selected models, diagnostic plots for all models were visually inspected to verify the normality of residuals, and Levene's test was used to evaluate homoscedasticity. The linear predictor was used to generate curves for each outcome variable measured. Summaries of all models for each measurement are provided in the Supplementary Information, Table1-4.

To assess correlations between outcome variables within participants, each outcome was standardized using a z-score transformation, ensuring comparability across scales by subtracting the mean and dividing by the standard deviation. This standardization allowed direct comparisons of effect sizes. A linear mixed-effects model (LMM) was then constructed to examine the effects of independent variables on these standardized outcomes while accounting for inter-individual variability. The model included fixed effects for the interaction between outcomes, positional conditions, feedback status, and activity status, while also incorporating a random intercept for each outcome within participants to capture inter-individual variability.

To further investigate relationships between outcomes within participants, the variance-covariance matrix of the random effects was extracted and transformed into a correlation matrix. This transformation enabled standardized interpretation of within-participant relations: positive values indicated that outcomes tended to increase together, negative values suggested inverse relationships, and values near zero implied minimal correlation.

All statistical analyses were conducted using R version 4.3.3 via RStudio, and plots were generated with the ggplot2 package. GLMMs and LMMs were implemented using the glmmTMB function from the glmmTMB package [68] and the lmer function from the lme4 package [69], respectively. The DHARMa package was used for diagnostic assessment [70]. Variance-covariance matrices were calculated using the VarCorr function from the nlme package [71] and converted to correlations using the cov2cor function. Adjusted means and contrasts were calculated using the emmeans package, with Tukey's Honest Significant Difference (HSD) correction for multiple comparisons, with a significance level set at $\alpha = 0.05$ (two-sided) [72].

2.4 Results

2.4.1 Explicit sense of agency

We found a significant difference between agency questionnaires and their control questionnaires, averaging the results over levels of the independent variables using the fitted generalized linear mixed model that included question type and independent variables (estimate = 1.44; SE= 0.0262; z.ratio = 55.04; $p < 0.001$ with Tukey's adjustment), Fig. 2a. Fig. 2 presents the estimated marginal means of SoA ratings, with 95% confidence interval, across experimental conditions.

The effects of the main independent variables on explicit SoA were also assessed, indicating that active control, the presence of tactile vibration feedback, and robotic hand position had significant effects on the estimated model compared to a reduced model ($\chi2$ = 17437.61; df = 1, $p < 0.001$ for active control, $\chi2$ = 51.91; df = 1, $p < 0.001$ for the presence of tactile vibration feedback, and $\chi2$ = 39.07; df = 2, $p < 0.001$ for robotic hand positions), Table 2.

Participants reported a significantly higher sense of agency when tactile vibration feedback was present during active control (BUZ; score: 2.07 ± 0.04), compared to when no feedback was given (NB; score: 1.87 ± 0.03) (Fig. 2a). This difference was statistically significant (Tukey-corrected post-hoc analysis 95% CI [0.29,0.40], $p < 0.001$). Furthermore, active control had a significant positive influence on agency scores across all position levels, compared to the WAT conditions in which participants only observed the robotic hand's movement ($p < 0.001$), which produced the lowest scores, ranging from -0.49 ± 0.09 to -1.14 ± 0.07 across all positions.

To assess potential interactions between spatial and sensorimotor factors, we conducted pairwise comparisons between spatial conditions within the two sensorimotor conditions (Fig. 2b). We found that placing the prosthetic hand farther from the participant's body significantly reduced the explicit sense of agency when intention, movement perception, and visual information were congruent along with tactile vibration feedback (BUZ) ($p < 0.001$). For example, in the BUZ condition, the agency score decreased from 2.07 ± 0.04 at the close position to 1.86 ± 0.04 at the far position, with a statistically significant difference (95% CI [0.24,0.35], $p < 0.001$).

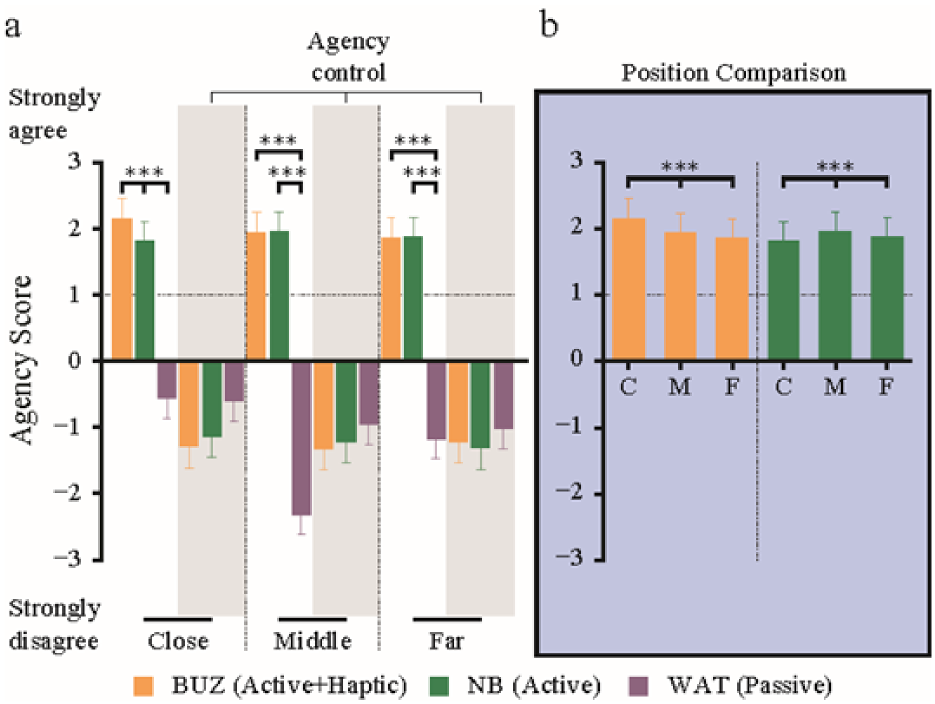

Fig.2 Measure of explicit sense of agency depending on sensorimotor conditions. Estimated marginal mean values of agency scores across participants with error bars indicating the 95% confidence interval. Values were obtained from a generalized mixed-effects model that included the prosthetic hand's position, voluntary control, and tactile feedback (BUZ: voluntary control with tactile vibration feedback, NB: voluntary control without tactile vibration feedback, WAT: passive control) as fixed effects, and participant (N=23) as a random intercept to account for individual differences. The cut-off for sense of agency score is 1, indicated by the horizontal,

dashed line [72,73]. a. Changes in explicit sense of agency- question ratings and control-question ratings (gray-shaded rectangles) across different experimental conditions (combinations of hand position and sensorimotor conditions: BUZ, NB, and WAT) b. Comparisons between different prosthetic hand positions within the BUZ and NB. The asterisk indicates statistically significant pairwise differences ($p < 0.001$, Tukey-corrected post hoc test) between conditions sharing the same position of the prosthetic hand and the same sensorimotor context.

2.4.2 Intentional binding

Fig. 3 illustrates how spatial congruency and sensorimotor factors influence perceptual time compression between intention and outcome (intentional binding). Fig. 3 indicates the estimated marginal means of the perceived time delay (between the LED illumination and the subsequent tone), with 95% confidence intervals across experimental conditions. According to the fitted model, the presence of tactile vibration feedback had a significant effect on intentional binding responses ($\chi 2 = 61.44$; df = 1, $p < 0.001$), while the presence of active control also had a significant but weaker effect ($\chi 2 = 4.75$; df = 1, $p = 0.03$), summarized in Table 2. Pairwise comparisons between conditions with and without tactile vibration feedback revealed that tactile vibration feedback enhanced intentional binding across all robotic hand positions (close: -82.61 ± 9.59 ms; medium: -75.48 ± 10.82 ms; far: -97.83 ± 10.17 ms), exhibiting a significant difference compared to the NB condition (95% CI's: [33.53,84.58], [24.59,75.65], and [42.11,93.16] for close, medium and far respectively, $p < 0.001$), as shown in Fig. 3.

Although participants had active control over the prosthetic hand without tactile vibration feedback (NB), Fig. 3 showed that it had slightly weaker binding than the involuntary control (WAT condition). However, these differences were not statistically significant (95% CI [-13.45,37.60], $p = 0.35$ for the close position; 95% CI [-12.24,38.81], $p = 0.31$ for the middle position; and 95% CI [-1.73,49.32], p = 0.06 for the far position). Moreover, robotic hand positions alone did not significantly affect intentional binding across conditions (p > 0.05).

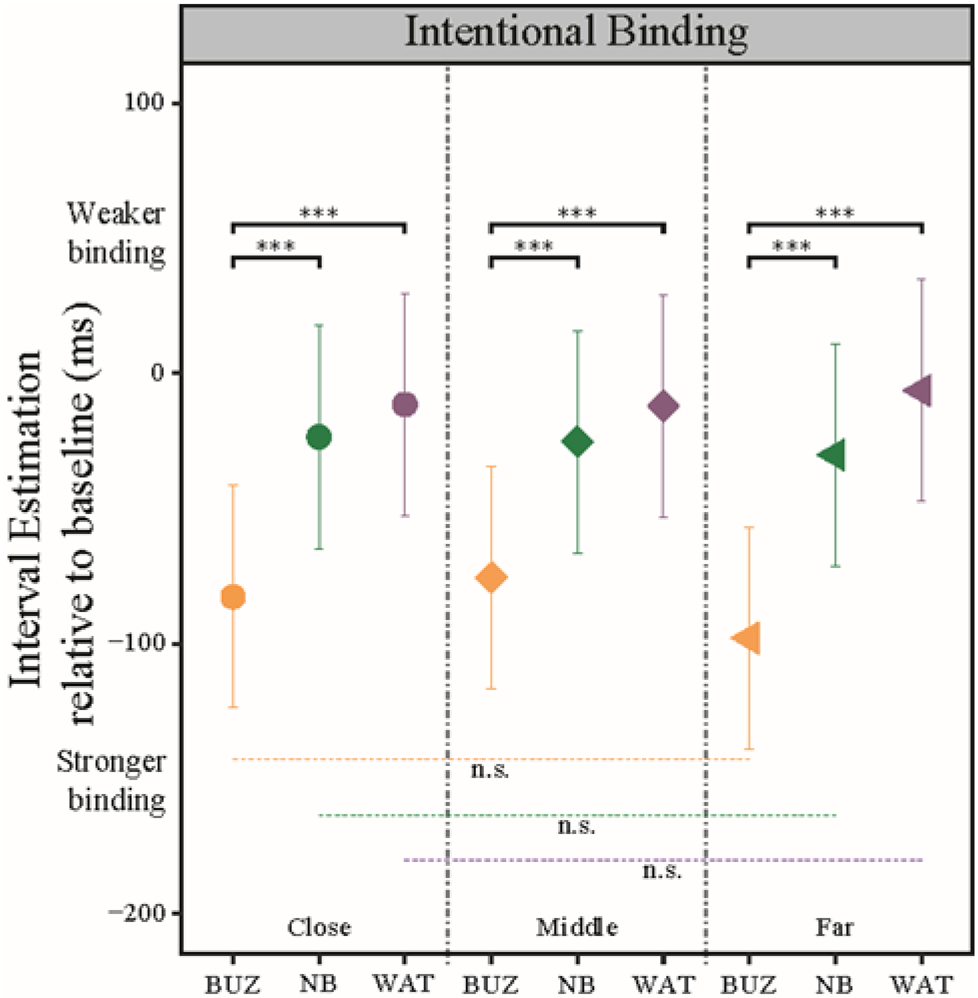

Fig.3 Intentional binding across sensorimotor conditions. Participants estimated the perceived time interval between an action (LED illumination) and its sensory outcome (auditory tone). After subtracting actual time delay from the estimated time, it was used to capture the effects of independent variables. Marginal mean values with 95% confidence intervals were derived from a generalized mixed-effects model which had prosthetic hand position, voluntary control, and tactile feedback as fixed effects, and participant (N=23) as a random intercept to capture variation among individuals. Asterisks indicate statistically significant differences between

pairwise comparisons between conditions with the same prosthetic hand position ($p < 0.001$, Tukey-corrected post hoc test).

