Exploring Methodological Factors in the Temporal Measurement of the Sense of Agency

Thesis submitted in partial fulfillment
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in
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by

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CERTIFICATE

It is certified that the work contained in this thesis, titled "Exploring Methodological Factors in the Temporal Measurement of the Sense of Agency" by Rohan Ravi Reddy Donapati, has been carried out under my supervision and is not submitted elsewhere for a degree.

Date	Advisor: Prof. Bapi Raju Surampudi

To

A comedy of errors

that shaped my academic odyssey

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Abstract

Time perception plays a crucial role in understanding conscious processing. Over cognitive history, various time perception methodologies have been used to measure conscious processes, with the Libet Clock method gaining attention for implicitly measuring the sense of agency through the intentional binding effect. During intentional binding, the perceived temporal distance between an action and its sensory consequence is shorter when the action is voluntary. This phenomenon is considered a proxy to measure intentionality and the sense of agency. One prominent theory explaining this effect is sensory recalibration, suggesting that the brain adjusts the interval between a voluntary action and its sensory consequence. However, a critical question can arise: does the recalibration cause the entire outcome to shift in time, or does it expand in time, compensating for the recalibration? Research indicates that the intended outcome expands in time but with an intriguing caveat—the expansion effect is highest with shorter action-outcome delays and disappears with longer delays. This observation contrasts with what the literature on the binding effect seems to suggest. Since the methodology employed to measure this effect is an inferential way to assess the intentional binding effect, it is expected that expansion should have been observed for longer and shorter delays, if not exclusively. The literature suggests a dissociation of the sensitivity of the binding effect based on action-outcome delay ranges, with predictive methods focusing on shorter delays and inferential methods on longer delays. The thesis explores the difference between objective measurements and literature suggestions, proposing that the discrepancy may arise from how components of the intentional binding effect are operationalised. The study argues that the dependence on the action-outcome delay range is not specific to the methodology but rather how voluntary actions and intended outcomes are processed within the intentional binding paradigm. In summary, this thesis delves into the assessment of conscious processing through time perception, contributing to a better understanding of the temporal dynamics of intended outcomes in the intentional binding effect. It highlights the importance of methodological factors like cues and delays in influencing binding development, extending insights into the sense of agency, intentionality, and causality.

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Chapter – 1

Introduction

What is an intention? Well, starting with the dictionary definition of something is always a good idea. According to the Oxford English Dictionary, an intention is characterised as something an agent wants or plans to do. While this definition serves as a fundamental starting point, from the point of view of this thesis, it is necessary to take on a more cognitive and process-based interpretation of intention.

Within the realm of cognitive science, intention takes on a richer significance. It embodies a mental state or process that encapsulates an individual's purpose or goal-directed behaviour (Searle, 1983). In essence, intention emerges as a cognitive representation of an envisioned result. It becomes the guiding compass that steers an individual's actions and decisions (Brand, 1982). Intentions are pivotal in the tapestry of human cognition and behaviour, acting as architects of our plans and the executors of our objectives. When people form an intention, they craft a mental blueprint of a future state they aspire to attain. This mental construct influences their attention, perception, memory, and decision-making processes. It empowers them to sieve through the maelstrom of information and prioritise actions that propel them toward their coveted goal. For example, my intention to finish this master's thesis as part of the criteria for obtaining a post-graduate degree is the objective that directs my mental efforts in achieving that particular goal. Therefore, the critical aspect of delineating an intention regarding cognition is that it is consistently oriented toward a specific goal and defines the cognitive processing required to reach it.

To draw a contrast, the lexical definition of an intention highlights the conscious and deliberate nature of forming a plan. Conversely, the cognitive interpretation delves deeper, plumbing the depths of cognitive mechanisms at play in the birth, sustenance, and realisation of intentions, going beyond the mere conscious aspect described in the lexical definition.

When we talk about intentions, it is followed by a subsequent goal-directed action. For instance, a famous quote from Ludwig Wittgenstein in his book "Philosophical Investigations" goes as follows (Wittgenstein, 1953).

"What is left over if I subtract the fact that my arm goes up from the fact that I raise my arm?"

This quote is a brilliant description of the question of where our actions come from and the intentional aspect associated with that event. Wittgenstein's insight invites us to peer into the origins of our actions and the inherent intentionality intertwined with every act. By discerning the physical ascent of the arm from the intentional act of raising it, Wittgenstein directs our focus toward what endures when empirical facts are stripped away. The realm of intentionality lingers—a domain replete with purpose, agency, and subjective experience, which collectively shape the act of raising an arm. This quote beckons us to ponder the dichotomy between the observable physical events or behaviours and the concurrent mental and intentional states. It underscores the notion that actions possess a more profound significance beyond their mere physical occurrences, highlighting the role of intentionality and subjective experience in understanding human behaviour.

1.1 The History of Intention as a Cognitive Process and its Relation to Time Perception

Using time perception to measure cognitive processing has laid its foundation throughout the history of cognitive science (Buonomano, 2017). Among the myriad aspects of human psychology explored, intention and conscious experience have stood out as prominent subjects of inquiry.

Intention is a conscious decision to do something, usually leading to an action committed in an environment and expecting a specific consequence that might align with said intention or lead to further intentions (Pacherie et al., 2010). The 'I' conjures intention, ultimately setting forth a cascade of actions. As previously discussed, intentions represent cognitive or mental representations that interact with diverse cognitive processes. These processes inherently consume time for execution, a pivotal realisation first put forth by the renowned 19th-century German physiologist and physicist Hermann Von Helmholtz (A. R. Jensen, 2006). Helmholtz was the first to realise that whatever our brains do, they do not unfold instantaneously. He ingeniously devised a mechanism—known as a spring kymograph or reaction time apparatus (Fig. 1). The apparatus had a simple working model where participants would press a key or lever in response to a stimulus, and the apparatus would measure the time it took for the response to occur. Helmholtz's method paved the way for studying reaction times in sensory perception, motor responses, and mental processes, yielding fundamental insights into cognitive functioning (Boring, 1950). His work, particularly in visual perception, has paved the way towards the understanding that acquiring the visual percept of a stimulus is not instantaneous or as soon as the stimulus appears, and the amount of time these processes take is potentially informative about how the perception is established (Von Helmholtz, 1896). Basically, boiling down to the point of telling when experiences occur can tell us something about the processes that generate experience.

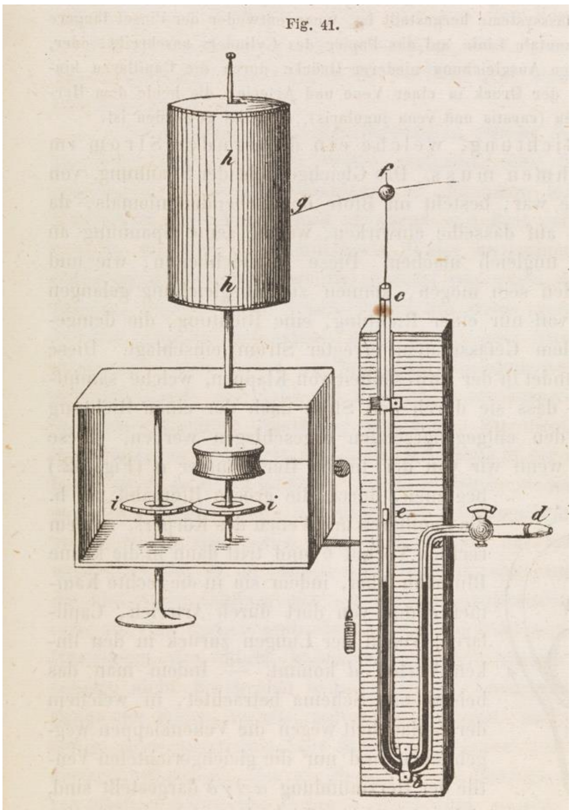
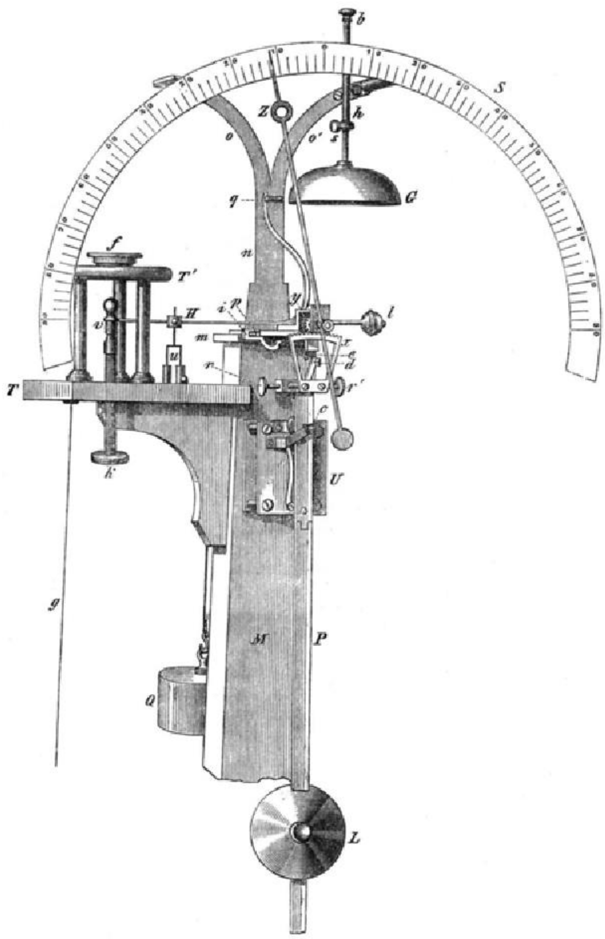


Fig. 1: Reference image of a Spring Kymograph. A kymograph is an analogue device that visually represents spatial position over time. Image sourced from (Höber, 1919)

Helmholtz's contributions served as the cornerstone for subsequent research in the field and shaped the way we measure and study the timing of cognitive processes. His insights were further taken up and refined by Wilhelm Wundt. Wundt, often regarded as the grandfather of modern experimental psychology, founded the first psychological laboratory in Leipzig in 1879. Wundt's work was focused on the measurement and analysis of mental processes, contributing significantly to the development of experimental psychology (Kim, 2022). He refined the methodology of mental chronometry by introducing standardised experimental procedures and apparatus, aiming for precision and reliability in measurements (Titchener, 1921). Wundt emphasised the role of introspection and conscious experience, seeking to correlate objective measurements with participants' subjective reports. It was one of the first instances in experimental psychology to integrate an implicit with an explicit form of measurement. His work applied mental chronometry to investigate perception and attention (Fig. 2), examining factors influencing reaction times in sensory discrimination tasks (Carlson et al., 2006; Wundt, 1886). Wundt's work laid the groundwork for comprehending the temporal intricacies of mental processes, indirectly illuminating our understanding of intention-related cognitive phenomena.



Source: Wundt, 1908-11, 3rd vol., p. 72

Fig. 2: Wundt's complication clock apparatus. It was used to measure attentional reaction times. Image sourced from (Wontorra, 2013)

An interesting overlap under Helmholtz's or Wundt's methods was that they were centred on "*when*" individuals experienced events, not "*what*" they experienced. This difference marks the juncture where intention, in the context of volition, entered the arena of mental chronometry and how we can use it to be informed about intentional mental processes. This work was famously taken up by Benjamin Libet, an influential neurophysiologist and psychologist who delved into the timing of conscious experiences and the intricate relationship between conscious awareness and neural processes. Building upon the foundations laid by Wundt and Helmholtz, Libet embarked on a series of experiments probing the temporal dynamics of conscious awareness and its link to volitional actions. Employing electroencephalography (EEG), he investigated the timing of neural events, notably the readiness potential preceding voluntary actions (Libet, 1985; Libet et al., 1983) (Fig. 3).

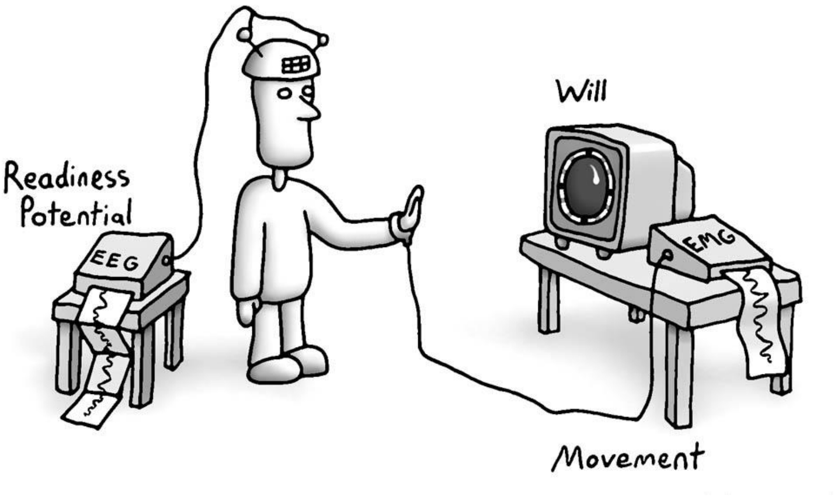


Fig. 3: Cartoon representing the Libet experiment. The participant is instructed to move their hand while looking at a constantly rotating clock while their EEG data is recorded. They are then asked to report the time instance on the clock at which they felt the "urge" to move their hand. Image sourced from Jolyon.co.uk

Libet's research employed mental chronometry to unveil the underpinnings of voluntary control experiences. His work delved into conscious intention, sparking profound discussions on free will (Libet, 1999) and introducing the notion of backward time referral, challenging the causal relationship between conscious awareness and actions (Libet, 1985). Libet's groundbreaking contributions expanded our comprehension of mental chronometry and catalysed dialogues at the intersection of conscious awareness, free will, and temporal dynamics, significantly influencing philosophy, neuroscience, and psychology.

The Libet method was later adopted by Patrick Haggard, a professor at the University College London, to investigate the relationship between voluntary movements and brain potentials (Haggard et al., 1999; Haggard & Eimer, 1999; Haggard & Libet, 2001).

Haggard's work culminated in a landmark experimental methodology aimed at assessing, through time perception, whether a participant had voluntarily initiated an action (Haggard et al., 2002a). His research consistently demonstrated that when a temporal gap separated a voluntary action and its outcome, participants perceived time as compressed, perceiving the outcome as occurring closer to their action than it did. This phenomenon is known as the intentional binding effect (Haggard et al., 2002b; Haggard & Clark, 2003) and signifies a subjective sense of causality and agency over motor activity. It indicated that when individuals consciously intended to act and viewed the outcome as a consequence of their action, they experienced a temporal link between the two events. By leveraging the intentional binding effect, researchers gained a quantitative means to explore the temporal dynamics inherent in intentional actions and their perceived outcomes.

In typical intentional binding experiments, participants engage in tasks necessitating voluntary actions (e.g., pressing a button) and subsequently perceiving outcomes (e.g., a tone or visual stimulus). Participants are then asked to estimate the temporal relationship between their actions and the outcome. The effect manifests when participants perceive the outcome as a result of their action, resulting in compressed estimates of the temporal interval between the action and the outcome, compared to control conditions devoid of causality. This temporal compression in time perception offers an implicit measure to probe the influence of intention on perceptions of causality and agency, which will be the predominant methodology this thesis would focus its exploration on.

1.2 Motivation for the Thesis

Subjective timing is not really interesting in itself it's just a clue about the content of experience. Ask "when?" to discover what. – Patrick Haggard

Pursuing a deeper understanding of intentions within the framework of modern experimental psychology promises many compelling benefits. First and foremost, it offers a glimpse into the complex realm of human agency and goal-directed behaviour. By immersing ourselves in the study of intentions, we embark on a journey to unravel the cognitive processes that underlie their formation and execution. In doing so, we illuminate the interplay between intention, cognition, and perception. This newfound knowledge contributes significantly to our grasp of how individuals exercise control over their actions.

Secondly, we can uncover the underlying cognitive mechanisms when we investigate intentions within an experimental framework like intentional binding. By employing rigorous methodologies, we can pinpoint and examine the cognitive processes that govern the exact influence and execution of intentions. These processes encompass facets such as attention, decision-making, and memory, and their interpretation not only enriches our comprehension of cognitive functioning but also provides insights into the determinants that mould intentional behaviours.

Moreover, exploring intentions within the realm of experimental psychology serves as a bridge between the subjective realm of experience and the realm of objective measurement. Intentions, by their very nature, are subjective experiences that wield influence over behaviour. By harnessing objective measurement techniques, we gain the capacity to scrutinise the interrelationship between subjective intentions and objective behavioural outcomes. This pursuit enables a deeper exploration of the mechanisms underlying intentional actions.

Lastly, advancing the study of intentions within modern experimental psychology contributes to the broader theoretical landscape of human cognition and behaviour. It not only refines existing theories and models but also nurtures the growth of new frameworks capable of capturing the intricate nuances of intention formation and action control. This evolution in our understanding contributes to a more comprehensive grasp of human psychology, paving the way for a unified framework dedicated to studying intentions.

Exploring this interplay between time perception, intentional binding, and intention can lead to novel insights into the nature of human cognition and behaviour. By examining how intentions shape our perception of time and how our perception of time influences the formation and execution of intentions, we can uncover the mechanisms that govern this temporal phenomenon.

In conclusion, pursuing this research opens the door to expanding our knowledge of human cognition and behaviour. By venturing into these correlated phenomena, we gain deeper insights into the complexities of human experience, thereby providing a robust foundation for future strides in cognitive science, promising practical applications that enhance our comprehension of time, intention, and human agency. Notably, the connection between intentional processing and the temporal dimension sheds light on how the timing of events can serve as a window into understanding intention and its influence on temporal processing within the intentional binding effect. The quantification and measurement of mental states, a challenging yet vital endeavour in psychology, are central to our exploration, urging us to deliberate carefully on this path. Therefore, this thesis explores the concept of intentions and their operationalisation within the framework of time perception and the intentional binding effect, striving to unearth new insights and connections within this intriguing terrain.

1.3 Contribution

Based on existing research on the intentional binding effect, there seem to be differences in the sensitivity of the intentional binding effect based on the methodology used to measure it. For example, sensory paradigms like the Libet method are sensitive to shorter action-outcome delays. In contrast, inferential methods like the interval estimation task or methods of constant stimuli seem to be sensitive to longer action-outcome delays. This thesis explores the reason behind this dissociative structure through experimental exploration. It proposes that the differential effect of delay is based on what components of the intentional binding effect are operationalised rather than on the methodology used. The thesis also explores the temporal dynamics of an outcome with and without intentionality and what other factors might affect it. By achieving these, we hope this thesis will provide a bridge to overcome the gap within the intentional binding literature, which is currently divided by the methodology used.

1.4 Thesis Overview

This thesis comprises seven chapters, encompassing an introduction and an appendix. The organisational structure of these chapters is outlined below.

- **Chapter 2** comprehensively introduces the subjective sense of control in conscious motor activities, known as the sense of agency. The definition of this concept is explored from a cognitive science perspective, examining its connection to intention. The chapter delves into related scientific fields and their applications. The sense of agency is then examined through various theories, such as the forward comparator model, the model of apparent mental causation, and the cue integration framework. Additionally, the methods used to measure the sense of agency in both explicit and implicit measures related to the measurements of cognitive processes are discussed, with a particular focus on the intentional binding effect.

- **Chapter 3** focuses on an implicit method of measuring the sense of agency—the intentional binding effect. The development of this effect is explored, along with different models describing the subjective temporal contraction between voluntary actions and expected sensory consequences. Various methodologies for measuring the intentional binding effect are discussed, highlighting their advantages and discrepancies.
- **Chapter 4** addresses discrepancies within a study using a modified temporal bisection task to measure participants' perception of intended outcomes compared to unintended ones. The chapter challenges conclusions drawn from the literature on the intentional binding effect, suggesting that the sensitivity of the binding magnitude to action-outcome delay depends on the methodology used. Instead, the chapter proposes that the sensitivity depends on how actions and outcomes are processed based on observations from the study.
- **Chapter 5** builds upon the speculation from the previous investigation, suggesting that the sensitivity of the binding effect to action-outcome delay is tied to how voluntary actions and outcomes are processed rather than the methodology itself. The chapter proposes a test of this hypothesis through a similar study, aiming to operationalise both components simultaneously during an intentional binding episode to gain independence from action-outcome delay sensitivities.
- **Chapter 6** concludes the exploration into measuring the temporal expansion of an outcome under intention, utilising various time perception strategies. The chapter summarises observations regarding the differential effect of sensitivity to action-outcome delay on the temporal expansion of intended outcomes.

- The appendix delves into the philosophical aspects of intention, exploring recent interest in the phenomenology of intention as a three-tier system rather than a single goal-directed phenomenon.

Chapter – 2

The Sense of Agency

In this thesis chapter, we will delve into the concept of the sense of agency, examining various models that aim to explain its nature and emergence. Subsequently, aligning with the thesis's overarching goal of investigating the evaluation methods applied to cognitive processes, this chapter will conclude by exploring diverse methodologies throughout the literature on measuring the sense of agency. Additionally, we will scrutinise their methodological limitations as they pertain to this cognitive phenomenon.

2.1 Definition

The sense of agency encompasses the subjective perception of being the initiator or controller of one's actions and ensuing consequences, particularly within physical movements (Gallagher, 2000; Haggard, 2017; Moore, 2016). It essentially denotes the conviction that our actions are deliberate and governed by our own will, enabling us to view ourselves as active agents within our environment (Christoff et al., 2011; Legrand, 2007; Legrand & Ruby, 2009). The sense of agency arises from the internal representation of our intentions, the monitoring of action outcomes, and the integration of sensory feedback. A fundamental prerequisite for a sense of agency in any context is the involvement of human volition (Haggard, 2008; Pacherie, 2008). In essence, this sense of agency can be thought of as what remains when considering Wittgenstein's earlier question (introduced in the preliminary section of this thesis).

This subjective experience of agency is crucial for our everyday interactions with the world. It is pivotal in shaping our self-perception and capacity to attribute causality to our actions. It enables us to distinguish between actions we generate ourselves and those externally imposed or involuntary (Ohata et al., 2021). In fact, the sense of agency, more often than not, becomes conspicuous when our intentions fail to align with the actual outcomes of our actions. For instance, as I write this thesis, I have a specific set of words in mind that I intend to type while the feedback is presented on the screen as sentences. However, when I make a typing error or misspell a word, I encounter a conflict and a violation of my expectations due to the disparity between my intended and actual action outcomes—resulting in a temporary loss of the sense of agency.

The sense of agency has garnered extensive attention and investigation across the disciplines of psychology, cognitive neuroscience, and philosophy (Berberian et al., 2012; Cornelio-Martinez, 2020; Haggard, 2017; Haggard & Chambon, 2012; Moore & Fletcher, 2012; Moore & Obhi, 2012; Polito et al., 2015; Wen & Imamizu, 2022). Researchers delve into the cognitive and neural mechanisms that underlie the development and maintenance of the sense of agency, exploring various facets, including action selection (Chambon & Haggard, 2012; Fleming et al., 2009), action monitoring (Kumar et al., 2015; Wen et al., 2015b), temporal binding between actions and their effects (Hoerl et al., 2020; Moore & Obhi, 2012; Nattkemper et al., 2010; Obhi & Hall, 2011; Poonian & Cunnington, 2013; Ruess et al., 2020), and the integration of sensory information (Herwig et al., 2007; Kemper et al., 2012; Klaffehn et al., 2021; Körding & Wolpert, 2004; Moore et al., 2009a; Sidarus et al., 2017; Synofzik et al., 2009; Wolpe et al., 2013).

Beyond the domains of cognitive science and its related fields, comprehending the sense of agency carries broader implications for our understanding of human behaviour, decision-making processes, and the conscious experience of being an agent, particularly in social interactions. For instance, the sense of agency is a fundamental requirement in the realm of law, where it plays a crucial role in determining criminal responsibility (Frith, 2014; Haggard & Tsakiris, 2009). Furthermore, it finds practical applications in diverse fields such as human-computer interaction (Aylett et al., 2014; Berberian et al., 2012; Coyle et al., 2012; Shneiderman & Plaisant, 2010), robotics (Caspar et al., 2015), and clinical psychology, especially in the context of disorders related to agency, such as schizophrenia (Graham-Schmidt et al., 2016; Pyasik et al., 2019; Synofzik et al., 2010; Thoenes & Oberfeld, 2017).

2.2 Theories of the Sense of Agency

While the definition of the sense of agency is relatively straightforward, there is a lack of a comprehensive theory that encompasses all its facets despite the considerable importance attached to this concept. Our focus will be on three theories that attempt to explain the origins of the sense of agency:

- The forward comparator model is characterised as a prospective or predictive model.
- The model of apparent mental causation is categorised as retrospective or causal.
- The Bayesian cue integration model seeks to integrate both predictive and retrospective perspectives.

2.2.1 Forward Comparator Model

The internal forward model, often referred to as the forward comparator model, is based on the efferent binding hypothesis and stands as one of the most influential models for explaining the intentional binding effect (Blakemore et al., 2002; Blakemore et al., 1998; Frith et al., 2000; Miall et al., 1996; Wolpert & Ghahramani, 2000; Wolpert & Kawato, 1998). According to this model (Fig. 4), an efferent copy of the perceptual representation of the intended outcome in the surrounding environment is generated whenever an individual intends to perform an action. Once the action is executed, the experienced outcome, now an afferent signal, is compared with the predicted outcome in a feedback loop. A match between these two representations signifies that the agent successfully carried out the action, resulting in a sense of agency over the action and outcome. Conversely, a mismatch implies a prediction error, suggesting a lack of control over the observed outcome.

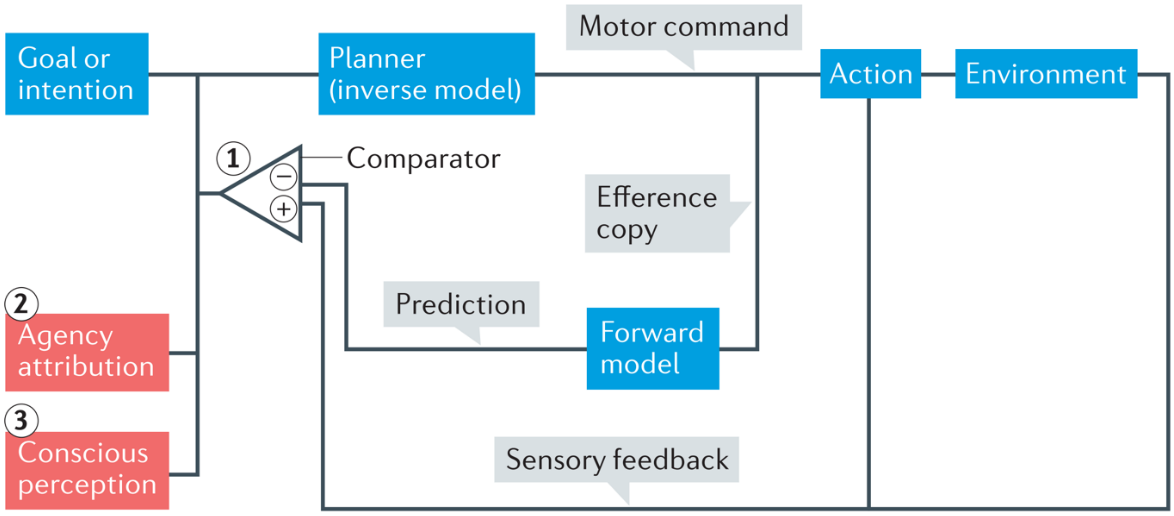


Fig. 4: Schematic of the "Forward Comparator Model". This model is used to define the sense of agency. In the comparator model of action control, an action is initiated by an intention or a desired goal state. The inverse model then calculates the motor command necessary to achieve the goal state or at least move towards it, generating the motor command that propels the action. A forward model utilises a duplicate of the current motor command, known as an efference copy, to anticipate the likely sensory outcomes of the command. This anticipation is then compared with sensory feedback signals, providing information about the ongoing action and its impact on the external environment. The outcome of this comparison can be employed in three ways: first, to adjust the existing motor command (1); second, to attribute agency for actions and environmental events (2) – whereby a result of zero indicates that one's action causes the event; and third, to diminish foreseeable, self-produced sensations (3). Image sourced from (Haggard, 2017)

The forward comparator model is the most widely embraced and applied explanation for the sense of agency. In this model, discrepancies between anticipated and actual outcomes typically diminish or lose the sense of agency (Carruthers, 2012; Eisner & Hommel, 2001; Sato & Yasuda, 2005). However, there are instances where this model falls short in explaining how the sense of agency comes about. For instance, in exploratory scenarios, it is not anticipated that agents would possess predictions about their surroundings. Nevertheless, individuals still experience a sense of agency over routine actions performed in such exploratory environments (Wen & Haggard, 2020). Alternative models or extensions to the existing forward comparator model become necessary to address these limitations.

2.2.2 Model of Apparent Mental Causation

The model of apparent mental causation was proposed by Wegner et al. in the theory of "apparent mental causation" (Wegner & Wheatley, 1999). According to this perspective, the sense of agency emerges when individuals perceive a correlation between their intentions, thoughts, actions, and subsequent outcomes. Wegner's proposition suggests that this sense of agency is not a direct perception of one's mental causation but rather an inference drawn from the perceived correlation between mental events (such as thoughts and intentions) and external occurrences or physical actions. The brain generates this sense of agency by associating the timing and content of one's thoughts with the corresponding actions and outcomes. Essentially, individuals feel like they influence events in the world because they observe a consistent relationship between their mental states and the resulting actions or outcomes. In summary, the subjective experience of control arises when individuals detect a meaningful link between their thoughts, intentions, and the unfolding events or actions, leading their brains to infer a causal connection.

This model challenges the assumption that conscious will is a direct report of the processes leading to action. It proposes that the sense of agency arises from inferences about causation, regardless of their accuracy. Wegner introduced the concept of "conscious will" within this framework, proposing that the feeling of consciously willing an action may not be a direct cause of the action itself but rather a component of inferred causality between a thought and an action. A consistent thought occurring before an action may lead to a perceived sense of causation even if the thought did not cause the action. The apparent causation between these two events leading to a sense of conscious will or agency is conditioned on three principles of causal perception and attribution (Michotte, 1963).