2.4.3 Explicit sense of ownership

To examine how participants perceive the feeling of "mine" toward their own body part, i.e., a sense of ownership, we manipulated sensorimotor variables along with spatial congruency. Using generalized mixed-effects models, we observed a significant difference between the explicit SoO scores (Q1-Q4) and explicit control scores (Q5-Q8), averaged across all levels of the independent variables, determined by pairwise comparison with Tukey' adjustment (mean difference = 0.89; SE = 0.02; $p < 0.001$), as shown in Fig. 4a.

Responses to the explicit questionnaires (Q1-Q4) indicate uncertainty, with scores falling within the uncertainty range of 0 to 1, where a score of 1 serves as the cut-off for a definitive sense of ownership [73, 74]. The explicit ownership scores for BUZ and NB at the close position were 0.98 ± 0.05 and 0.71 ± 0.05, respectively, both slightly below the cut-off score of 1 and not significantly different from it (z.ratio = -0.18; $p = 0.858 > 0.05$ for BUZ; z.ratio = -1.83; $p = 0.0674 > 0.05$ for NB) based on Wald tests with post-hoc comparisons using Sidak adjustment (see Fig. 4a). While the estimated scores remained in the positive uncertainty region, Fig. 4a shows that the explicit ownership was significantly influenced by the presence of active control ($\chi2 = 1027.00$; df = 1, $p < 0.001$), the presence of tactile vibration feedback ($\chi2 = 20.85$; df = 1, $p < 0.001$), and robotic hand positions ($\chi2 = 110.90$; df = 2, $p < 0.001$), Table 2.

Ownership scores decreased from BUZ to NB, indicating a reduced sense of ownership over the robotic hand in the absence of tactile vibration feedback, particularly at the close and middle positions. These placement-related differences were statistically significant (95% CI [0.15,0.38], $p < 0.001$ for close position; 95% CI [0.09,0.36], $p < 0.001$ for medium position). Similarly, when participants actively controlled the robotic hand without tactile vibration feedback (NB), they reported a higher sense of ownership than in the WAT condition (estimated marginal mean difference between NB and WAT: 95% CI [1.20,1.44], $p < 0.001$ for the close position; 95% CI [0.78,1.02], $p < 0.001$ for the medium position; 95% CI [1.03,1.27], $p < 0.001$ for the far position),as shown in Fig. 4a.

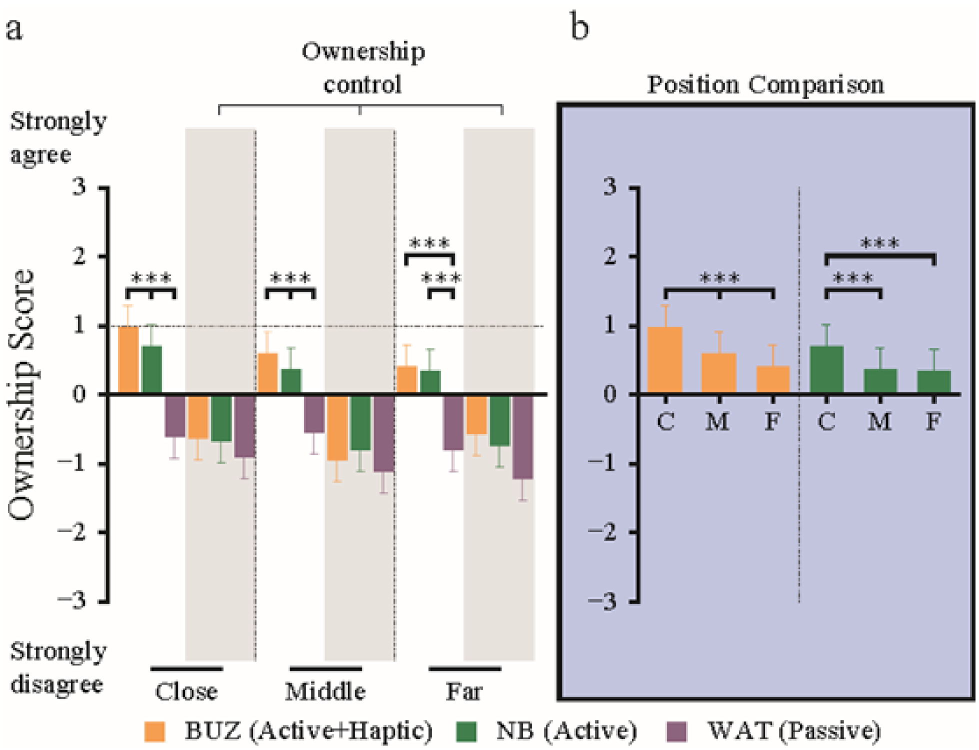

Fig.4 Explicit sense of ownership across sensorimotor conditions. Estimated marginal mean values with 95% confidence interval from the generalized mixed-effects model that include prosthetic hand's position, voluntary control, and tactile feedback (BUZ: voluntary control with tactile vibration feedback, NB: voluntary control without tactile vibration feedback, WAT: passive control) as fixed effects and participant (N=23) as a random intercept to capture variation among individuals. The cut-off score for sense of ownership is 1, indicated by the horizontal, dashed line (72,73). a. Change in the explicit sense of ownership ratings and control-question ratings (gray-shaded rectangles) across different experimental conditions (combinations of robotic hand position and sensorimotor feedback condition: BUZ, NB, and WAT) b. Comparisons between different prosthetic hand position within the BUZ and NB. The asterisk indicates statistically significant differences between pairwise comparisons of (Tukey-corrected

post hoc test, $p < 0.001$) conditions sharing the same position of the prosthetic hand and sharing the same sensorimotor condition.

We next assessed the impact of position levels within the same sensorimotor condition. As Fig. 4b shows, placing the robotic hand farther from the participant's real hand significantly decreased the ownership score. For example, in the BUZ condition, the score dropped from 0.98 ± 0.05 at the close position to 0.40 ± 0.05 at the far position, with a statistically significant difference (95% CI [0.45,0.69], $p < 0.001$).

2.4.4 Peripersonal space

We examined how participants perceived the expansion of body-self representation by manipulating robotic hand position and the sensorimotor conditions. Fig. 5 illustrates the estimated spatial expansion relative to the robotic hand's position, with 95% confidence intervals. An ANOVA was conducted to evaluate the effects of the experimental conditions on proprioceptive drift. The results indicated statistically significant main effects of tactile vibration feedback ($\chi2 = 69.35$; df = 1, $p < 0.001$) and position ($\chi2 = 777.77$; df = 2, $p < 0.001$), while active control showed no significant effect ($\chi2 = 0.81$; df = 1, $p = 0.37$), summarized in Table 2.

To assess how each factor influenced the peripersonal space, post-hoc pairwise comparisons were performed using Tukey's adjustment. While participants generally maintained their perceived body representation near their actual hand's position across all sensorimotor conditions, tactile vibration feedback (BUZ) significantly expanded this representation compared to the absence of feedback (NB), as shown in Fig. 5a (mean difference between BUZ and NB: 95% CI [0.94,1.63], $p < 0.001$ at the middle position; 95% CI [0.98,1.74], $p < 0.001$ at the far position). Furthermore, when the robotic hand was placed further from the participant's hand position, their perceived body space substantially expanded within the BUZ condition, as shown in Fig. 5b. This effect was supported by a statistically significant difference between the close and far positions (95% CI for the mean difference from the close position: [2.86,3.60], $p < 0.001$ for the middle position; 95% CI [3.39,4.12], $p < 0.001$ for the far position).

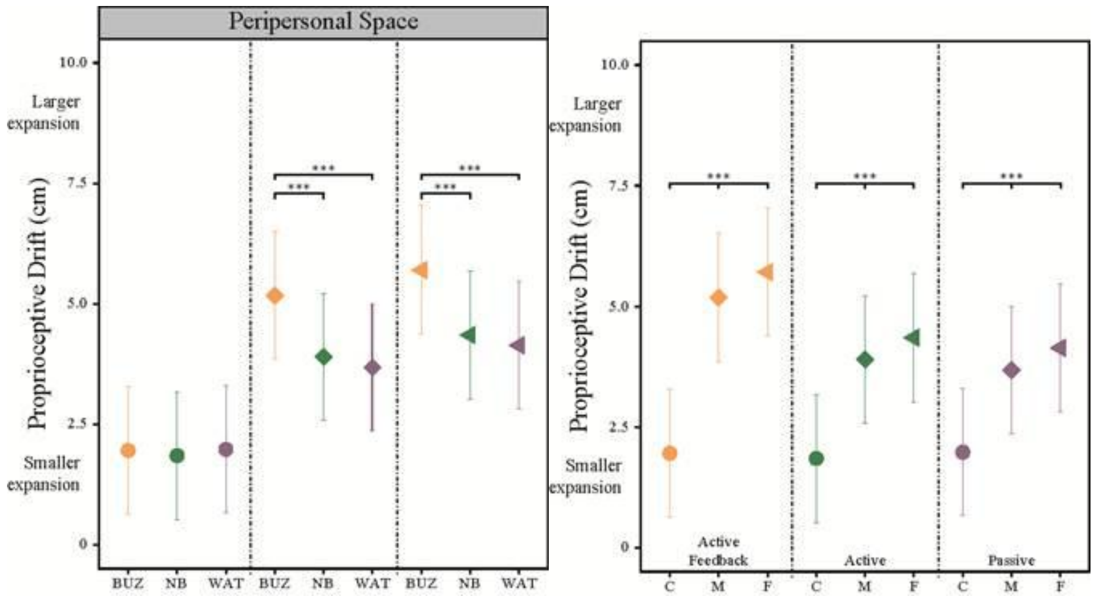

Fig.5 Proprioceptive drift across sensorimotor conditions. Participants estimated the perceived location of their right hand; the proprioceptive drift (unit: cm) was the distance between the participant's perceived and actual hand location. With this measurement, estimated marginal mean values with 95% confidence interval from the generalized mixed-effects model that included prosthetic hand's position, voluntary control, and tactile feedback (BUZ: voluntary control with tactile vibration feedback, NB: voluntary control without tactile vibration feedback, WAT: passive control) as fixed effects and participant (N=23) as a random intercept to capture variation among individuals. a. Change of proprioceptive drift depending on varied independent variables (different positions along with BUZ, NB, and WAT) b. Comparisons between different prosthetic hand positions within the BUZ and NB. Asterisks indicate statistically significant differences (Tukey-corrected post hoc test, $p < 0.001$) in pairwise comparisons between conditions sharing the same prosthetic hand position and the same sensorimotor condition.