- Priority: The thought should precede the action at a proper interval, where it is understood that causal events precede their effects promptly. The feeling of conscious will is heightened when the thought happens before the action.
- Exclusivity: The thought should be the only apparent cause of the action. One of the basic principles of causal inference is that we tend to discount the causal influence of one potential cause if others are available, and successful outcomes are more likely to be associated with conscious will.
- Consistency: The thought should be compatible with the action. It draws on the observation that thoughts that serve as potential causes of actions typically have semantic associations with those actions and that external influences or the presence of other actors can diminish the sense of willful control.

As long as the two mental events (thought and action) follow these principles, it is assumed that the agent is imbued with a sense of agency through the experience of conscious will.

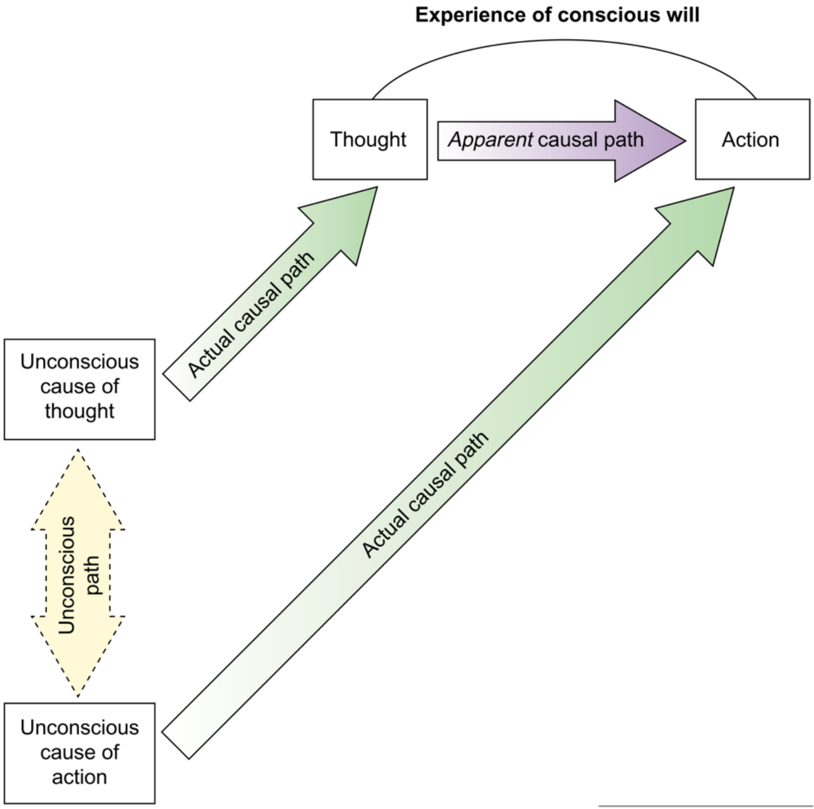


Fig. 5: The model of apparent mental causation. The model shows how it generates an experience of conscious will through apparent causality. The sensation of conscious will emerges when an individual deduces a perceived causal connection from thought to action (depicted by the purple arrow). The actual causal pathways (depicted in green) remain outside the person's conscious awareness. Unconscious mental events prompt thoughts, and actions are likewise instigated by unconscious mental events. The perception of conscious will is a consequence of what appears to be happening rather than an accurate representation of reality. Image sourced from (Wegner, 2003)

This model has sparked considerable discussion and debate within the psychological community, with some researchers supporting Wegner's ideas and others proposing alternative explanations for the complex phenomenon of the sense of agency. Under this framework, a prediction is no longer necessary, and explorative actions (as mentioned in the previous sub-section) that lack specific predictions can still generate a sense of agency if the above principles are satisfied.

2.2.3 Dual Nature of the Sense of Agency (Bayesian Cue Integration Model)

While we have explored the two primary perspectives of how the sense of agency comes about—the prospective forward comparator model based on prediction and the retrospective model of apparent mental causation relying on perceived causality or inference—both fail to account for various aspects of the sense of agency. In this sense, these theories overlook specific observations and factors influencing the sense of agency. Factors such as task performance (Aoyagi et al., 2021; Inoue et al., 2017; Metcalfe & Greene, 2007; Wen et al., 2015b), mental state (Demanet et al., 2013; Howard et al., 2016), and social interactions (Beyer et al., 2017; Sidarus et al., 2020) play a role in shaping the sense of agency. The existing theories seem unable to adequately explain how these factors impact the sense of agency.

One way to answer these questions might be related to a "best of both worlds" situation. According to the literature, within the sense of agency, we encounter a crucial distinction between what we can term the 'feeling of agency' and 'judgment of agency' (Saito et al., 2015; Synofzik et al., 2008). These two facets encapsulate distinct dimensions of how individuals perceive and attribute their actions to themselves (Pacherie, 2007, 2008) (Fig. 6).

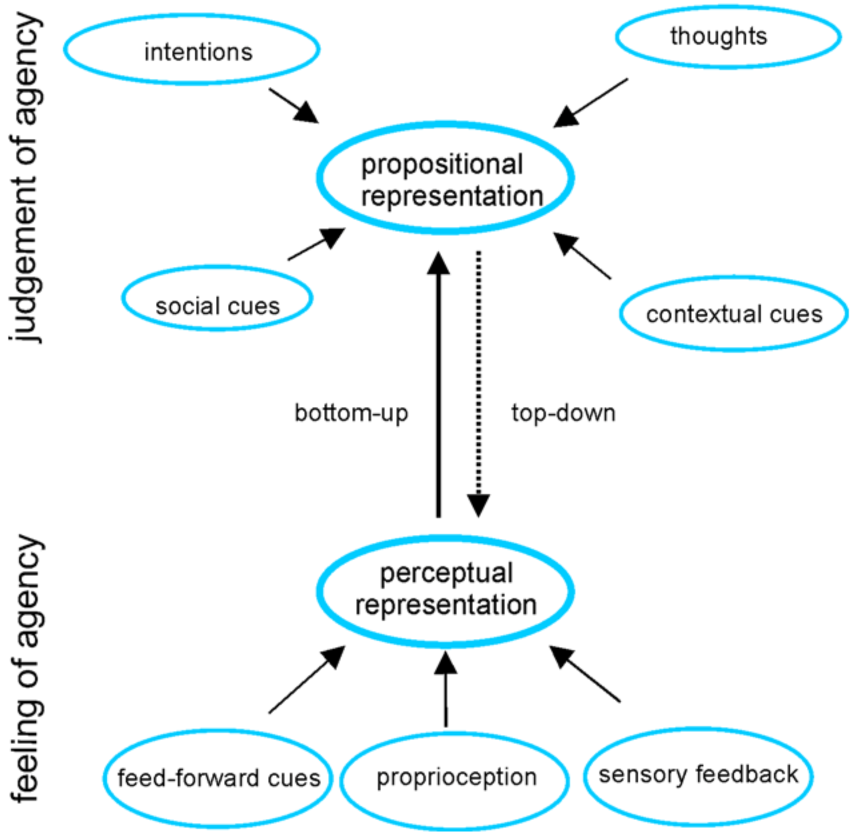


Fig. 6: The two-process account of agency. The primary, non-conceptual sense of agency results from a flexible and gradual sub-personal weighting process involving various perceptual and motor cues related to actions (the feeling of agency). This pre-conceptual core is then subject to further processing by conceptual capacities and attitudes, such as beliefs and desires, leading to the formation of an attribution of agency (the judgment of agency). The relative contributions of the feeling and judgment of agency to the overall sense of agency depend on the context and task requirements. Image sourced from (Synofzik et al., 2008)

The "feeling of agency" refers to the subjective experience of controlling one's actions and perceiving oneself as the originator or author of those actions. It encompasses a sense of volition, conscious awareness of intending and initiating an action, and the accompanying feeling of control over one's actions. The feeling of agency engages with the phenomenological aspects of this sense, including the subjective experience of intentionality, control, and self-initiation. This feeling of agency is understood to primarily come about by comparing efferent representations of the expected or intended outcome and the actual outcome or feedback experienced.

On the other hand, the "judgment of agency" refers to the cognitive evaluation or attribution process by which individuals assess the causal relationship between their actions and the ensuing outcomes. It necessitates conscious reflection and cognitive appraisal regarding whether one's actions are responsible for the observed consequences or events. Typically, this involves explicitly attributing causality, determining whether the action was self-initiated or externally induced (Georgieff & Jeannerod, 1998; Sirigu et al., 1999; Tsakiris et al., 2005).

While the feeling of agency delves deeply into the immediate subjective experience and phenomenological aspects of control and authorship, the judgment of agency engages in a higher-level cognitive process that evaluates and attributes causality (Wegner, 2003; Wegner & Wheatley, 1999). The feeling of agency primarily focuses on the immediate subjective experience of control and initiation. In contrast, the judgment of agency involves a retrospective assessment and cognitive reasoning concerning the causal connection between action and outcome.

To illustrate this distinction, let us consider a scenario: two individuals are placed in separate rooms, each tasked with switching on a light bulb using a wall-mounted button. When one person presses their button, the light turns on, leading to a clear feeling of agency as they intentionally caused the expected outcome. Unbeknownst to both individuals, we secretly switch the control of the buttons so that when one person presses their button, it no longer affects the light in their room but instead activates the light in the adjacent room. In this altered scenario, both individuals experience a “judgment of agency” as they retrospectively attribute agency to themselves or another agent.

While the feeling of agency and the judgment of agency can be considered two complementary aspects within the sense of agency, it is essential to note that the feeling of agency and the judgment of agency are not strict dualistic opposites (Synofzik et al., 2009, 2013). Instead, they represent different dimensions within the sense of agency, interconnected and interrelated, working in harmony to shape our overall sense of agency. The feeling of agency provides the immediate, subjective experience of control and authorship, which, in turn, can influence subsequent judgments of agency. Simultaneously, the judgment of the agency, achieved through cognitive evaluation and attribution, can influence and mould our subjective experience and interpretation of control.

This dualistic paradigm behind the sense of agency is established using Bayesian cue integration. This framework offers a structure capable of assimilating additional elements pertinent to the sense of agency. It asserts that the likelihoods of self-agency, both at the sensorimotor level (associated with the feeling of agency) and the cognitive level (related to the judgment of agency), are computed based on the prior distribution of outcomes and actual input. These computations are weighted by the variabilities inherent in the prior distributions. The resultant probabilities from the two levels are fused into a comprehensive judgment of agency (Fig. 7).

The sensorimotor level encompasses factors directly tied to actions and their outcomes. In contrast, the cognitive level involves elements not directly associated with actions and outcomes but rather connected to intentions, expectations, and inferences. The probability of experiencing a sense of agency is determined by applying Bayes' rule at each level, factoring in the variabilities of the outcome distributions. This approach parallels the statistically optimal weighting observed in integrating visual and haptic information in multisensory processing (Ernst & Banks, 2002).

The theory of Bayesian integration can elucidate the impact of various factors that may not be directly linked to actions but influence the prior distribution of outcomes. These theoretical frameworks offer a basis for comprehending how the sense of agency, or instances of its impairment, can be computed from both internal and external inputs. Exploring the neural foundations of the sense of agency in studies may yield valuable insights into the emergence of this perception and its interconnectedness with other cognitive systems, such as decision-making, causal inference, and reinforcement learning.

Further influence of the cue integration theory behind the sense of agency will be discussed in the chapter related to intentional binding, an implicit measurement related to the sense of agency.

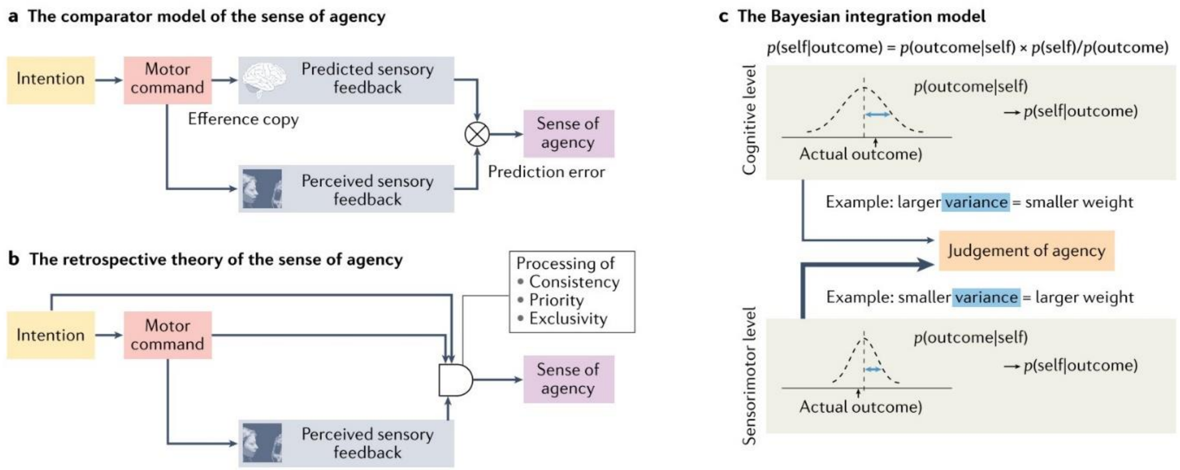


Fig. 7: The three theories that try to define how the sense of agency comes about. a) the forward comparator model of the sense of agency. According to the comparator model, the sense of agency arises from comparing predicted sensory feedback with the actual perceived sensory feedback. b) In contrast, the retrospective theory does not rely on a prediction in the brain. Instead, it suggests that a sense of agency is experienced when the outcome aligns with the action/intention principles of priority, exclusivity, and consistency. c) the Bayesian cue integration model. It proposes that self-agency probabilities are computed at both sensorimotor and cognitive levels. These probabilities are derived from the prior distribution of outcomes and actual input, with weights determined by the variabilities of the prior distributions. The probabilities from both levels are then integrated to form a judgment of agency. Image sourced from (Wen & Imamizu, 2022)

2.3 Measurements of the Sense of Agency

In the realm of cognitive assessment, the sense of agency can be measured through two distinct approaches as identified in the literature: explicit and implicit measurements (Dewey & Knoblich, 2014; Ebert & Wegner, 2010; Imaizumi & Tanno, 2019; Majchrowicz & Wierzchoń, 2018; Moore et al., 2012; Saito et al., 2015).

Explicit measures of the sense of agency typically involve direct judgments concerning one's perception of causal efficacy or experience as an agent. These measures are predominantly qualitative and often rely on participants' subjective self-reports (Sato &

Yasuda, 2005; Wegner & Wheatley, 1999). Explicit measures delve into the personal and conscious assessment of one's agency, offering valuable insights into the individual's introspective experience.

In contrast, implicit measures of the sense of agency adopt a quantitative perspective, emphasising observable perceptual differences. These measures often investigate sensory phenomena, such as sensory attenuation (Blakemore et al., 1999a; Blakemore et al., 1999b; Blakemore et al., 1998; Stenner et al., 2014; Waszak et al., 2012) or delve into time perception via processes like temporal binding (Hughes et al., 2013; Moore & Obhi, 2012; Tanaka et al., 2019). Implicit measurements uncover subtle, non-conscious aspects of agency perception by examining how individuals respond to sensory and temporal cues without direct self-reporting.

These two distinct approaches, explicit and implicit, provide complementary lenses through which the sense of agency can be examined, each offering valuable insights into different facets of this intricate cognitive construct.

2.3.1 Explicit Measurement of the Sense of Agency

Explicit cognitive measurements capture conscious and deliberate processes that individuals can readily reflect upon and explicitly articulate concerning their sense of agency. These measurements typically involve methods such as self-report measures, interviews, or questionnaires that directly inquire about individuals' subjective experiences of control, ownership, authorship over their actions, and their perceived causal relationships with outcomes (Farrer et al., 2008) (See Fig. 8 for an example of a study involving explicit agency judgement, adapted from (Sirigu et al., 1999)). By eliciting explicit judgments and introspective reports, researchers gain valuable insights into how individuals consciously contemplate and attribute their actions to themselves, shedding light on their reflections regarding the sense of agency (Synofzik et al., 2010).

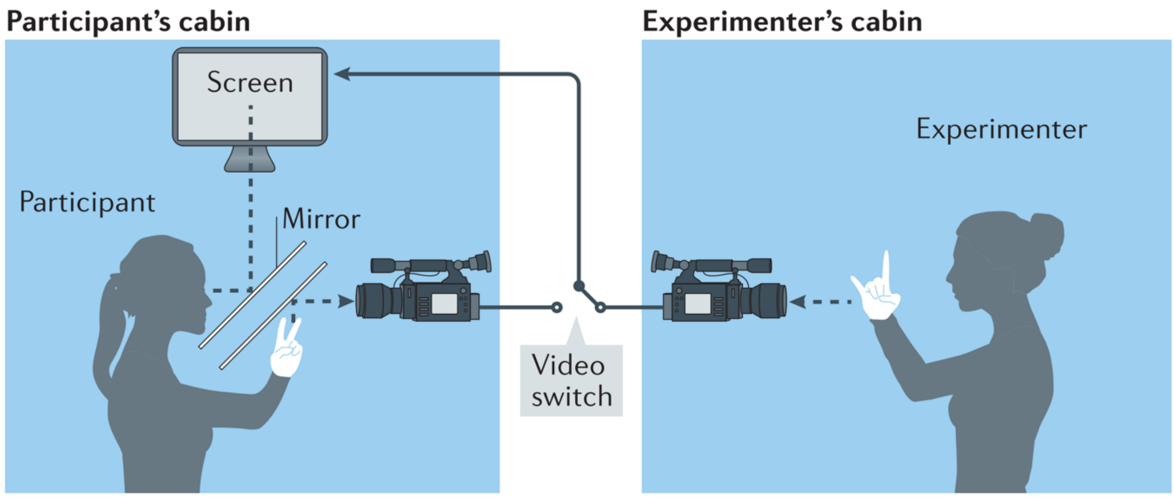


Fig. 8: Example of a study involving the explicit judgement of agency. The figure describes an experiment where individuals determine whether a video they observe depicts their hand movements or those of another person. Participants are instructed to execute a specific hand movement pattern. A screen connected to a video switch controlled by the experimenter allows participants to view either their hand or the hand of the experimenter, who wears an identical glove. The experimenter then performs either the same hand movement as the participant or a different one. If the participant indicates that they are observing their hand action, they attribute authorship of the observed action to themselves. Image sourced from (Haggard, 2017)

However, it is worth noting that this thesis primarily focuses on investigating the intentional dimension of agency through the lens of time perception. Explicit agency measurements, as described here, will not be the central focus of this study.

Beyond the scope of this thesis, it is crucial to recognise that explicit agency measures possess certain limitations. Firstly, people may not always provide accurate ratings, especially considering that the sense of agency is often described as a phenomenologically subtle experience (Clark et al., 2013; Haggard, 2005). Secondly, explicit measures may fall short of capturing implicit or unconscious processes that can influence behaviour without individuals' conscious awareness. These processes may encompass automatic or habitual responses, emotional factors, or subconscious mechanisms that individuals may not be able to express explicitly. Consequently, explicit measures may overlook these underlying influences, potentially offering an incomplete understanding of agency. Finally, it is essential to acknowledge that the feeling of agency can be context-dependent and susceptible to situational factors, such as specific circumstances or environmental cues. Explicit measures may not adequately capture these contextual nuances, potentially providing a static or incomplete portrayal of agency.

2.3.2 Implicit Measurement of the Sense of Agency

Implicit measurements in the context of the sense of agency are designed to uncover unconscious or automatic processes that contribute to the perception of control and self-initiation of actions. These measurements typically involve tasks that indirectly assess implicit associations, biases, or unconscious influences on one's sense of agency. Through the study of perceptual changes, implicit measurements offer valuable insights into the automatic processes underpinning the sense of agency, processes that may not be readily accessible through conscious introspection.

One well-explored perceptual method for measuring an implicit sense of agency is the concept of "intentional binding" (Haggard et al., 2002b; Moore & Obhi, 2012). Intentional binding is an implicit measure because it captures an automatic perceptual distortion reflecting an individual's subjective experience of temporal contiguity and causality between their actions and subsequent outcomes. It indirectly gauges how individuals perceive and attribute the causal relationship between their voluntary actions and resulting outcomes, all through the lens of time perception. Unlike explicit measurements, participants engaged in intentional binding tasks are not prompted to judge agency or consciously report their sense of control or causality. Instead, this effect is observed through objective measures of time perception, sidestepping the potential biases and limitations associated with self-reported agency measures.

In a typical intentional binding scenario, participants partake in a task where they perform voluntary actions (e.g., pressing a button) and observe the timing of a subsequent outcome (e.g., an auditory tone or a visual stimulus). The observed temporal compression, characterising the intentional binding effect, occurs automatically and beyond conscious awareness, contingent upon the action's voluntary nature.

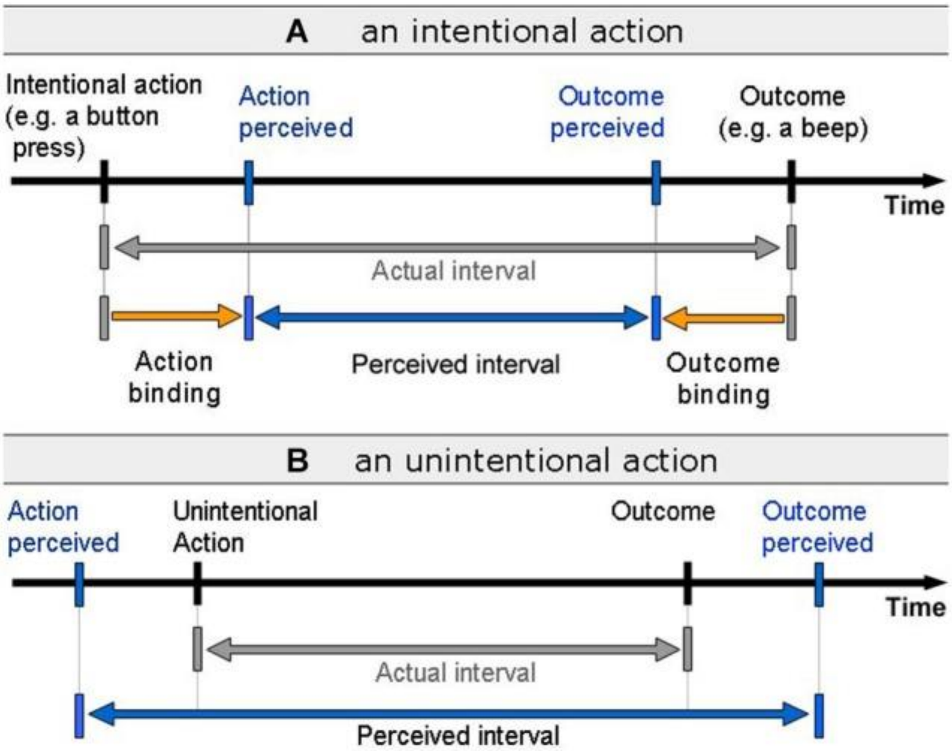


Fig. 9: Depiction of results from a typical intentional binding study. A) In the context of voluntary actions, the perceived time of both action and outcome are shifted toward one another, leading to a shorter perceived interval between the action and its consequence. B) Conversely, in the case of involuntary actions, the perceived interval between the action and its outcome is longer than the actual delay. Image sourced from (Limerick et al., 2014)

Additionally, sensory attenuation is another implicit indicator of the sense of agency (Blakemore et al., 2000; Blakemore et al., 1999a; Blakemore et al., 1999b; Blakemore et al., 1998). According to influential theories and models of motor control, specifically the forward comparator model (Miall & Wolpert, 1996; Wolpert & Ghahramani, 2000; Wolpert & Kawato, 1998), the sense of agency is inferred by comparing predicted and observed experiences of voluntary actions. One consequence of this model is the attenuation of sensory feedback signals, which is why we cannot tickle ourselves. The model predicts that when we make a tickle-like movement, the perceptual sensation of being tickled attenuates the actual sensory consequence of the tickling.

The sense of agency is inferred by comparing predicted and observed experiences of voluntary actions. A byproduct of this model is that sensory feedback signals are attenuated. This attenuatory behaviour is one of the reasons why we cannot tickle ourselves. The motor prediction that once a tickle-like movement is made, the perceptual feeling of being tickled attenuates the actual sensory consequence of being tickled.

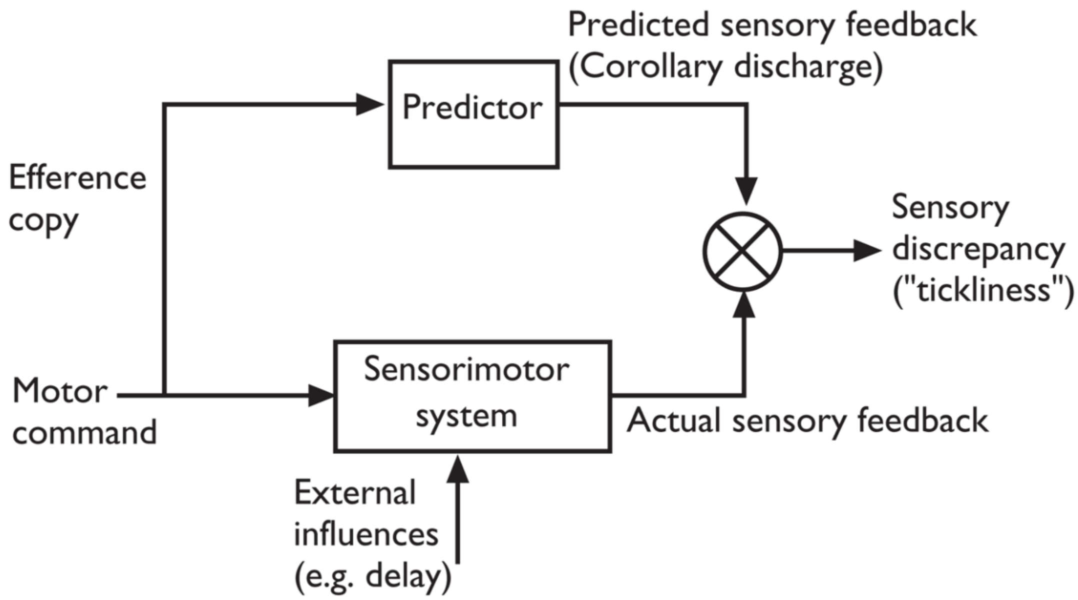


Fig. 10: An adaptation of the forward comparator model for predicting sensory outcomes of movement. It utilises an internal forward model to predict sensory feedback based on motor command. The system compares predicted feedback with actual sensory input. Self-produced sensations, accurately predicted by the motor command, exhibit minimal sensory disparity. Increased sensory disparity, caused by factors like delays or altered trajectories, suggests externally generated sensations. This system allows for distinguishing between sensory events resulting from self-motion and those from environmental factors like object contact. Image sourced from (Blakemore et al., 2000)

While both intentional binding and sensory attenuation are relevant indicators of an implicit sense of agency, this thesis primarily focuses on investigating the implicit measure of agency through the intentional binding effect and its associated components, as will be discussed in further detail in the upcoming chapter.

Chapter – 3

The Intentional Binding Effect

Patrick Haggard and colleagues first reported the intentional binding effect in a landmark study wherein the authors explored the effect of intention/volition on the time perception of voluntary actions and consequences separated at a temporal distance (Haggard et al., 2002b). As mentioned earlier, the effect refers to a subjective or perceived shortening of the interval between the action and its causal consequence. Haggard and colleagues have since suggested that this effect can be considered a proxy for the sense of agency and is an implicit measure of it. In this thesis chapter, we will go through how the intentional binding effect was developed, the different models that try to explain it, and the various methodologies used to measure this perceived effect. By the end of this section, we will also discuss the methodological discrepancies associated with measuring the intentional binding effect.

3.1 Benjamin Libet and the Neuroscience of Free Will

In the 1980s, a prolific scientist named Benjamin Libet set out to explore the idea of human beings as "conscious automata". T.H. Huxley coined the term itself in 1874, describing humans as entities devoid of free will (Huxley, 1874). Huxley's assertion was rather explicit: "*Volitions do not enter into the chain of causation…. The feeling that we call volition is not the cause of a voluntary act, but the symbol of that state of the brain which is the immediate cause.*" This notion was shared by many contemporary scientists and philosophers who adhered to materialist viewpoints, contending that free will was nothing more than an illusion. For instance, Daniel Wegner succinctly put it: "*The experience of willing an act arises from interpreting one's thought as the cause of the act*" (Wegner, 2003; Wegner & Wheatley, 1999). In essence, this implied that our brains had already made all the decisions for us, and we only became conscious of these decisions after the fact, erroneously attributing them to our intentions.

The evidence for this idea was found in a seminal study in neuroscience and psychology that probed the temporal dynamics of conscious decision-making and the intricate relationship between conscious intentions and neural activity (Libet, 1985; Libet et al., 1983) (Fig. 11). In Libet's experiment, participants were instructed to execute a simple voluntary action, such as lifting their hand, at a moment of their choosing while closely monitoring a continuously rotating clock that completed a full revolution every 2560 milliseconds (Fig. 12). Simultaneously, their brain activity was recorded using electroencephalography (EEG), and they were asked to report the time at which they decided to act based on the constantly rotating clock. The pivotal discovery here was that the neural activity associated with initiating the action termed the "readiness potential", was detected by the EEG electrodes approximately 350ms before participants reported their conscious intention to act. In simpler terms, the neural processes linked to the action had already commenced before participants were aware of their conscious decision to execute it.