Table 2 Summary of effects of manipulated sensorimotor conditions on each measurement.

	Explicit SoA	Intentional binding	Explicit SoO	Peripersonal space
Tactile vibration feedback	17437.6	61.4	1027.0	69.4
Active control	51.9	4.8	20.9	777.8
Robotic hand positions	39.1	1.0	110.9	0.81

2.4.5 Relationships between explicit and implicit sense of agency and sense of ownership

By combining the results from both explicit and implicit measures of SoA and SoO, we illustrated the relationship between these perceptual experiences in Fig. 6. We observed a positive relationship (Fig. 6), indicating that stronger intentional binding, reflected by shorter reported time intervals, is associated with a greater explicit SoA. As shown previously, voluntary control (BUZ and NB conditions) significantly influenced both explicit SoA and intentional binding (see Fig. 2a and 3), supporting this relationship. Furthermore, as described earlier, when tactile vibration feedback and active control were presented (BUZ condition), it led to greater explicit SoO and an expanded PPS toward the robotic hand (see Fig. 4a and 5a). Although differences in explicit SoO were observed between the NB and WAT conditions, no such difference was found in PPS. These patterns are reflected in the correlation shown in Fig. 6, further highlighting the relationship between explicit SoO and PPS.

2.4.6 Relationships between each component of the sense of embodiment

To enable comparisons between the outcome variables of the sense of embodiment, all outcomes were scaled using z-score transformation. A linear mixed-effects model was applied to account for inter-individual variability. The variance-covariance matrix of its random effects was extracted and converted into a correlation matrix to quantify correlations between outcomes, as shown in Fig. 7.

It revealed a moderate positive correlation (r = 0.48) between explicit agency and intentional binding, an implicit measure of agency. Explicit ownership exhibited a strong positive correlation with explicit agency (r = 0.70) and a moderate positive correlation with implicit agency (r = 0.56). These findings suggest a strong interrelationship between explicit and implicit measures of agency and ownership within the embodiment framework. However, we observed that peripersonal space showed no relationship with explicit ownership, with a correlation coefficient of -0.03, and exhibited weak negative correlations with explicit agency, with a coefficient of -0.29, and implicit agency, with a coefficient of -0.11, as shown in Fig. 7. These findings suggest that while agency and ownership are closely linked, peripersonal space may be independent of explicit ownership and only weakly related to agency.

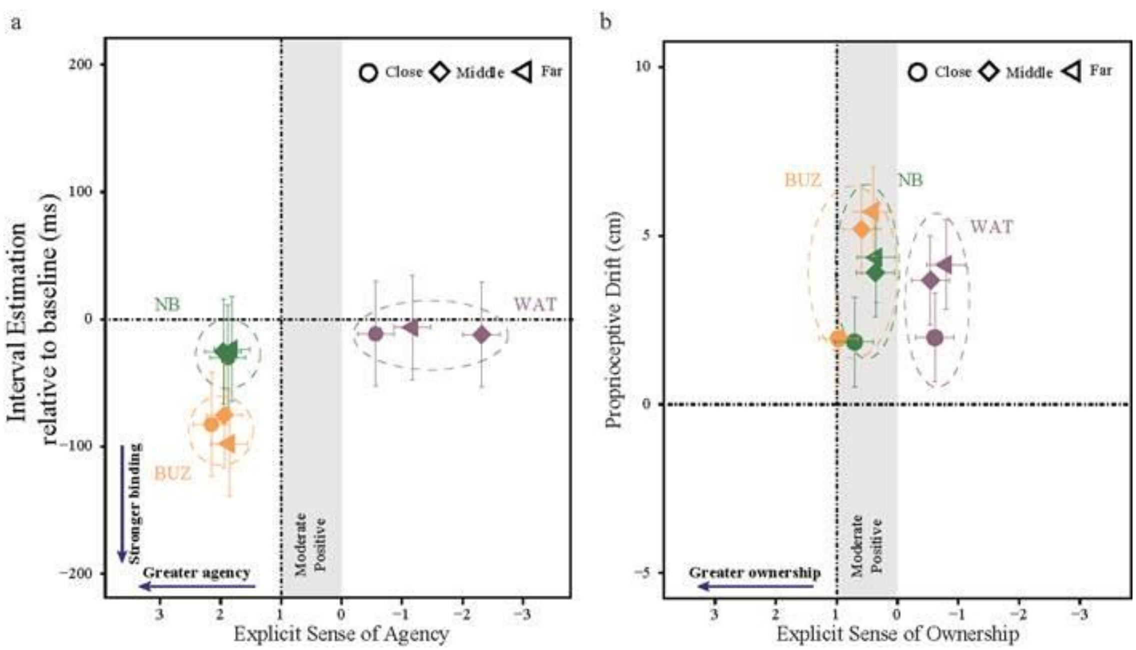

Fig.6 Relationships between each component of sense of embodiment. Estimated marginal means values with 95% confidence intervals for each measurement of each variable are plotted to illustrate the relationship between them. a. Comparison between the explicit and implicit sense of agency. The horizontal dashed line denotes no difference in time interval estimation

from the baseline (intentional binding), and the vertical dashed line indicates +1 cut-off score for an experience of agency. b. relationship between explicit and implicit sense of ownership with the vertical dashed line indicating a cut-off score of 1 for an experience of ownership, and the gray-shaded rectangle highlighting the moderate positive region (where the score of explicit sense of ownership is between 0 and 1).

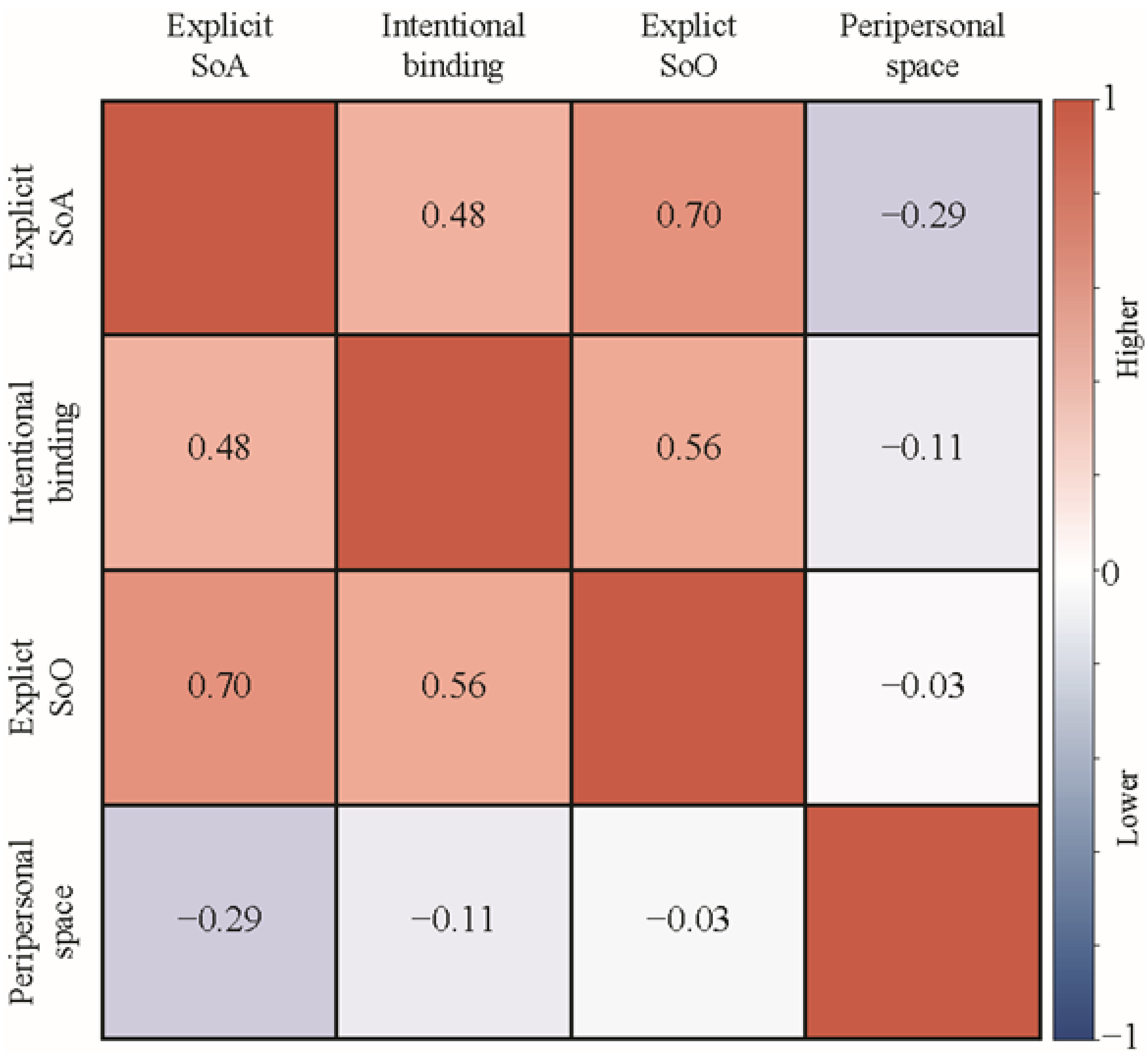

Fig.7 Correlation matrix between four measures of explicit ownership and agency, intentional binding, and peripersonal space**.** Covariance matrix was transformed into correlation matrix, allowing for standardization of relationships between each component of sense of embodiment.

Positive values (red) indicated that outcomes increased together, and negative values (blue) indicated inverse relationships.