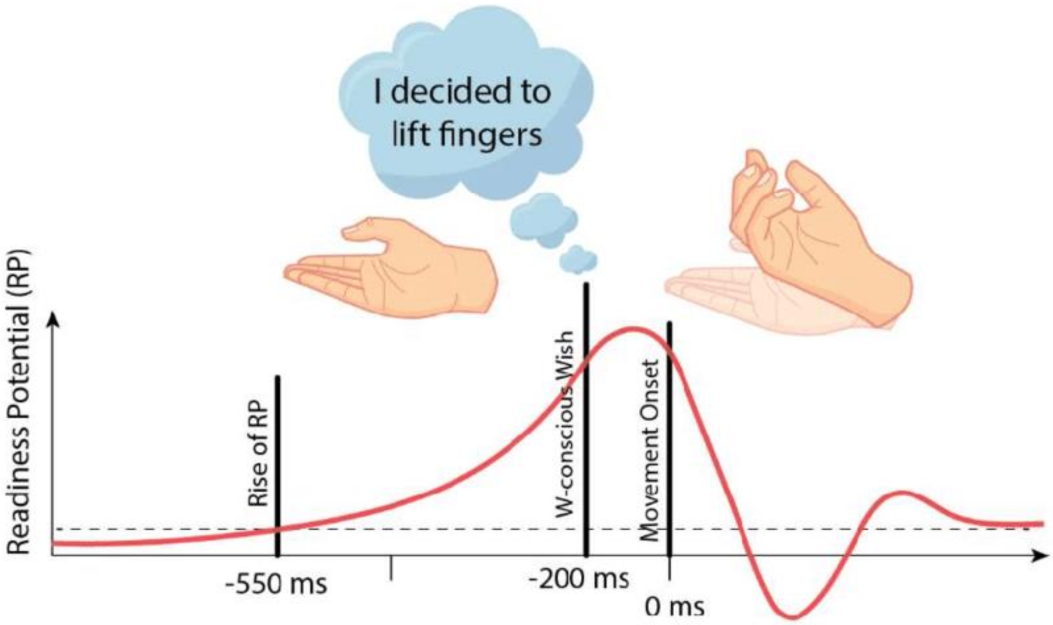


Fig. 11: Diagram illustrating the readiness potential over time in Libet's experiment. The experiment deals with the timing of free will and various events. The readiness potential starts increasing 350ms before the conscious intention (the feeling of free will). Image sourced from (Jamali et al., 2019)

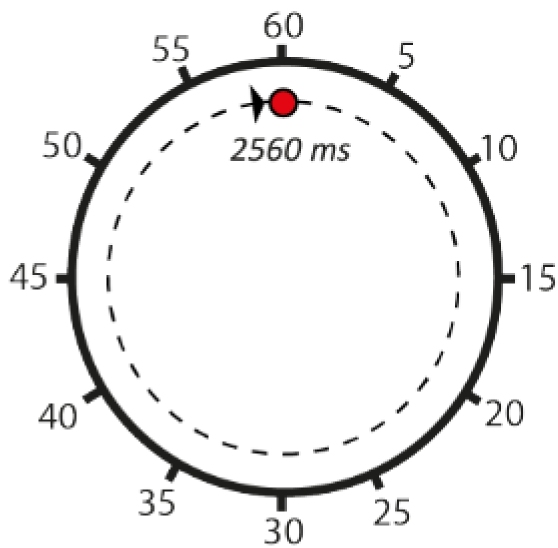


Fig. 12: Reference illustration of the constantly rotating Libet Clock. 5 units demarcate the ticks on the clock. The clock is designed to complete one revolution in 2560ms. Image sourced from (Cornelio-Martinez, 2020)

However, it is essential to acknowledge that despite its significance, this experiment was not without its share of flaws and controversies. These issues spanned from methodological considerations to divergent interpretations of neural activity (Gomes, 2002; Klein, 2002; Neafsey, 2021). For instance, certain studies suggested that the readiness potential might reflect the natural fluctuations in background neural activity rather than the result of a specific neural event pinpointing the onset of movement (Schurger et al., 2012, 2016, 2021; Shibasaki & Hallett, 2006). Nevertheless, the focus of our study is not to address these intricate issues but rather to shed light on the origins of this methodology and its relevance in assessing agency and conscious intentions.

3.2 The Libet Method

In the 2000s, neuroscientist Patrick Haggard expanded upon Libet's findings, introducing a novel approach to investigate the sense of agency. Haggard's innovation involved introducing a time delay between a voluntary action and its resulting outcome, with the intriguing consequence that our minds subjectively stitch these two events together. Initial evidence towards this perceptual effect was found in a simple reaction time experiment where it was found that voluntary actions had a consistent perceptual delay in their reaction times. On the other hand, consequences of voluntary actions were shown to have faster reaction times (Haggard et al., 2002a). This temporal distortion offers a fascinating window into understanding the sense of agency, and its conceptual foundation is particularly elegant, drawing from various strands of cognitive science and philosophy.

- **Association of Action and Outcome:** Agency fundamentally revolves around the association between an action and its subsequent outcome. Intention causes movement (which here is the action), which causes an effect/outcome/goal within the environment. Planning goal-directed actions always includes anticipating possible action effects (Ziessler & Nattkemper, 2002). Moreover, as per David Hume's theory of causality (Hume, 2011), the mind naturally associates actions and consequences, recognising them as temporally contiguous events. Haggard's method capitalises on this intrinsic link.

- **Mental Chronometry:** Reductions in reaction time, facilitated by predictive learning processes, often stem from associations between stimulus and response representations (Simon & Craft, 1989). Similarly, a decrease in the temporal gap between action and consequence percepts can be seen as evidence of an association between these representations' conscious elements.
- **Predictive Learning and Perceptual Attraction:** When an outcome consistently follows an action, our cognitive system tends to learn to predict this association. This concept aligns with the idea of perceptual attraction, akin to the findings of Yeo et al. (Yeo et al., 1997), where when an animal learns an association between two events, the response to the unconditioned stimulus is temporally shifted back towards the conditioned stimulus due to predictive learning.
- **Efferent Binding and Coherent Representation:** The notion of perceptual attraction harmonises with the concept of efferent binding, wherein conscious states are bound together to form a coherent representation of intentional action. This binding process allows the brain to integrate related information or events (Engel et al., 1999; Shadlen & Movshon, 1999).
- **Temporal Attraction and the Unity of Consciousness:** The observed temporal attraction effects between percepts align with the overarching function of consciousness to unify experiences across space and time (Brook & Raymont, 2021).

Haggard coined the experimental procedure as the "Libet Clock method," with the observed phenomenon termed the "intentional binding effect." Importantly, this effect is only observed in the presence of intentional, voluntary actions, underlining its relevance in probing the sense of agency.

3.2.1 Libet Clock Method – Procedure

The experimental procedure employed by Haggard et al. had four distinct experimental conditions (Haggard et al., 2002a; Haggard et al., 2002b). Two conditions were labelled as "operant" or “experimental”, while the remaining two served as baseline conditions. The nomenclature "operant" was assigned because these conditions encapsulated the complete action-outcome cycle, wherein participants initiated a voluntary action (e.g., pressing a button) and, after a temporal delay, experienced a corresponding outcome (e.g., hearing a tone). The rationale behind this setup was to foster an association in the participant's mind between the action and its outcome, which, in turn, might be reflected in their temporal estimations of either the action or the outcome.

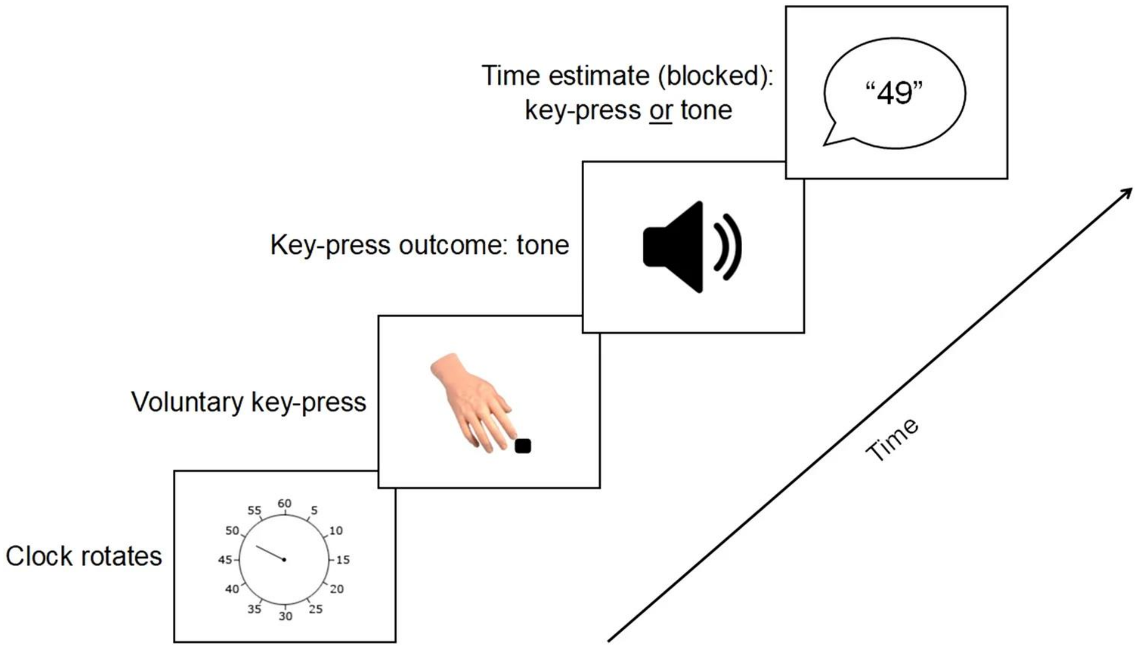


Fig. 13: Typical trial structure in operant blocks as employed in the Libet Clock method developed by Haggard et al. Participants were required to press a key at their own pace, followed by a tone after 250 ms. Depending on the type of operant block, participants were instructed to either report the timing of their action or the timing of the outcome of their action. Image sourced from (Ivanof et al., 2022)

On the other hand, the "baseline" conditions were designed to isolate either the action or the outcome, independent of one another. This isolation allowed Haggard et al. to gauge the temporal estimations of actions or outcomes without the influence of the reciprocal association. The key measure of interest was the judgment error, computed by contrasting participants' temporal estimates of button presses (actions) or tones (outcomes) in single-event baseline trials with their respective estimates in operant or experimental conditions.

In all these conditions, participants provided time estimates based on an on-screen clock called the "Libet clock" (Fig. 12). This clock completed a full revolution every 2560 milliseconds. It featured conventional time intervals, such as 5, 10, 15, and so forth, up to 60. As soon as the participant pressed the button, based on the current condition block (baseline or operant), they would experience a tone as an outcome. Subsequently, participants were required to estimate the time at which either the action or outcome occurred based on the condition.

To be specific, the conditions were (Fig. 14).

- **(Baseline) Action Only Condition:** Participants pressed a button and estimated the clock's position when they initiated the action.
- **(Baseline) Outcome Only Condition:** Participants did not press buttons but awaited a computer-generated tone. They then estimated the clock's position when they heard the tone.
- **(Operant) Action Estimate:** Participants pressed a button, experienced a delayed outcome, and estimated the clock's position when they initiated the action.
- **(Operant) Outcome Estimate:** Participants pressed a button, experienced a delayed outcome, and estimated the clock's position when they heard the tone.

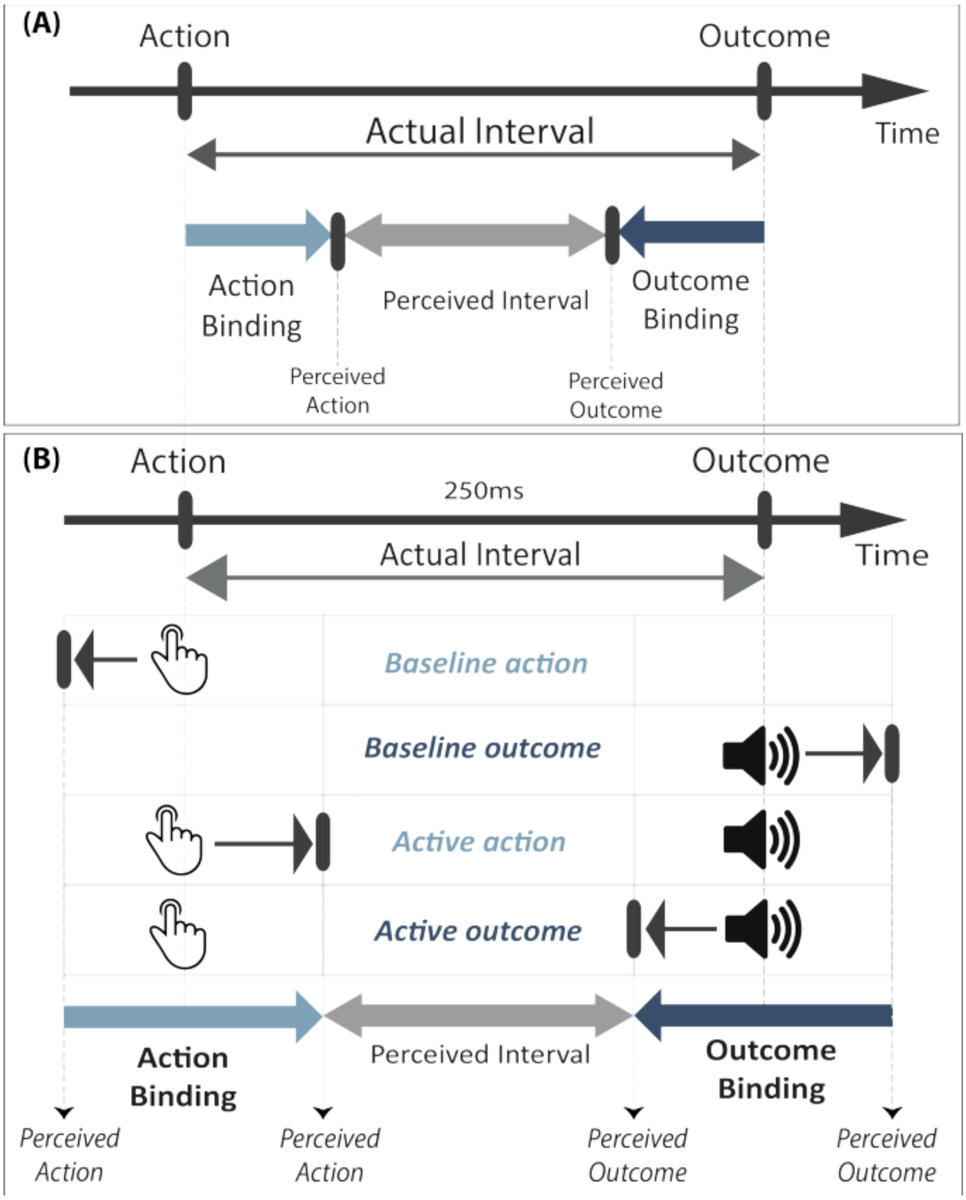


Fig. 14: The various conditions employed to measure the intentional binding effect using the Libet Clock method. A) Typical results observed during an intentional binding episode. B) The various measurement blocks required for measuring intentional binding using the Libet Clock method. Under baseline conditions, only a single event occurs (the action or the outcome). On the other hand, In active or operant conditions, both the action and the outcome occur. Image sourced from (Cornelio-Martinez, 2020)

Mean baseline-corrected judgment errors were calculated and compared, which involved subtracting the baseline estimates from the experimental condition estimates. Intriguingly, it was observed that in conditions where a tone followed voluntary actions as an outcome (i.e., experimental conditions), the action was perceived as occurring closer in time to the outcome. Conversely, the outcome was perceived as happening closer to the action. These temporal shifts were termed "action binding" and "outcome binding," respectively. The perceived reduction in the temporal gap between the voluntary action and its outcome was labelled as the "intentional binding effect," as this effect was exclusively evident during voluntary, intentional actions.

Four additional conditions were introduced to confirm that this effect was indeed linked to intention and volition, again divided into operant and baseline categories. However, in this case, the actions were triggered by an involuntary TMS (transcranial magnetic stimulation) pulse targeting the motor cortex, leading to involuntary hand twitches. The data collection paralleled voluntary actions, with mean baseline-corrected judgment errors being analysed. Interestingly, in the involuntary/TMS/sham setup, the action was perceived as occurring further away from the outcome, and the outcome was likewise perceived as being more distant from the action, in the opposite direction (Fig. 9), i.e., perceptual repulsion instead of attraction. This outcome implied an expansion in the perceived temporal interval between the involuntary action and its observed effect.