2.5 Discussion

Our findings underscore the importance of understanding the complex and dynamic nature of the sense of embodiment for the given context in which it is being assessed, particularly in populations with atypical sensorimotor function such as upper limb prosthesis users. This includes considering how the specific constituent components shaping the sense of embodiment are measured, how these measures relate to one another, and how they may differ from the wealth of literature describing data derived from normative, able-bodied populations. By employing a prosthetic-like system, our study offers a pathway toward a more comprehensive understanding of embodiment in the context of advanced mechatronic upper-limb prosthesis use. Through systematic manipulation of motor control and sensory feedback, we demonstrated that specific components of embodiment, including SoO, SoA, and PPS, can be selectively elicited or suppressed, either independently or in combination. Furthermore, the observed relationships between sensorimotor conditions and embodiment measures, as well as the interrelationships among these measures, did not consistently align with findings reported in the able-bodied cohorts, highlighting the need for tailored approaches in prosthetic embodiment research.

Our results revealed that explicit SoO was present when the robotic hand was actively controlled in both the BUZ and NB conditions, with the strongest effects observed in the BUZ condition, where congruent tactile vibration feedback was present at the participants' fingertips. These results highlight the tight link between internal sensorimotor representations and externally delivered feedback in shaping greater ownership experiences and are consistent with previous studies [75], including studies involving able-bodied individuals [9, 76, 77]. Yet, our data showed ownership questionnaire scores remained within the moderate positive range (a positive score between 0 and 1), not surpassing the established cut-off score for “strong” ownership (> 1) [73, 74]. One possible explanation is that our participants had intact limbs, and the presence of biological kinesthetic and proprioceptive feedback may have had minor incongruencies with the visual and tactile feedback from the prosthetic hand. Nonetheless, the observed strengthening of explicit SoO with tactile vibration feedback suggests that even limited artificial feedback can partially overcome the absence of natural sensation, supporting greater incorporation of a prosthetic limb into the user’s body representation. While the tactile vibration feedback used in our experiment, similar to that employed in many prosthetic systems, inherently lacks the richness and subtlety of natural tactile input, it nonetheless provided sufficient information to modulate ownership experiences. This finding aligns with previous studies [28, 78, 79] and reinforces the notion that some form of tactile feedback, even if simplified, is better than none at all when promoting explicit ownership effects.

We found a greater SoA developed during active control of the robotic hand reinforcing that motor control is a critical contributor to explicit SoA [80, 81]. Additionally, spatial alignment consistently influenced explicit SoA, but only when both active control and tactile vibration feedback were present. This pattern may be explained by the contribution of SoO: when tactile vibration feedback is available, spatial congruency enhances the perception that the prosthesis is part of the body, which in turn strengthens the sense of agency. For example, the BUZ condition (associated with the strongest explicit SoO) also elicited the strongest explicit SoA, suggesting that agency is most robust when directed toward movements of body parts most strongly perceived as one’s own. Our findings support the idea that the explicit SoO and SoA are interrelated, and that achieving both in prosthetic systems may have compounding effects that promote a stronger sense of embodiment of the device. This aligns with existing evidence suggesting that the sense of agency is closely tied to actual bodily movement and is informed by activity from peripheral somatosensory receptors [13, 36]. Thus, when users volitionally actuate a prosthesis, this contributes to forming a sense of authorship over the resulting movement (SoA), which is related to, and may strengthen, the SoO. Conversely, when a prosthetic limb is already associated with a strong sense of ownership, engaging it in movement may further reinforce the SoA. Furthermore, the effect of tactile vibration feedback on the explicit SoA was limited to situations in which the robotic prosthesis was spatially aligned with the actual hand (close position). In contrast, tactile vibration feedback did not significantly influence agency when the hand was positioned at medium or far positions. These findings suggest that voluntary control, when combined with spatially congruent visual and tactile feedback, is critical for maximizing the sense of agency, whereas tactile vibration feedback alone may be insufficient to override the influence of proprioceptive mismatch, as the intact somatosensory system continues to signal the location of the biological limb. Although voluntary motor intention is a key driver of agency, the integration of tactile feedback to enhance the SoA appears to require alignment with internal proprioceptive maps.

We examined two implicit measures that contribute to the greater sense of embodiment: intentional binding, a temporal marker conventionally described as relating to implicit SoA, and peripersonal space, often interpreted as an implicit measure of SoO although some argue it is a distinct perceptual phenomenon [9, 13, 18, 36, 37, 39, 74, 82]. Our findings showed that intentional binding was significantly greater in the BUZ condition, indicating enhanced temporal binding when artificial tactile feedback matched the outcomes of volitional control (the prosthesis contacting the light box). This finding appeared to be independent of spatial alignment. In contrast, no significant difference in intentional binding was found between the NB (voluntary control without tactile vibration feedback) and WAT (passive control) conditions, suggesting that motor intention alone is insufficient to produce temporal compression effects [15, 83–86].

Interpreted within the framework of a comparator model underlying volitional motor control - which states that the brain monitors and adjusts goal-directed movements by comparing predicted sensory outcomes of motor commands with actual sensory feedback - our results suggest that when volitional movement and sensory outcomes align, intentional binding occurs regardless of the spatial congruency of the robotic hand. This highlights the importance of appropriate sensory feedback tightly linked to prosthetic motor actions and suggests that intentional binding depends on the convergence of motor output, predicted sensory consequences, and actual sensory feedback generated during the action [80, 87].

We also found PPS expanded toward the robotic prosthesis only when voluntary control was paired with tactile vibration feedback (BUZ condition), supporting the role of sensory input in integrating the prosthesis into the body's spatial representation. Specifically, the BUZ condition elicited greater PPS expansion compared to the NB and WAT conditions, which lacked this effect. These results align with previous findings demonstrating that artificial tactile vibration, despite its limitations in replicating natural touch, can facilitate prosthetic limb integration into body representation [88, 89].

While proprioceptive drift has traditionally been used as an implicit measure of the sense of ownership (SoO) and reflects the dynamic nature of peripersonal space [9, 13, 74, 82], our findings revealed no significant correlation between explicit SoO and the magnitude of proprioceptive drift. In line with previous work in able-bodied individuals, this suggests that explicit self-reports and implicit indicators of ownership, such as proprioceptive drift, may reflect distinct aspects of embodiment rather than two converging measures of SoO [18, 36, 37, 39]. The lack of correlation in our results supports this dissociation, suggesting that proprioceptive drift and SoO questionnaire sets may capture separate underlying processes of embodiment. This dissociation is further emphasized by the differential influence of sensorimotor factors on each measure. For example, while voluntary control without tactile feedback (NB condition) elicited a sense of ownership as reflected in the questionnaire responses, it did not lead to an expansion of peripersonal space, as indicated by the lack of significant proprioceptive drift relative to the passive observation condition (WAT condition, Fig. 5). These results imply that the presence of tactile feedback appears to serve as a key sensory cue for extending the body's spatial boundary, yet this induced proprioceptive drift may be a separate, perceptually distinct phenomenon from explicit SoO.

Furthermore, both SoA questionnaires and intentional binding are conventionally assumed to reflect the underlying sense of agency. Consistent with this view, our findings showed that participants who explicitly reported a greater sense of agency over robotic movements also exhibited stronger intentional binding effects (Fig. 7). However, we also found that intentional binding was not modulated by the robotic hand position but was modulated by tactile vibration feedback (Fig. 3). However, when examining SoA questionnaire scores, tactile vibration feedback only had an effect in the close hand position (BUZ vs. NB conditions), and position did in fact have a significant effect (Fig. 2). The fact that SoA questionnaire scores and intentional binding results were correlated yet held different relationships with haptic feedback and hand position may support the view that SoA is a multidimensional construct. In line with this suggestion, others have proposed SoA comprises of a 'feeling of agency' that is prereflective and at the fringe level of consciousness, and a 'judgement of agency' is a higher order and belief-like process [90]. From this perspective, intentional binding may capture more subtle, pre-reflective aspects of agency that are less influenced by spatial configuration. Together our findings show that explicit SoA and intentional binding are distinct yet complementary measures of agency. Their distinct behaviors under varying sensorimotor conditions provide further insight into the interconnected layers underlying agency perception [35, 44–48].

Together, our findings showed a positive correlation between explicit SoO and both explicit SoA as well as intentional binding (Fig. 7). Interestingly, explicit SoO and SoA exhibited the strongest correlation among all measures examined. This suggests that these components may reflect closely related aspects of embodiment, and explicit top-down judgments of SoO and SoA may draw on similar cognitive-perceptual processes rather than representing entirely independent constructs. A positive correlation was found between explicit SoA and intentional binding results, which are conventionally used as explicit and implicit SoA measures, respectively. Interestingly, PPS, which is often considered an implicit measure of SoO, showed weak-negative to no correlation with the other measures, including SoO questionnaire responses. This suggests that PPS may reflect a perceptually distinct aspect of embodiment, rather than directly aligning with other ownership-related measures.

2.6 Conclusion

Our study demonstrates how individual components of embodiment can be independently modulated in the context of embodying prosthetic limb systems by manipulating motor control and sensory feedback. We provide detailed empirical evidence showing that while SoO, SoA, and PPS are often interrelated, they are mediated by distinct yet sometimes overlapping sensorimotor mechanisms. Although these components co-occurred under conditions of congruent sensorimotor feedback, their dissociation under other conditions suggests that embodiment is not a binary phenomenon in which a prosthesis is either embodied or not. Rather, it is a fluid and emergent experience shaped by interdependent processes, each influenced by specific sensory and motor conditions. Our findings revealed patterns of both correlation and dissociation among embodiment measures and the sensorimotor conditions that elicited them, often diverging from findings reported in studies involving biologically intact limbs. For example, PPS, which is often considered an implicit measure of SoO, showed virtually no correlation with explicit SoO questionnaire responses. Additionally, while explicit and implicit measures of agency (e.g., questionnaire responses and intentional binding) were strongly correlated, their relationship with ownership varied depending on sensory feedback.

However, it is critical to note that these differences may be application-specific, as prosthetic systems can present sensorimotor conditions that diverge from those of biological limbs, including control delays, predefined movement patterns, and feedback that relies on sensory substitution. In our system, for example, we observed a control delay of 142.6 ± 21.0 ms [91]. Furthermore, bench-top testing found that the delay between prosthetic hand contact and the onset of tactile vibration feedback reached up to 90 ms. Although these values fall below commonly accepted thresholds at which users describe perceiving the delays as diminished control (> 300 ms, [92]) or tactile asynchrony (> 111±62.0) ms, [93]), such delays, whether consciously perceived or not, may still affect the sensorimotor integration processes that underpin SoA and SoO, respectively. As such, understandings of the constituent components of embodiment derived from able-bodied participants may not fully generalize to prosthesis users. Our findings underscore the importance of validating embodiment measures in these distinct contexts to better understand the unique experiences of prosthesis users.

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Chapter 3. Measuring Intention: The Sense of Agency, Intentional Binding, and The Temporal Difference Limen

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3.1 Preface

This chapter precisely quantifies intentional binding as a measure for the sense of agency, using inverse cumulative normal function analysis on a forced two-choice latency estimation experiment. In the previous chapter, we highlighted limitations in the generalizability of embodiment metrics across experimental paradigms. A lack of validity could be one possible explanation for weak correlations between implicit and explicit metrics found in Chapter Two. The sense of agency is a critical dimension of embodiment, offering potential benefits to human–machine interaction such as improving trust [34], reducing fear and hesitation in adoption [35], [36], and clarifying perceptions of social responsibility in joint human–machine actions [37]. These qualities make it a particularly valuable target for investigation, which is why we chose to analyze it over alternative measures such as proprioceptive drift. This chapter introduces a new framework for interpreting intentional binding, including a temporal difference limen metric that can guide methodology for evaluating the sense of agency.

This study is a multiauthor collaboration. My specific contributions included iterating the experimental design, recruiting participants, collecting and analyzing the data, and drafting the manuscript. I received input from collaborators on experiment conceptualization, data processing, and manuscript review. Precisely quantifying intentional binding could lead to better standardization and opportunities to investigate its validity as a measure for SoA. It directly supports the overarching objective of this thesis: to translate embodiment theory into practical, reliable evaluation frameworks that can guide the design of autonomous and collaborative technologies, ultimately fostering greater user acceptance, trust, and performance.

3.2 Introduction

The sense of agency (SoA) defines the feeling of authorship we hold over our actions and the outcomes those actions have in our environment [1]. It is useful for distinguishing our intentional behavior from externally driven events and is relevant to a wide range of research and engineering applications. In the social sciences, SoA can have important implications in attribution and learned helplessness theories [2], [3]; in clinical psychology, SoA can inform self-perception in motor and psychotic disorders, including Parkinson's and schizophrenia [4]; and in human-machine interactions research the SoA could play a critical role in the adoption of technologies, including prostheses, BCIs, and other human-machine cooperative technologies [5], [6], [7], [8], [9], [10]. However, the validity of some methods used to reliably quantify the SoA has come under recent debate [9], and there is still no consensus on how the phenomenon should be measured.

SoA can be divided into two subcomponents: the perception of control over our body (internal SoA), and the perception of control over outcomes in our external environment (external SoA) [11]. We can measure it through both explicit and implicit methods. Explicit measures, such as questionnaires, are easy to administer and often align well with theoretical constructs. However, they are prone to response biases, including social desirability and impression management, which can compromise their reliability [1], [4], [12], [13]. In contrast, implicit measures capture neurocognitive and physiological correlates of the SoA that occur outside of conscious awareness. These include physiological responses like skin conductance or shifts in time perception [1], [4]. Because they are less susceptible to cognitive bias, implicit metrics offer a more reliable evaluation of the SoA, although they are often difficult to validate and interpret consistently across contexts [1], [4], [12], [14], [15], [16].

One of the most prominent implicit measures for the sense of agency is intentional binding (IB): the non-conscious shortening of perceived time between a voluntary action and its sensory outcomes [2], [4]. IB characterizes the way we perceive latency, best portrayed in an internal comparator model between what we sense and what we expect [4], simplified in Figure 1. In this model, our expectations and what we sense are being constantly compared to reach a final agreement of what we perceive. According to IB theory, when our intentional action causes an outcome, we will perceive the time between that action and outcome as shorter compared to if the action was performed by another agent: commonly referred to as time compression bias [4].

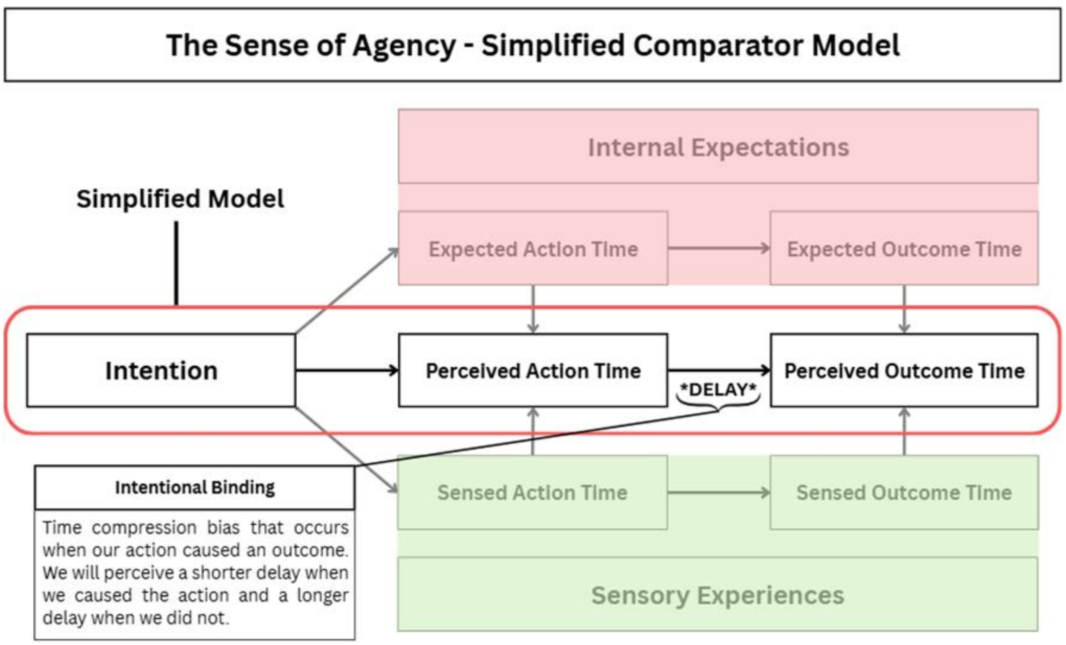

Fig 1. Simplifying the comparator model used to understand intentional binding. The top red box represents our internal expectations over how long actions and their outcomes should take. The green box represents the sensory feedback we receive to inform the duration of our actions and their outcomes. The middle white boxes represent our final perception after comparing our internal expectations and sensory experiences. The delay between the end of an action and the start of an outcome is measured and used to evaluate intentional binding and subsequently the sense of agency. Intention, on the far left, is what triggers a specific action and feeds the comparator model.

While time compression has been recognized broadly as a behavioral signature of the sense of agency [1], [4]. However, its validity as a proxy for the SoA has become increasingly contested in recent literature [9], [17], [18], [19]. Several studies have demonstrated similar temporal compression effects in contexts lacking intentional action, such as passive movements or externally triggered outcomes [9], [17], [18], [19]. These findings suggest that intentional binding may reflect general causal inference mechanisms, what Suzuki et al. termed causal binding, rather than a unique signature of voluntary action [9]. In this view, temporal binding emerges from the brain's expectation that one event causes another, independent of whether the initiating event was intentional [9]. This has led to growing concerns about the specificity of intentional binding as a measure for the sense of agency, and whether it can reliably differentiate between self-initiated and externally imposed action-outcome contingencies. The absence of consensus on this issue highlights a critical gap in the field; that is, the need for experimental paradigms that can dissociate intention from causality.

Current approaches for measuring intentional binding have limitations. Traditionally, intentional binding is assessed using either the Libet clock paradigm or direct interval estimation, both of which require participants to make retrospective timing judgments [4], [13]. These approaches are subject to high attentional demand and estimation variability, complicating the accurate measurement of intentional binding [14], [16], [20], [21].

To overcome the limitations of traditional paradigms and differentiate between the intentional binding and the confounding causal binding theory, we developed a forced two-choice psychophysical paradigm that quantified temporal judgments using a cumulative normal (psychometric) model in an experiment controlling for causality [14]. We structured as a nonadaptive reminder task [22], where participants experienced pairs of action-outcome sequences in which the delay between the action and outcome and control of a robotic device varied, but were otherwise identical. In each trial, they compared the two latencies of the action-outcome pairs to judge latency, which avoided the need for direct interval estimation, focusing participants' attention on the movement task [14]. Psychophysics offers well-established and widely accepted frameworks in perceptual neuroscience [23], [24], with psychometric regression providing the point of subjective equality (PSE), a precise estimation of a participant's perceptual bias [23], [25], making it well suited for validating intentional binding theory's perceptual time compression bias. Beyond precise bias estimation, psychometric regression also offers quantification of temporal precision using just-noticeable differences [23], [25], [26], which adds another dimension of analysis to evaluate temporal perception in intentional binding theory.

In prior work, we proposed a novel psychometric approach to measure the sense of agency by modeling time perception biases across action-outcome delays. In a small cohort study (N=8), the method demonstrated feasibility in precisely estimating perceptual shifts associated with intentional action, suggesting that we may capture intentional binding more accurately through continuous psychometric functions rather than binary measures. Building on those methods, the objective of the present work is to rigorously characterize time-events and time-perception during intentional and passive movements as they relate to intentional binding and the SoA. We incorporate both active and passive movement conditions to isolate the role of intention, and we introduce a control group to quantify order effects that commonly influence forced-choice paradigms [27]. By applying psychometric regression, this experiment evaluates both points of subjective equality and just-noticeable difference as complementary dimensions of intention-dependent time perception. In accordance with intentional binding theory, we hypothesized that the experimental group would perceive action-outcome latencies as shorter than the control group.

Our objective was to evaluate the time compression bias of intentional binding as a valid measure for the sense of agency by decoupling intentional outcomes from causal associations using psychophysical modeling experimentation and modeling strategies.

3.3 Methods

3.3.1 Participants

We recruited 38 healthy participants (31 females and 7 males, aged between 18 and 44 years mean age = 22.63 years, SD = 4.8). We randomly assigned participants to either an experimental or control group, with 19 participants in each, sufficient to detect between group differences and consistent with sample sizes in psychophysics and motor control literature. The mean ages were comparable between groups: 22.3 years for the experimental group and 23.0 years for the control group. Two participants in the experimental group were left-handed; all other participants were right-handed as verified using the Edinburgh Handedness Survey [28]. The Institutional Review Board of the University of California, Davis, approved this protocol, and all participants provided written informed consent prior to testing.

3.3.2 Experimental Set-up

Our protocol employed a Kinarm robotic apparatus (End-Point Lab, Kingston, Canada), a robotic system featuring dual handles capable of accurately tracking arm movements and replicating recorded movements via motorized controls (Figure 2A). Participants performed a cursor-targeting task on a computer system by moving the Kinarm handle, which controlled the cursor represented as a white dot corresponding to the occluded hand position.

Participants sat at a table equipped with the Kinarm and grasped the right handle with their right hand (Figure 2C). A horizontal screen positioned sixty centimeters above the table surface displayed visual cues, target positions, and cursor location. This screen prevented participants from viewing the Kinarm handles and their arms during the task (Figure 2B and 2C). Participants rested their left hand over two mechanical buttons on the table, which they used to report perceptual judgments.