These findings provide compelling evidence that intentional binding manifests exclusively during voluntary actions and is conspicuously absent, or even reversed, in the context of involuntary actions.

3.3 How does the Intentional Binding Effect come about?

The intentional binding effect has been the subject of various models and theories in cognitive psychology and neuroscience, and it is understood to be a complex perceptual phenomenon developed through an artefact of a combination of various cognitive processes. This variety is established within multiple models which aim to explain the intentional binding effect. It is worth noting that these models are not mutually exclusive, and the intentional binding effect likely involves a combination of cognitive, neural, and perceptual processes. Thereby, no model can thoroughly explain this perceptual phenomenon, and each model has its situations where it works and others where it fails. A few of them, which are further discussed in detail, are as follows.

- Efferent Binding Hypothesis and Common Coding
- Sensory Recalibration
- Temporal Attention Model
- Cue Integration Theory

3.3.1 Efferent Binding Hypothesis and Common Coding

The efferent binding hypothesis can be described as a theoretical cognitive process similar to how we perceive and combine visual objects. According to this hypothesis, consciousness seems to have a role comparable to how visual objects are combined, as suggested by Engel et al. (Engel et al., 1999). This hypothesis suggests that efferent binding is responsible for associating our intentions with the actions they generate and the perceptual representations of the environmental consequences resulting from these actions, which are received as afferent signals.

Experimental support for the efferent binding hypothesis was demonstrated by Blakemore et al. (Blakemore et al., 1998) through a sensory attenuation system (Fig. 10). In this experiment, participants were unable to tickle themselves because the proprioceptive signals from their actions were effectively cancelled out by the predicted sensory signals (efference) associated with the tickling movement. Interestingly, proprioceptive input was not cancelled similarly when an external agent caused the tickling movement. This experimental evidence is significant as it highlights the connection between conscious awareness of physical stimuli resulting from one's actions and the predictive associations that occur.

More speculatively, it seems likely that efferent binding may play a vital role in constructing self-consciousness. The representation of 'I' as a conscious agent may hinge on binding our conscious intentions to our actions and their effects. When there is alignment between our intentions and external events, these two representations of action and consequence become fused and are recognized as intentional actions of the agent. This phenomenon, known as intentional binding, manifests as a temporal perceptual effect associated with this process.

To empirically test the efferent binding hypothesis, a simple reaction time task inspired by the Libet Clock method was employed (Libet et al., 1983). The hypothesis posited that if conscious activity binds intentions, actions, and perceptual consequences, the reaction times for each process should reveal a directional attraction. The results of this reaction time experiment showed a consistent positive perceptual error in the reaction times of actions, indicating that actions were perceived as occurring later than they did. In contrast, the reaction times for the perceived consequences of actions have exhibited a consistent negative perceptual error, suggesting that these consequences were perceived as occurring earlier than they did. This pattern held for voluntary or causal actions, not just sequences of events (Haggard et al., 2002a).

From the initial hypothesis to the experimental results, it becomes evident that the efferent binding model provides a viable framework for explaining the intentional binding effect. When a voluntary action triggers a sensory stimulus within the sensorimotor context, it leads to temporal shifts in the perceived event timings, reflecting an attraction effect between the perception of the action and its sensory consequences. This attraction effect aligns with the efferent binding process, connecting conscious representations of events with their associated actions. Moreover, the efferent binding hypothesis can be extended to the common coding view proposed by Prinz (Prinz, 1992), suggesting that motor and perceptual processes share a common representational code in the brain. In essence, the same neural representations underlie the planning and execution of actions and the perception of sensory outcomes. In the context of efferent binding, this suggests that the brain operations responsible for conscious awareness are fundamentally intertwined with the neural codes that govern stimulus and action representations in the common coding view.

3.3.2 Sensory Recalibration

Sensory recalibration is a phenomenon that encompasses our perception's ability to adjust and modify the timing of sensory events based on prior experiences and expectations. This process involves updating our internal representation of the temporal relationships between various sensory stimuli, and it provides a novel perspective on the connection between temporal contiguity and intentional binding, a concept initially introduced by Stetson et al. in their experiments (Stetson et al., 2006).

It was found from their studies that participants who were adapted to a fixed delay between a voluntary action (such as a key press) and its sensory consequence (like a colour flash) could experience an intriguing illusion. Occasionally, presenting the colour flash with a shorter-than-expected delay could lead to an illusory reversal in the perceived order of the action and its sensory consequence. In other words, after participants had adapted to a delay, flashes occurring with unexpectedly short delays after the keypress were sometimes perceived as happening before the keypress. This finding highlighted the recalibration of temporal order judgments (Fig. 15).

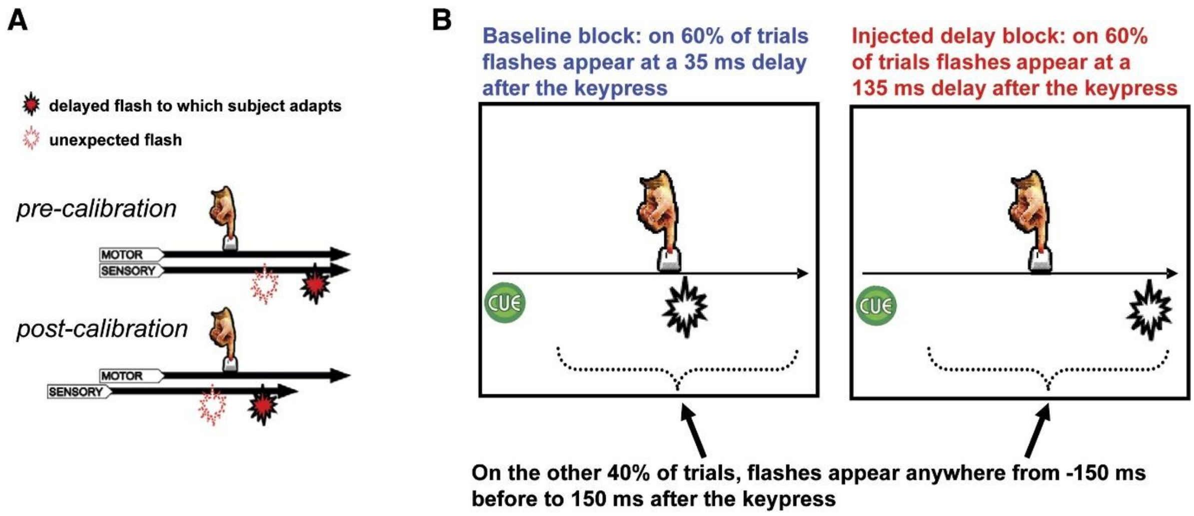


Fig. 15: The sensory recalibration experiment. A) Schematic of hypothesis: participants are exposed to delayed sensory feedback (depicted by a filled flash). This exposure leads to a recalibration of temporal order judgments, reducing the delay between motor output and sensory feedback. Following recalibration, the delayed feedback is perceived as closer in time to the keypress. This creates an illusion where an unexpected flash (depicted by a hollow flash) appearing sooner is mistakenly perceived as occurring before the motor act. B) Task design: Each trial involves the presentation of only one flash. In the task design, participants are prompted to press a key after a cue, and a flash appears on the screen before or after the key press. In 60% of trials, the flash appears at a fixed time relative to the keypress (35ms afterwards in the baseline block and 135ms afterwards in the injected delay block). In the remaining 40% of trials, the flash appears unexpectedly. At the end of each trial, participants report whether the flash appeared before or after their keypress. Image sourced from (Stetson et al., 2006)

The sensory recalibration model strongly emphasises the accurate judgment of the order of actions and sensations to understand causality, a fundamental aspect of learning and survival. This emphasis leads to exploring two interconnected concepts related to this illusory reversal. The first is the compression of time between actions and sensations, often referred to as intentional binding. The second is a shift in the perceived timing of sensory events relative to actions, driven by the brain's recalibration of timing judgments based on prior expectations.

The latter concept suggests that our perception of the temporal relationship between our actions and sensory events can dynamically adapt based on the temporal patterns we encounter. Our sensory system adjusts to these patterns and updates our internal representation of the temporal order, resulting in a recalibration of our perception. This happens because the brain interprets the sensory outcome as a consequence of the action performed and adjusts its timing judgments to align with the prior expectation that actions and their consequences are supposed to be contiguous (Eagleman & Holcombe, 2002; Yarrow et al., 2001).

It was also explored whether this recalibration effect would occur for non-voluntary actions. While evidence supported the occurrence of recalibration, it was not as statistically significant as with voluntary actions. This raised the possibility that intentional binding, although not directly related to sensory recalibration, could be the mechanism behind it. This connection emerges from the role of temporal expectations and the update of internal temporal representations. The sensory system adapts its temporal processing based on consistent pairings, effectively shifting the perceived timing of the outcome closer to the action. This, in turn, leads to the intentional binding effect, resulting in the subjective compression of time between the action and its sensory consequence.

In essence, the intentional binding effect can be viewed as a manifestation of sensory recalibration within the context of temporal perception. The brain recalibrates its temporal expectations and representations based on the consistent pairings of voluntary actions and their sensory outcomes, resulting in a compressed perception of time between the action and its outcome. An interesting side effect of this system is its relevance to contingency learning (Moore et al., 2009b). It is well-understood that goal-directed behaviour is mediated by contingency learning (Balleine & Dickinson, 1998; Di Costa et al., 2018; Moore et al., 2009b), and during this learning process, individuals acquire knowledge about the causal relationship between voluntary actions and their outcomes. By computing this contingency information, individuals can purposefully control their environment.

3.3.3 Temporal Attention model

In time perception research, a prominent framework often relied upon is the internal clock model, which seeks to explain perceptual discrepancies in how time is perceived (Gibbon et al., 1984; Treisman, 1963; Wearden, 2016). This model consists of three key components: the pacemaker, the switch, and the accumulator (Fig. 16). Time estimation is based on the accumulation of pulses within the accumulator, generated by the pacemaker and gated by the switch. Discrepancies in time perception typically arise from two primary sources: differences in the rate of the pacemaker or variations in the latency of the switch. These parameters are believed to be controlled by attentional processes, where attention can either accelerate the pacemaker's rate or prolong the switch's latency. This modulation enables more pulses from the pacemaker to be recorded in the accumulator, impacting our perception of time.

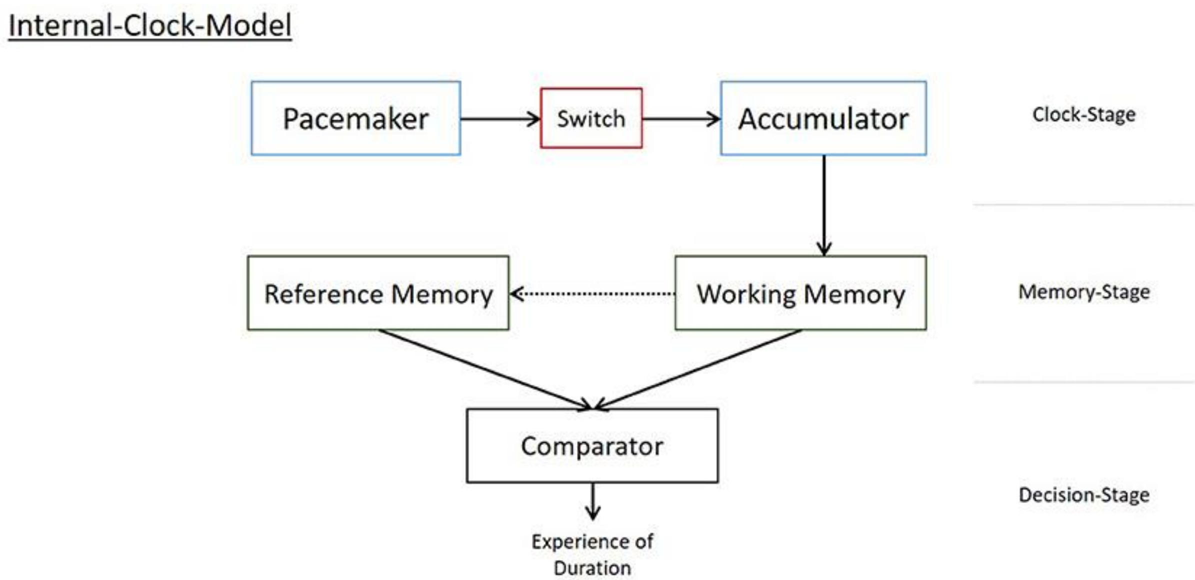


Fig. 16: Illustration of the different components of the internal clock model as adapted from (Wearden, 2016)**.** Image sourced from (Kosak & Hilbert, 2021)

Within the internal clock model, the temporal attention model provides a theoretical framework for understanding how attentional processes influence the processing and perception of temporal information (Zakay & Block, 1995). It posits that attention plays a pivotal role in shaping our perception of time, enabling us to selectively focus on specific temporal events or intervals and allocate cognitive resources accordingly.

In the context of intentional binding, these attentional mechanisms profoundly impact how we perceive the temporal relationship between a voluntary action and its associated sensory outcome. When an individual performs a voluntary action and anticipates the consequent sensory feedback, attention is drawn towards the expected outcome due to its salience and relevance. This attentional bias towards the sensory consequence leads to heightened perceptual processing of the outcome and compression of the perceived time interval between the action and its result.

Specifically, voluntary actions seem to momentarily slow down the internal clock as they anticipate their effects, resulting in a perceptual phenomenon known as the intentional binding effect (Wenke & Haggard, 2009). The research findings indicate a dynamic adjustment of the internal clock, aligning with the concept of temporal attention being selectively applied to specific events in the intentional binding effect (Fig. 17). In essence, the deceleration of the internal clock following a voluntary action can be seen as a manifestation of our predictive and attentional processes. In the case of intentional binding, the anticipation of the action's effect likely involves motor prediction, influencing the allocation of temporal attention to the action-effect interval, thereby shortening it and leading to an underestimation of time.

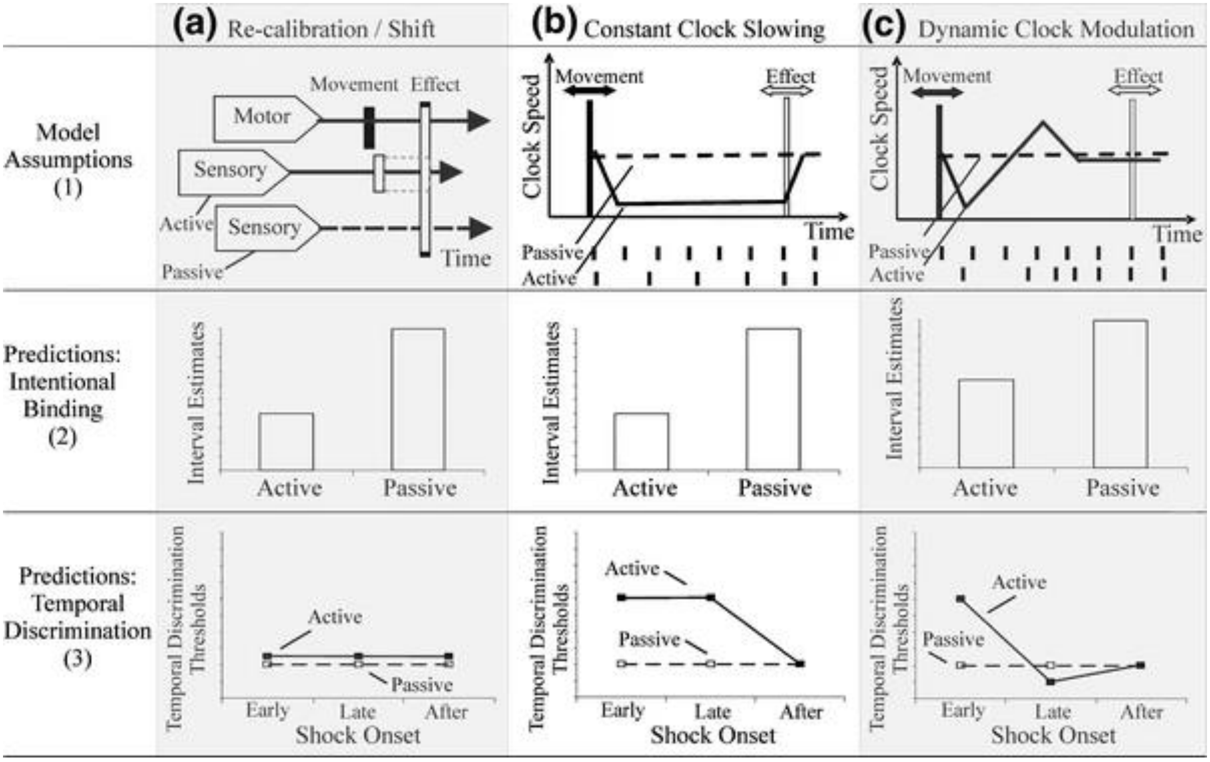


Fig. 17: Various models of subjective time which might explain the intentional binding effect. The results observed by Wenke et al. seem to support the data relevant to the column under 'c', "Dynamic Clock Modulation", where Initial clock slowing is succeeded by an increase in clock rate that partially compensates for the "lost" time. They had observed a transient decrease in the clock rate followed by an increase in the clock rate to compensate for lost time. It was also observed that compensatory improvements followed early impairments in temporal discrimination. Image sourced from (Wenke & Haggard, 2009)

Therefore, the temporal attention model can be used to explain the intentional binding effect by highlighting the role of attention, motor prediction, and dynamic modulation of the internal clock during the voluntary action outcome sequence. However, it is essential to note that while the temporal attention model can explain certain aspects of the intentional binding effect, it does not encompass the whole picture, as it does not consider explanations regarding specific event shifting.

3.3.4 Cue Integration Theory

The cue integration theory, also known as the optimal integration theory, is a theoretical framework that explains how the brain combines multiple sources of information to form a unified perception or estimate. Drawing from Bayesian principles (Bernardo & Smith, 1994), this theory proposes that when the brain faces multiple cues or pieces of evidence, it optimally integrates them to generate a more accurate and reliable perception (Körding & Wolpert, 2004). Each cue contributes information about the perceptual attribute under consideration, be it the location, size, or duration of an object or event. However, individual cues are inherently imperfect subject to various sources of noise or error. The brain mitigates cue-specific errors by integrating multiple cues, generating a more reliable estimate of the underlying perceptual attribute (Hillis et al., 2002). Notably, this integration is not a mere averaging process; instead, it involves a weighted combination that considers the reliability or precision of each cue. Cues with higher reliability receive greater weight, while less reliable cues are assigned lower weight.

Although the cue integration theory does not immediately explain how the intentional binding effect is formed, the same way it is used as a way to explain the sense of agency, it does, however, provide evidence towards how the intentional binding effect is modulated (Fig. 18). The theory represents a very parsimonious and straightforward account of intentional binding and how it extends to the broader concept of the sense of agency, wherein intentional binding could be produced by the motor components related to the prediction of the sensory consequences of an action or could be the result of components related to retrospective inference triggered by the presence of the sensory consequences of movement. This modulatory behaviour connects these two components (Synofzik et al., 2008, 2013), essential to building a neurocognitive understanding of the sense of agency (Moore & Fletcher, 2012). The two components are as follows.

1. **Components of Prediction:** These are processes dedicated to controlling voluntary actions, emphasizing the importance of predictions about future states derived from forward models of motor control (Wolpert & Ghahramani, 2000).
2. **Components related to Retrospective Inference:** These are processes related to the general-purpose inferential mechanism relying on external cues, distinct from the

predictive components. Their primary role is establishing actions' causal origins and effects (Wegner, 2003; Wegner et al., 2004; Wegner & Wheatley, 1999).

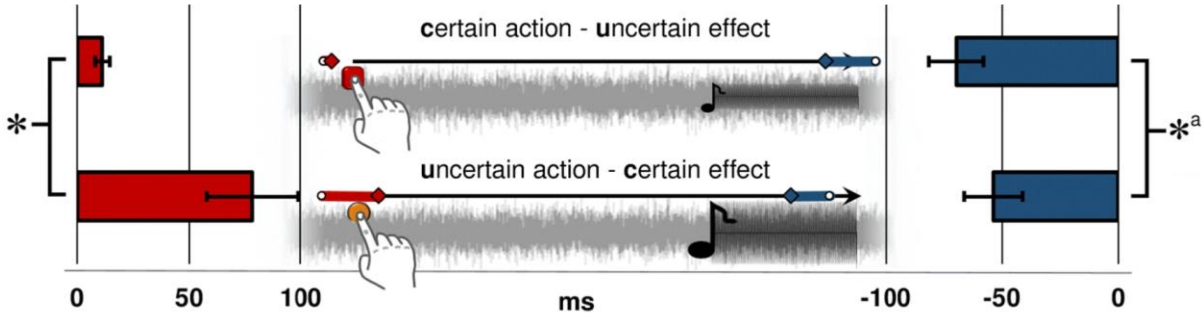


Fig. 18: Results depicting the effects of modulations in certainty across actions and outcomes in an intentional binding episode. Modulations within the action/outcome binding are represented as red/blue bars in the intentional binding effect investigated by incorporating certain and uncertain actions and effects in the results. A keypress on a keyboard indicated certainty of action, while uncertainty was denoted by a keypress on a force sensor. Similarly, a certain effect was represented by a 200ms, 600Hz beep tone, while an uncertain effect was represented by the rise and fall of white noise over 827ms. The observed binding effect showed clear modulations based on the certainty of the action or outcome. Image sourced from (Klaffehn et al., 2021).

Empirical evidence supporting the integration of these components emerged from a study by Moore and Haggard (Moore & Haggard, 2008). They discerned the contributions of predictive and retrospective components within the intentional binding effect, highlighting the importance of outcome predictability. Notably, intentional binding was evident even when outcomes were absent, emphasizing the role of retrospective processes and suggesting a link between learning and the modulation of the intentional binding effect.

Their study assigned two sets of outcome probabilities to distinct keys. One key resulted in an outcome 75% of the time, while the other led to an outcome in only 50% of these instances. It can be interpreted that the 50% condition involved unpredictable tones, while the 75% condition featured predictable tones. This experimental design allowed the authors to separate the influence of predictive and retrospective components.

The authors verified the impact of predictive elements by observing an increase in action binding during trials where participants voluntarily performed an action. However, there was no subsequent tonal outcome in the 75% condition compared to the 50% condition.

This finding implies that the more predictable the outcome, the more pronounced the action binding. Notably, action binding was evident even when no outcomes were presented.

Conversely, retrospective components were established by noting an increase in action binding in the 50% trial condition when an outcome followed the action and when an action occurred without any subsequent outcome. In cases where the outcome followed the action, binding likely occurred due to retrospective inference, given the unpredictability of the outcome. Consequently, the tone retrospectively triggered a shift in the perceived time of the action. In situations where the action occurred alone without an outcome, action binding was influenced by the recent reinforcement history, specifically when an action produced an outcome in the preceding trial.

Overall, this study underscores the significance of outcome prediction in intentional binding and introduces the initial evidence supporting the involvement of predictive and retrospective processes as an integrative system which can modulate the intentional binding effect. Furthermore, the observed recency effect suggests that learning and contingency play crucial roles in modulating the intentional binding effect.

In a later investigation by Moore et al. (Moore et al., 2009a), the impact of primes on intentional binding was explored. The study noted that when primes aligned with the outcomes, there was an increase in the strength of binding. Despite the notable influence of prime congruence, it was also observed that the effect of a prime diminished significantly when the movement was voluntary. This implies that while the retrospective components contribute to the generation of intentional binding, its significance appears to be more pronounced in the absence of predictive motor processes.

Combining these two studies, it was determined that the notion of distinct processes independently contributing to the effect is overly simplistic. Instead, a more nuanced perspective suggests that the sense of agency relies on various agency cues, and their impact on intentional binding hinges on their reliability (Wolpe et al., 2013) (Fig. 19). This insight laid the foundation for the cue integration theory, which is employed to elucidate both the sense of agency and the modulatory nature of the intentional binding effect.

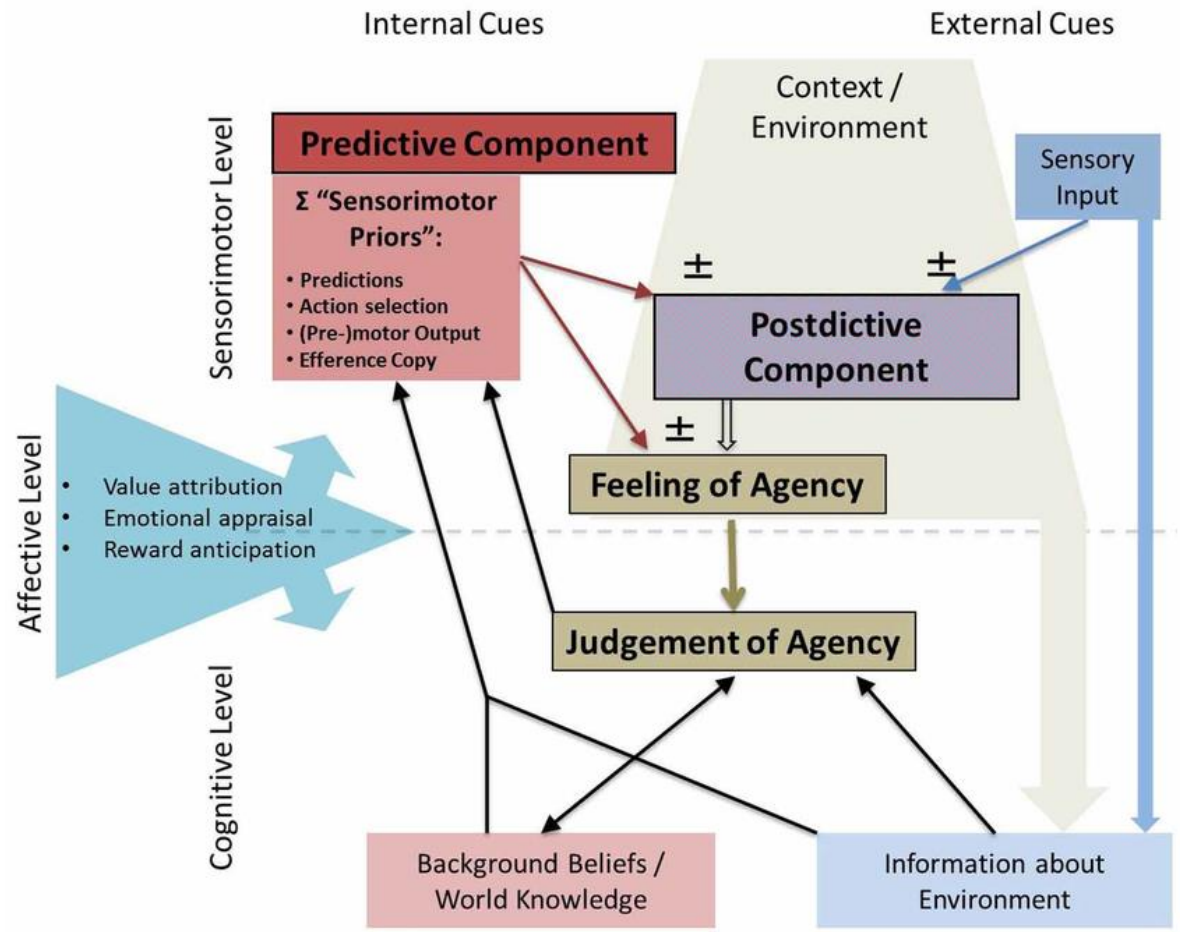


Fig. 19: The proposed model of Bayesian cue integration, shaping the sense of agency and impacting the intentional binding effect. The model involves a dynamic interplay between predictive and postdictive components. At the sensorimotor level, the predictive component encompasses "sensorimotor priors," including internal cues like motor predictions (computed in a forward model), action selection, motor output signals, and an efference copy of the motor command. The emergence of a sense of agency depends on the context and environment, where internal signals alone or in conjunction with external cues can lead to this experience. A pre-reflective sense of agency at a low level may contribute to explicit judgments of agency at the cognitive level. Cognitive judgments are influenced by background information, internal knowledge, and beliefs, shaping the priors at the sensorimotor level. Emotional appraisal, anticipation of reward or punishment, and value attribution further influence the weighting of internal and external signals on both the sensorimotor and cognitive levels. Image sourced from (Synofzik et al., 2013).

3.4 Critiques of the Libet Method

While the intentional binding paradigm, as developed by Haggard et al. (Haggard et al., 2002a; Haggard et al., 2002b), has provided valuable insights into the sense of agency and the temporal aspects of intentional actions, there have been criticisms regarding the design of the experimental task and its potential impact on observed results. In the realm of time perception, the intentional binding paradigm primarily examines the perceived time of the sensory outcome in relation to the action or vice versa. However, it is crucial to recognize that time perception is a multifaceted cognitive process influenced by attention, memory, and contextual cues. While indicative of the sense of agency, the intentional binding effect may not exclusively capture the temporal aspects of agency but could also involve other cognitive processes. Therefore, a critical examination of the Libet clock method, used to measure the intentional binding paradigm, underscores the importance of exploring alternative methods, such as interval estimation and the method of constant stimuli, for assessing the intentional binding effect.

3.4.1 Confounding Factors

Potential confounding factors, such as attentional or response biases, may influence the intentional binding paradigm. Participants' attention and expectations regarding the timing of sensory outcomes could impact their judgments, introducing biases into the results. An illustrative phenomenon highlighting this susceptibility is the flash-lag effect (Nijhawan, 1994), observed in behavioural experiments, particularly in vision and motion perception. This effect occurs when a moving object and a briefly illuminated object are presented simultaneously, with the flashed object being perceived as lagging behind the moving one. In other words, if a moving object and a flashed object are aligned at a certain point in space and time, observers tend to perceive the flashed object as trailing behind the moving object.

In the context of the Libet Clock method for measuring the intentional binding effect, the flash-lag effect may be relevant to how participants anticipate and process moving stimuli, represented by the continuously moving clock hand used for temporal estimates. For example, suppose the clock hand is not perfectly synchronized with the participant's action or the sensory outcome. In that case, the flash-lag effect might create an illusion of temporal closeness between the action and outcome. This potential misperception could introduce confounds, complicating the isolation of the intentional binding effect from other perceptual phenomena related to visual processing and timing. This inherent flaw in the Libet Clock method raises concerns about the reliability of observed binding magnitudes, as they may be susceptible to confounding factors in the perception of temporal estimates (Gomes, 2002; Klein, 2002; Libet, 2002; Pockett, 2002).