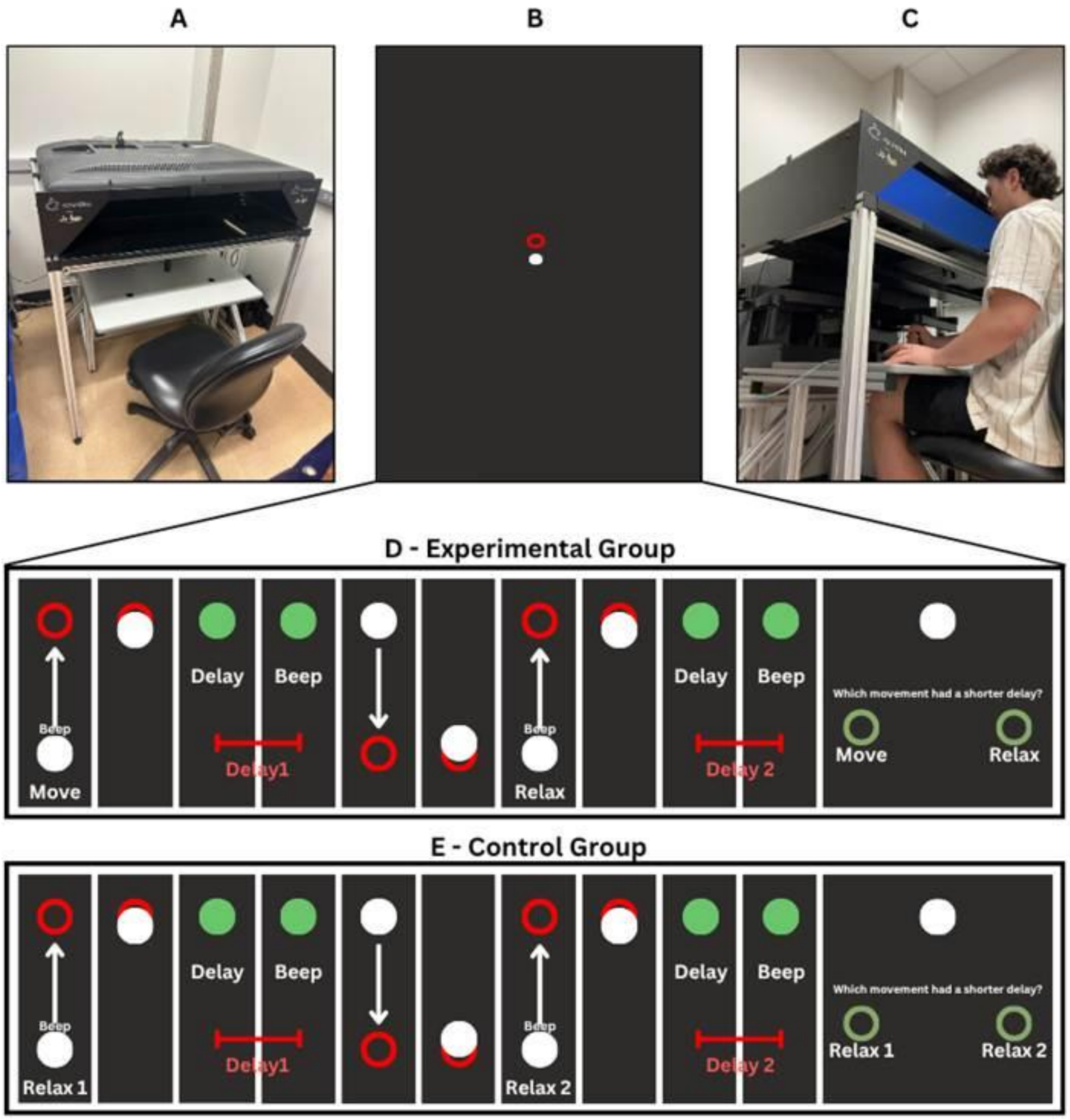

Fig 2. Visual Summary of the Experimental Set-up and Paradigm. The experimental set-up. **A** The Kinarm equipment, with the chair, screen, and table. **B** White cursor and red target as viewed by the participant. **C**[DB1] A photograph of how a participant interfaces with the Kinarm, holding the right handle with their right hand and their left hand on the buttons while watching the screen for instructions. **D** Sequential progression of one trial with the active movement first followed by a passive movement and the prompt screen. **E** Progression of task for the control group with two passive movements.

The Kinarm was programmed to (1) record active movements, in which the participant actively moved their arm, and (2) perform passive movements, where the handle moved the arm of the participant. Each trial consisted of a pair of movements: one active, followed by one passive, replicating the previous active movement in the experimental group (Fig. 2D), or two identical passive movements in the control group (Fig. 2E). Velocity profiles were carefully matched across active and passive movements to ensure consistency. Movement was constrained along the y-axis in the participant's sagittal plane during each trial (Figure 2C). Participants were instructed to maintain an average movement velocity between 13 and 22 cm/s, receiving real-time visual feedback through cursor color changes upon reaching the target: green indicated compliance with the velocity range, red indicated excessive velocity, and yellow indicated insufficient velocity. These velocity constraints aimed to standardize trials and limit variability during movements.

Participants in the control group underwent a similar perceptual task but exclusively compared pairs of identical passive movements, removing the active intentional component (Figure 2E). At the start of each block, control group participants performed thirteen active movements, recorded and subsequently replayed passively in pairs for perceptual comparison within the same block. These pairs involved identical movements differing only in auditory interval delays, identical to those described in the experimental group protocol. Both groups completed an identical number of trials.

3.3.3 Experimental Design

Participants in the experimental group performed a perceptual task but were told that it was an audio acuity assessment to obscure the true experimental objectives, minimize potential biases, and increase task engagement. Using the buttons, participants judged which of two presented time intervals between a visual cue and an auditory tone felt shorter. Each trial comprised an initial active movement, triggered by the participant's motion onset and accompanied by a tone. Participants moved the cursor toward a circular target positioned twelve centimeters away along the y-axis. Upon cursor arrival, the cursor changed color and then a visual cue was displayed followed by a second auditory tone sounded after a predetermined delay (described further below). Participants then returned the cursor to the initial position (Figure 2D). The following passive movement replicated this procedure exactly, initiating automatically one second after participants returned to the starting position. After each active-passive movement pair, participants indicated which movement had the shorter interval between the visual cue and auditory tone.

The intervals between the cursor reaching the target and the subsequent tone were systematically varied. The active movements consistently featured a fixed 600ms delay, whereas passive movements incorporated randomly chosen delays from a predefined set of thirteen values (0ms, 200ms, 300ms, 400ms, 500ms, 550ms, 600ms, 650ms, 700ms, 800ms, 900ms, 1000ms, and 1200ms). Each delay condition appeared twelve times during the experiment (156 total trials), divided equally across three blocks (52 trials per block).

3.3.4 Data Analysis

Collected data were processed using the Bkin_Toolbox_3.8 within MATLAB (MathWorks, Natick, USA). Participant responses were analyzed using psychometric regression generated with the Psignifit toolbox (Heiko Schütt, AG, NIP, University of Tübingen). The 50% threshold of these curves was used to identify intentional binding biases; a negative bias indicated participants perceived intervals following active movements as shorter than those following passive movements, consistent with established intentional binding phenomena (Figure 3). We used parametric statistical methods to evaluate differences between the intentional motion (experimental) group and passive motion (control) group. The data analysis code that supports the findings of the study are available from the corresponding author upon reasonable request.

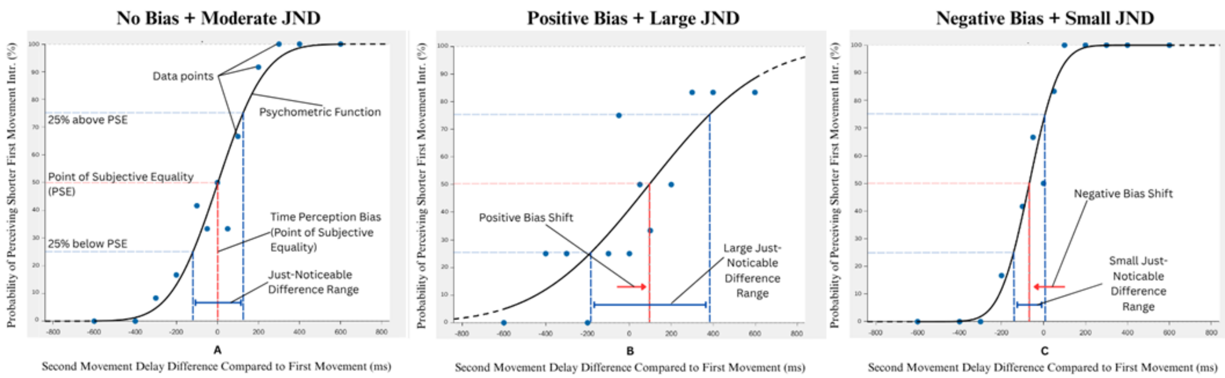

Fig 3. Example Psychometric Function Plots Highlighting Perceived Subjective Equality (PSE) and Just-Noticeable Differences (JND). Example psychometric curves derived from three participants to showcase bias and just noticeable differences within psychometric functions. Each participant's curve is plotted in black, with their response data denoted by the blue circles. The red dotted lines represent time perception biases - the point of subjective equality (PSE) where participants can not differentiate latency differences following the first and second motion (50% probability of responding for either). Red arrows denote the shift of the bias from zero: panel B shows a positive bias shift, and panel C shows a negative bias shift. The blue dotted lines report a participant's just noticeable difference (JND) range: the point at which the probability for reporting a shorter first movement interval is between 25% and 75%. The JNDs are half the just-noticeable difference range for each participant. Smaller JNDs denote more acute temporal discrimination as opposed to large JNDs.

3.4 Results

Each participant had a psychometric function fit to 156 response trials. Figure 4 shows the psychometric function fits for each participant, separated by group. The mean group biases are similar in magnitude and direction. The experimental group had less variance in the bias distribution as opposed to the control group. The slopes of the psychometric curves are also steeper in the experimental group, yielding smaller just-noticeable difference ranges than the control group. Quantitative analysis of the bias, resolution ranges, and variances is presented below.

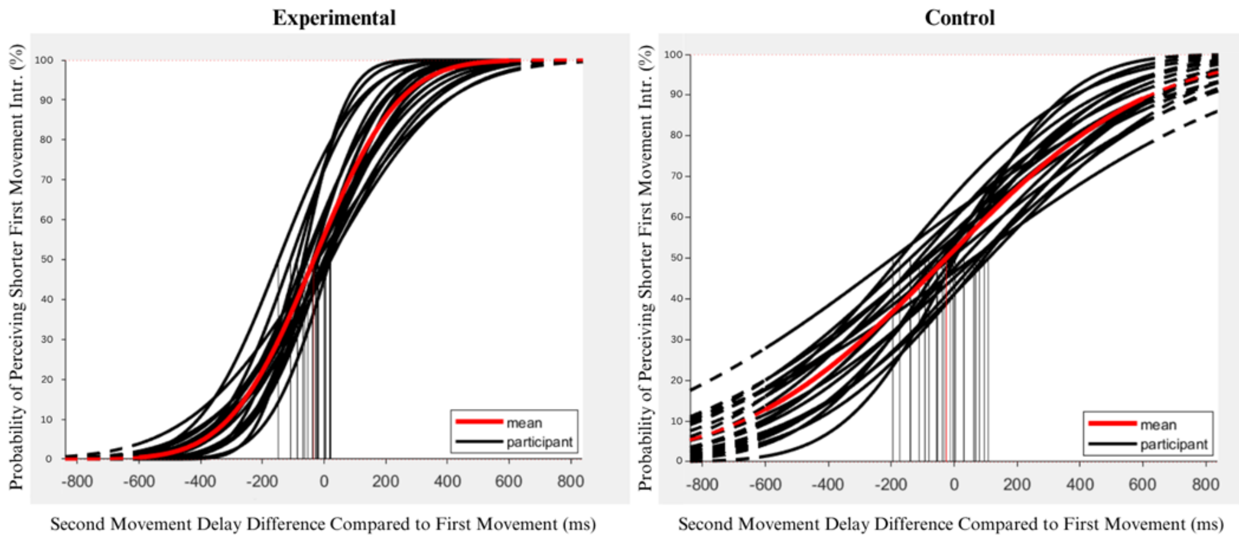

Fig 4. Psychometric Function Plots of Our Control and Experimental Group Participants. Each participant psychometric function is plotted in the respective experimental (N = 19) and control (N = 19) groups above. The x-axis denotes the difference in the delay interval of the second movement compared to the first movement: the first movement is always set to 600ms delay between action and outcome. The y-axis represents the probability that the participant will perceive the first movement as shorter than the second movement. The red curves denote the average psychometric curves derived from averaging the data points at each second movement delay difference. Time compression biases are shown by the vertical lines drawn to the x-axis. Mean experimental bias is - 31.5ms and mean control bias is -28.2ms.

3.4.1 No Difference in Mean Time Compression Bias Between Control and Experimental Groups

Figure 5 presents a boxplot of participant bias values of both groups and quantifies the similarities and differences in time compression bias between the groups.

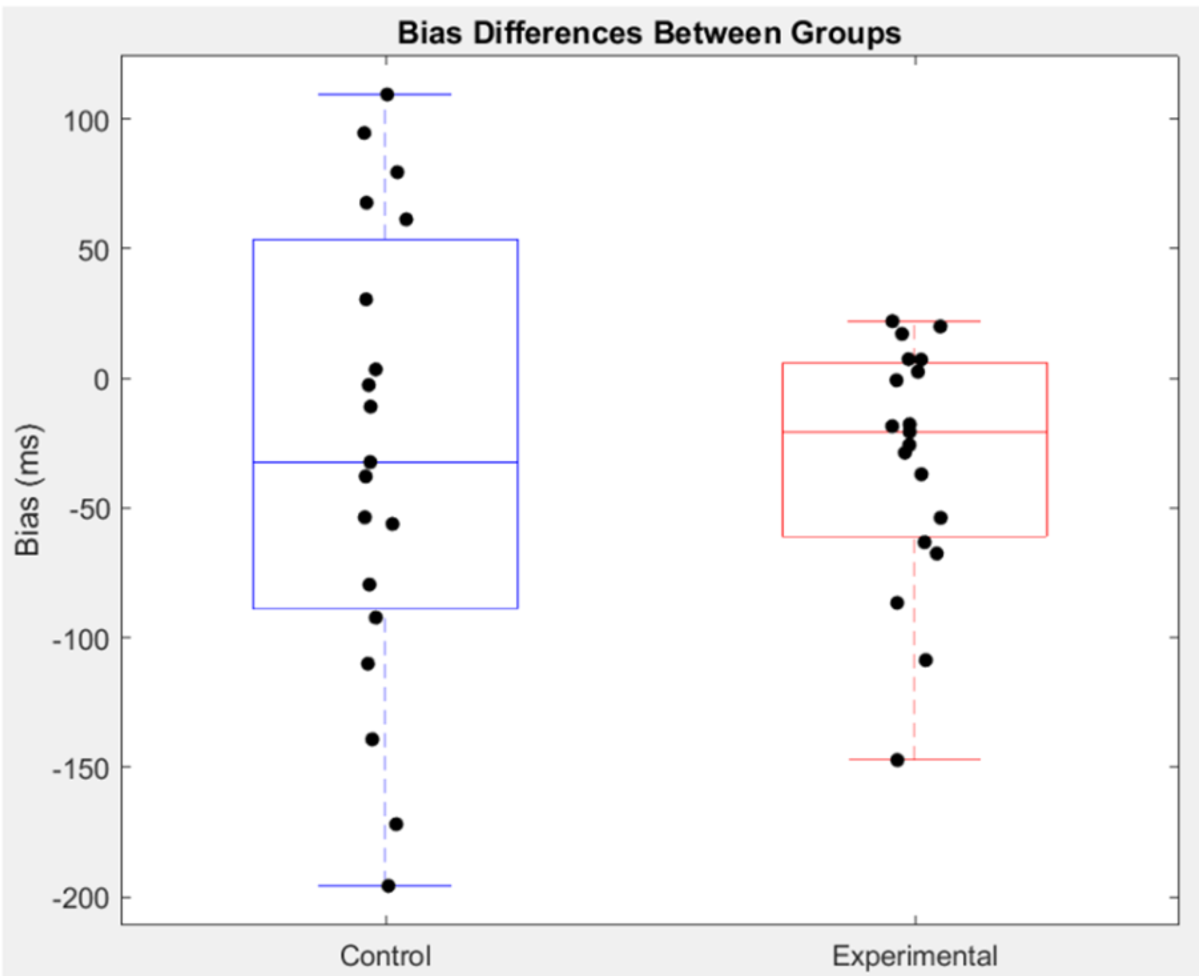

Fig 5. Boxplot of the Perceived Subjective Equality Points for Participants in the Experimental and Control Groups. Time perception biases during time interval comparison between the experimental and control group are shown above. Boxplots denote the range and quartiles of the groups as the black circles denote participant values. There was no significant difference between the two group distributions ($p = 0.887$). A Levene's test revealed that the experimental

group had significantly lower variability compared to the control group ($p = 0.0091$). Both groups experienced an average bias below 0ms: EXP = -31.6ms, CNTRL = -28.2ms.

Derived from a Shapiro Wilks test, both experimental ($p = 0.085$) and control ($p = 0.784$) group biases were normally distributed. A student t-test showed that there was no difference between the biases of the two groups ($p = 0.887$). A Levene's test showed that there is significantly greater variability in the bias distribution of the control group ($p = 0.0091$). A one-tailed t-test showed that the experimental group is significantly lower than 0ms ($p = 0.0083$) as the control group is not significantly lower than 0ms ($p = 0.1866$), likely due to the variability of the control group bias distribution.

3.4.2 Just-Noitceable Difference Scores are Significantly Smaller in the Experimental Group

We found that just noticeable differences, derived in accordance with figure 3 in the methods, were significantly smaller in the experimental group through a sign rank test ($p < 0.001$). Figure 6 shows the just noticeable differences and their distributions between the two groups.

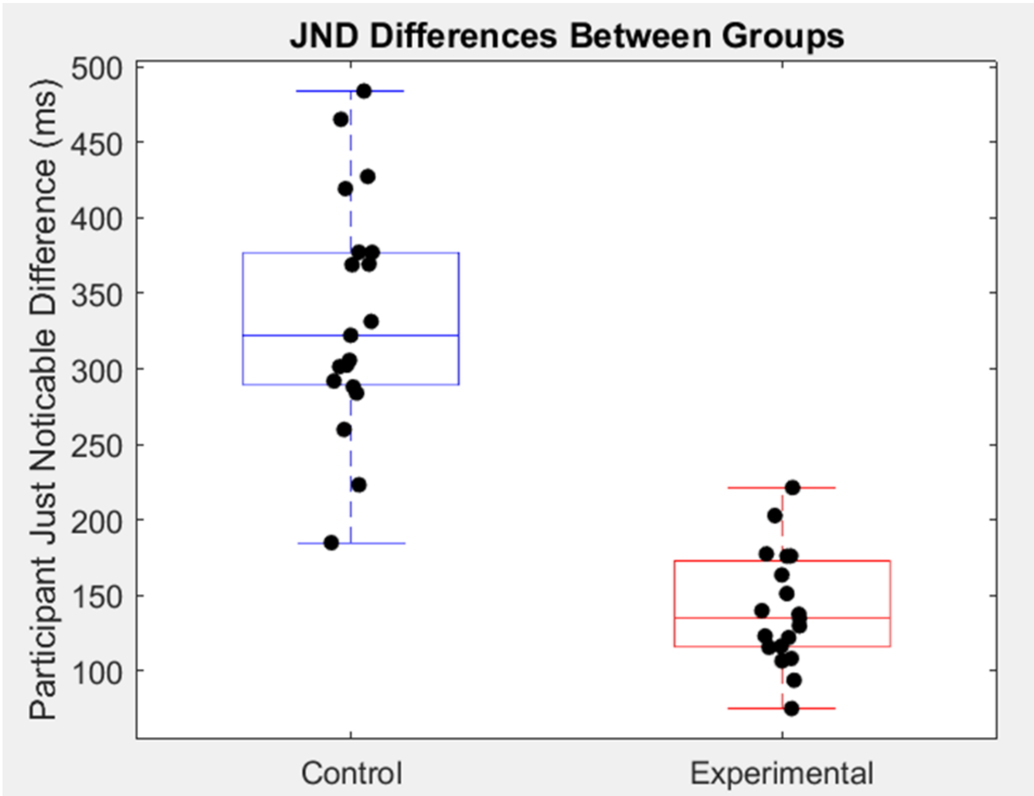

Fig 6. A boxplot showing just noticeable differences between the experimental and control group's psychometric functions. A sign rank test shows significantly higher Just-Noticeable Difference scores in the experimental group ($p < 0.01$). A Levene's test reveals that the experimental group had significantly greater variability in the data compared to the control group ($p > 0.01$).

In this application, just noticeable differences quantify how temporally precise a participant is when discriminating between different latencies. Interestingly, all experimental group participants were able to discriminate latencies below 445 ms, as only one control group participant was able to do the same. A signrank test returning a p-value < 0.01 shows a strong, significant difference between the temporal precision of the two groups. Post Hoc analysis showed that the experimental group differed from the control group by 195.4ms, corresponding to a Cohen's *d* of 3.169 (n = 19 per group, N = 38, and $p < 0.01$). Furthermore, Levene's test shows greater variability in the experimental group participants ($p < 0.01$).

3.5 Discussion:

The purpose of this experiment was to decouple intentional from casual effects on time perception as they relate to intentional binding and the sense of agency (SoA). To isolate intentional control, our task carefully replicated visual, auditory, and proprioceptive sensory outcomes across both active (intentional) and passive movements. Participants were required to discriminate between action-outcome latencies, allowing us to quantify temporal perception that depended on intentional movement. We found no differences in perceptual time compression bias associated with intentional movement. Instead, our results identify a novel relationship between just-noticeable difference values and intention-action association, what we refer to as the temporal difference limen (TDL). Building on recent findings which support time compression bias as a measure of causal association between actions and outcomes, and incorporating the TDL, we propose an updated intentional binding framework for evaluating the sense of agency (Figure 7). Our results suggest that time perception becomes more precise when users experience a sense of agency over a device, and our framework offers insight for quantifying this perceptual experience.

Contrary to predictions based on conventional descriptions of intentional binding, our results did not reveal a significant difference in time compression bias between participants who moved voluntarily and those who were moved passively. Using a rigorous psychophysical approach with carefully controlled causal conditions and matched sensory outcomes across groups, we found that average bias, i.e. point of subjective equality, values were comparable regardless of intentional movement. If time compression bias reliably indexed intentional control, we would expect reduced bias in the intentional movement group. Instead, our findings suggest that time compression bias may not consistently reflect intention as previously theorized. By isolating intention as the main independent variable, our design enabled precise estimation of perceptual bias while minimizing confounds related to action-outcome association. Our results contribute to a growing body of research that questions the robustness of intentional binding and challenges the use of time compression bias as a reliable implicit measure of the sense of agency [9], [17], [18], [19].

Given the challenges that time compression bias is facing as a measure for SoA, our analyses introduce the temporal difference limen (TDL) building on previous psychophysics work to offer a precise and interpretable measure of the SoA. The TDL captures the degree to which participants can discriminate action-outcome latencies in a forced-choice design. It is grounded in the psychological principle of just noticeable differences (JNDs), which define the smallest change in a stimulus that a person can reliably detect [26]. JNDs are typically calculated as half the range between 25 percent and 75 percent consistency on a psychometric function [26], and we use them to quantify TDL. This metric offers a new dimension for evaluating the sense of agency implicitly, but further work is required to validate it beyond arm movement paradigms.

The TDL may offer an extension to the theoretical model of intentional binding. Our results revealed significant group differences in temporal precision, demonstrating that intentional action enhances the precision of perceived action-outcome intervals. This finding supports the idea that intentionality sharpens temporal discrimination, offering a new dimension to measure the sense of agency. Traditional models of intentional binding emphasize time compression bias as the primary indicator of the sense of agency [4], [15], [21], yet our data suggest that time compression bias alone may not reliably differentiate between intentional and non-intentional action. Instead, we propose an updated framework to intentional binding theory where the TDL reflects internal agency, the association between the action and our intentions, and causal binding reflects external agency, the association between the action and its consequences. Together, the temporal difference limen and causal binding offer a more complete account of the sense of agency by distinguishing between the experience of generating an action and the experience of witnessing its effect (Figure 7). This framework can inform both theoretical development and practical evaluation of the sense of agency across a range of actions.

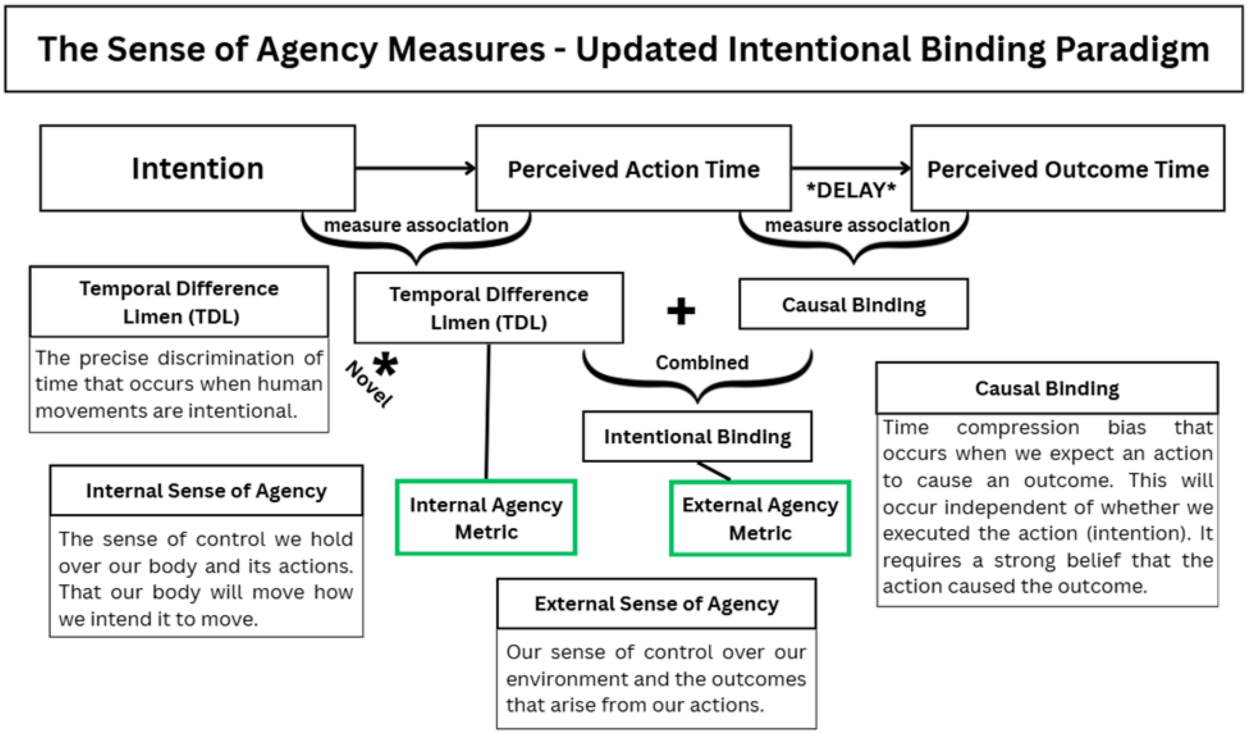

Fig 7. An updated intentional binding framework, based on the simplified comparator model figure introduced above (Fig. 1), adjusting for the temporal difference limen as an internal agency metric. It shows how the temporal difference limen can be used as a measure for the perceptual association between intention and action. Causal binding is introduced as a measure of the perceptual association between an action and an outcome. Boxes introduce the internal and external sense of agency as well as define the temporal difference limen and causal binding.

Our method uses a binary forced-choice task, making it directly compatible with A/B comparison designs that are widely used in interface testing, behavioral research, and product evaluation [29]. This structure enables precise extraction of the Point of Subjective Equality (PSE) and Just Noticeable Difference (JND), allowing researchers to quantify user agency across different interface conditions and contexts. For example, the framework could be applied to study the sense of agency in clinical technologies, e.g., to evaluate a prosthesis wearer's sense of embodiment of their artificial limb, by comparing their perceptual metrics when the experimenter varies latencies between action and feedback to the user, potentially aiding in optimizing parameters for enhanced sense of agency. Similar strategies can be applied to users' control over voice-controlled systems, driving of autonomous vehicles, AR/VR environments, brain-computer interfaces, etc. yielding interpretable metrics for SoA under varied feedback and control parameters. While these applications hold promise, the framework requires further validation with other SoA metrics and neuroscience theories, across different modalities and user populations.

Our findings also raise important questions about the cognitive basis of latency perception in intentional movement. The subcomponents of intentional binding, action binding (the belief that our action came later in time) and outcome binding (believing that our outcome came earlier in time) [30], may help explain why participants in the experimental group were more temporally precise. By consistently perceiving the endpoint of their own actions, participants likely anchored their perception of action-outcome intervals more precisely. This may offer a perceptual reference point that enhances consistency in temporal judgments. Future research could examine how this anchoring effect varies with task complexity, feedback modality, or interface design.

Our primary aim was to evaluate the sense of agency, due to its clinical relevance and broad applications to human technology interfaces. Tourette syndrome, Parkinson's disease, corticobasal syndrome, amputation, and especially schizophrenia have been associated with impaired agency, often linked to altered temporal processing and atypical intentional binding effects [31], [32]. These conditions highlight how fundamental the sense of agency is to distinguish self-initiated actions from external events. Our new intentional binding framework may inform clinical assessment and guide the design of technologies that support diverse cognitive profiles. In this way, clinical insights and human autonomy research converge to advance more equitable and responsive interfaces.

Future research investigating the correlation between the TDL and explicit SoA questionnaires and applications of this metric across different devices, and actions (button presses, social instruction, etc.), will help further evaluate if this metric is a reliable and valid measure for the SoA. There is also an opportunity to explore the neural mechanisms underlying our findings. Prior work shows that temporal acuity improves during active movement [33], and our results complement this observation by showing that temporal precision can also improve after movement.

3.6 Conclusion:

Our study introduces intentional acuity as a precise and interpretable metric for quantifying the sense of agency and proposes a revised framework for intentional binding in the context of human–machine interaction. By capturing volition-dependent changes in temporal discrimination, this framework offers valuable tools for evaluating perceived control across a wide range of technologies, including artificial intelligence systems and autonomous vehicles. Interfaces that enhance the sense of agency can increase user trust, improve recovery after system errors, and clarify responsibility in shared control environments. While our findings are based on controlled experimental settings, the intentional acuity framework may also inform future research on individual variability, accessibility, and inclusive design. Together, these contributions position intentional acuity as a foundational metric for advancing both the study and application of user agency in an increasingly autonomous world.

3.7 Chapter 3 References

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Chapter 4. Conclusion and Future Directions

Translating embodiment metrics to human-machine interfaces is not a straightforward endeavor and many studies have reported conflicting results [1-15]. The second chapter of this thesis quantitatively examined the relationships between four commonly used embodiment metrics, finding that implicit and explicit metrics are not as strongly associated as formerly thought. In the third chapter, we shifted our focus to intentional binding and the sense of agency, finding that time compression bias was not sensitive to volitional motor control. Instead, we discovered the temporal difference limen metric that shows promise as a measure for the sense of agency. We updated the framework of intentional binding to incorporate the temporal difference limen as a measure for the internal sense of agency, but further validation is needed to effectively establish the framework.

Future work should examine the correlation between just-noticeable differences and the explicit sense of agency. Our chapter two methods offer a paradigm for doing this. As automation technology propagates, the temporal difference limen could be used to measure the control users perceive over devices. Adapting the methods of chapter three to modern technological interfaces may be an effective avenue to evaluate user perceptions of control, especially in autonomous systems. However, this metric should first be validated in specific applications before it can be applied directly. A reliable and validated implicit measure for the sense of agency can help define the lines of social responsibility between users and autonomous agents, reduce fear of new technologies, and promote forgiveness during interaction [16-19] (Haggard, 2017; Khogali & Mekid, 2023; Schofield et al., 2021; Wen & Imamizu, 2022), and could eventually lead to the increased adoption of technology into society. This thesis advances methods for quantifying embodiment and proposes future directions to aid its translation to human machine interactions.

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