3.4.2 Measurement Issues

As mentioned earlier, the Libet Clock method encompasses four conditions, with two involving voluntary actions and the remaining two devoid of such actions. The intentional binding magnitude is derived from calculating relative judgment errors in perceptual temporal estimates of actions or outcomes between voluntary (operant) and non-voluntary (baseline) conditions. Essentially, this method indirectly assesses the perceived reduction in the action-outcome delay rather than providing a direct evaluation. The indirect nature of this measurement raises potential concerns.

Not only is the measurement of the intentional binding effect through the Libet Clock method indirect, but evidence also suggests that specific clock parameters may variably affect participants' awareness times (Danquah et al., 2008). Considering these findings and other unexplored issues with the paradigm omitted here for brevity, there are wide-ranging implications for using the Libet Clock method to measure the intentional binding effect. This challenges the notion that the method is robust and largely resistant to minor parameter changes, providing further support for the idea that the method is associated with inherent biases that require additional scrutiny (Joordens et al., 2002).

3.5 Alternative Methods to Measure the Intentional Binding Effect

Drawing on the wealth of behavioural research employing the Libet Clock method to gauge intention through time perception, it becomes apparent that the intentional binding effect is a notably robust phenomenon. However, in light of the critiques levelled against the Libet Clock method in the preceding section, there arises a necessity for alternative avenues in assessing the binding effect. Typically, tasks related to prospective time perception encompass activities such as estimating or judging time, often concerning established or observed reference temporal durations (Block et al., 2018; Block & Zakay, 1997; Vatakis et al., 2018). An emerging trend within the binding effect literature includes adopting these alternative methodologies to quantify the intentional binding effect, with several notable approaches gaining traction. A few of these well-employed methodologies are further discussed in detail below.

- Magnitude Estimation
- Methods of Constant Stimuli
- Interval Reproduction

3.5.1 Magnitude Estimation

Magnitude estimation is a method used in time perception research to measure the perceived duration of a stimulus or temporal intervals between two events. In this method, participants are presented with a stimulus or an interval between two events, and they are then asked to estimate the duration of that stimulus or the time interval between those two events. Participants usually provide a numerical estimate of the perceived duration or interval when prompted.

As the intentional binding effect measures the temporal relationship between deliberate action and an anticipated outcome, employing magnitude estimation proves more suitable for directly gauging this effect compared to the indirect estimation approach employed in the Libet Clock method. Participants assess the interval between their voluntary action and the resulting sensory consequence, offering a quantitative measure of the intentional binding effect. Specifically, participants are prompted to provide a numeric estimate of the perceived time interval between their self-initiated action and the ensuing tone. Alternatively, participants could estimate the delay between the action and outcome by positioning a slider along a scale that spans the shortest to the longest delays utilized in the study.

Previous studies have successfully replicated the intentional binding effect by employing the magnitude estimation task to measure the action-outcome delay (Engbert et al., 2007, 2008; Engbert & Wohlschläger, 2007). However, Humphreys et al. (Humphreys & Buehner, 2009) managed to replicate the temporal binding effect across a broader spectrum of action-outcome delays, contrasting with the narrower ranges utilized in the original study by Haggard et al. and previous studies utilizing the magnitude estimation procedure. This thorough testing approach enabled Humphreys et al. to evaluate the empirical robustness of the magnitude estimation procedure, demonstrating its applicability beyond the Libet Clock method. The specified ranges employed in their study are as follows.

1. Experiment 1a (Fig. 20): 150, 250, 350, 450,550, and 650ms
2. Experiment 1b (Fig. 21): 750, 850, 950, 1,050, 1,150, and1,250ms
3. Experiment 1c (Fig. 22): 0, 250, 500, 750, 1,000, 1,250, 1,500,1,750, and 2,000ms

4. Experiments 1d (Fig. 23) and 1e (Fig. 24): 0, 500, 1,000, 1,500,2,000, 2,500, 3,000, 3,500, and 4,000ms

Regarding the methodology, all experiments adhered to a consistent trial structure. Two types of trials were conducted: operant and observational. In operant trials, participants initiated a voluntary action, followed by a 100ms, 1kHz audible tone delivered after a randomly determined action-outcome delay within the specified ranges for each experiment. Conversely, observational trials involved a predefined interval between an audible click (mimicking an involuntary key press) and the same 100ms, 1kHz tone.

Their results consistently indicated that Temporal estimates for operant trials were consistently underestimated. Significantly shorter than those for corresponding observational trials across all experiments and action-outcome delays (Fig. 20, Fig. 21, Fig. 22, Fig. 23, Fig. 24). An intriguing aspect of their results, however, was the presence of a significant interaction effect between the action-outcome delay and the type of trials (operant versus observational). This interaction effect suggests that as the action-outcome delay lengthened, the disparity in temporal estimates between operant trials (involving voluntary actions) and observational trials (involving an audible click followed by a sensory outcome, denoting involuntary actions) widened. This observation differs from the results of Haggard et al. using the Libet Clock method, where an increase in the delay between action and outcome led to a decrease in the magnitude of binding.

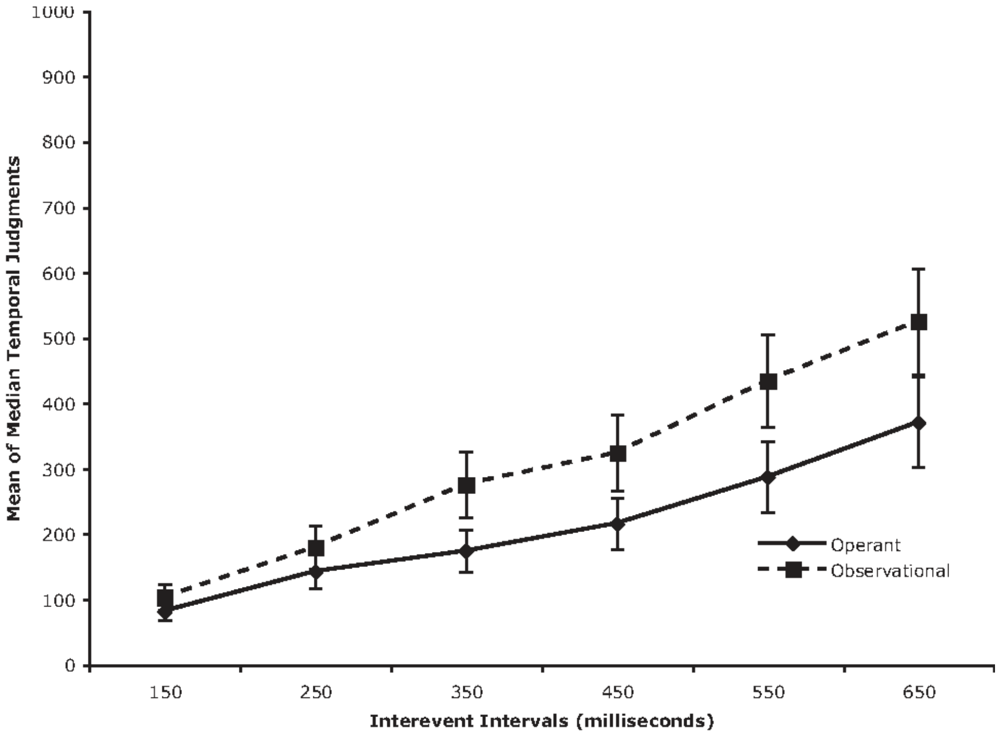


Fig. 20: Mean of the median magnitude estimations provided by participants in experiment 1a (interval estimation). Image sourced from (Humphreys & Buehner, 2009)

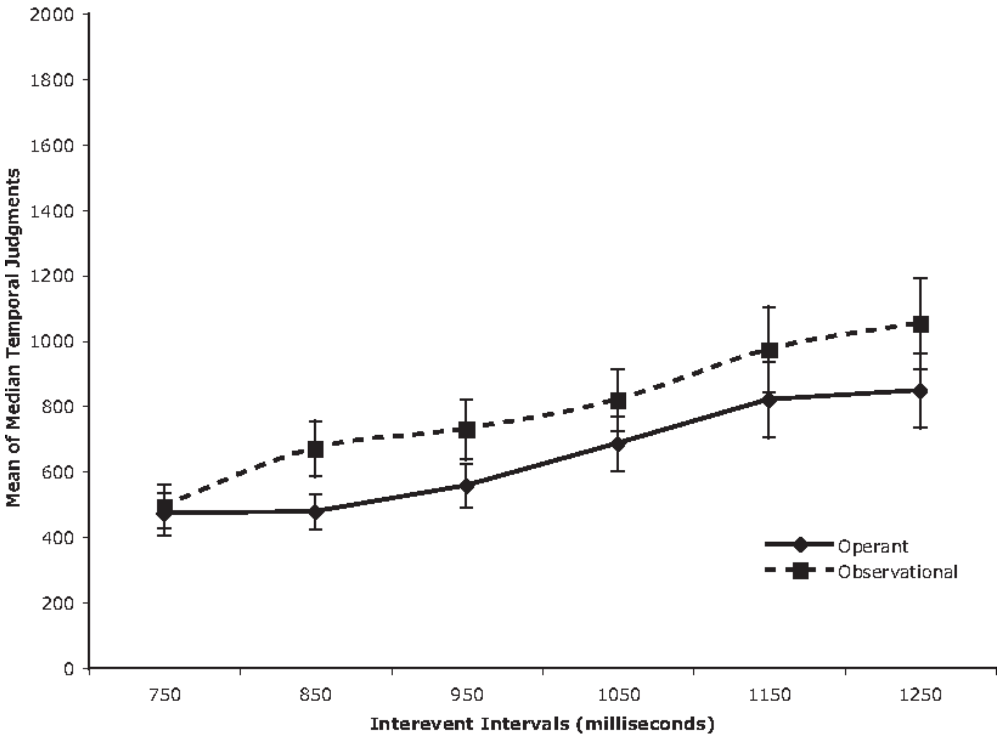


Fig. 21: Mean of the median magnitude estimations provided by participants in experiment 1b (interval estimation). Image sourced from (Humphreys & Buehner, 2009)

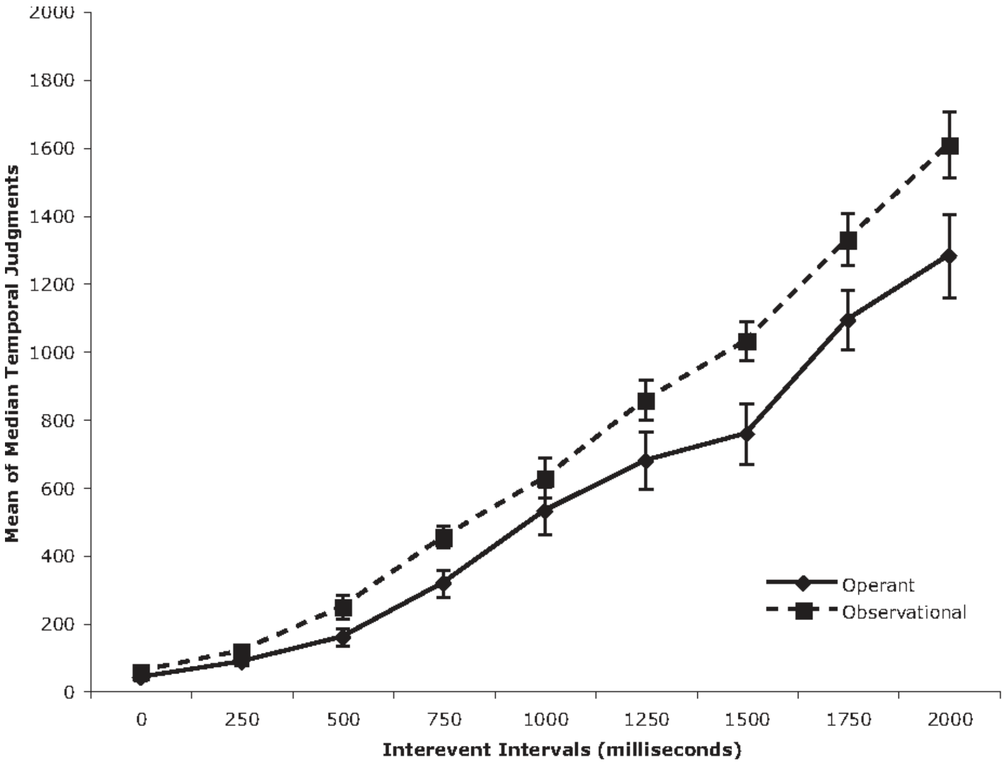


Fig. 22: Mean of the median magnitude estimations provided by participants in experiment 1c (interval estimation). Image sourced from (Humphreys & Buehner, 2009)

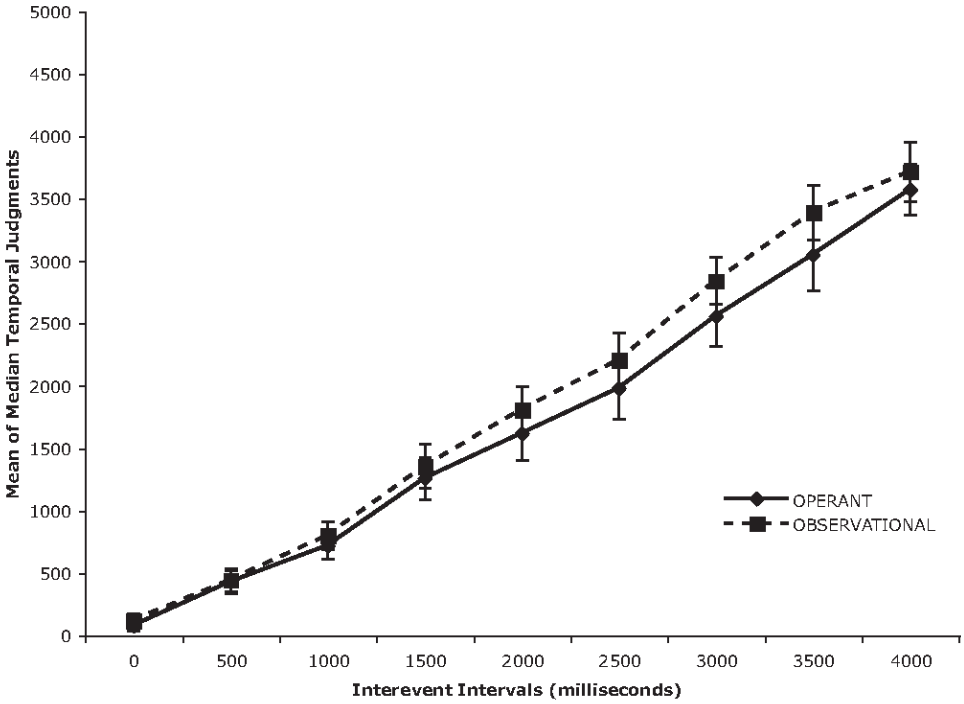


Fig. 23: Mean of the median magnitude estimations provided by participants in experiment 1d (interval estimation). Image sourced from (Humphreys & Buehner, 2009)

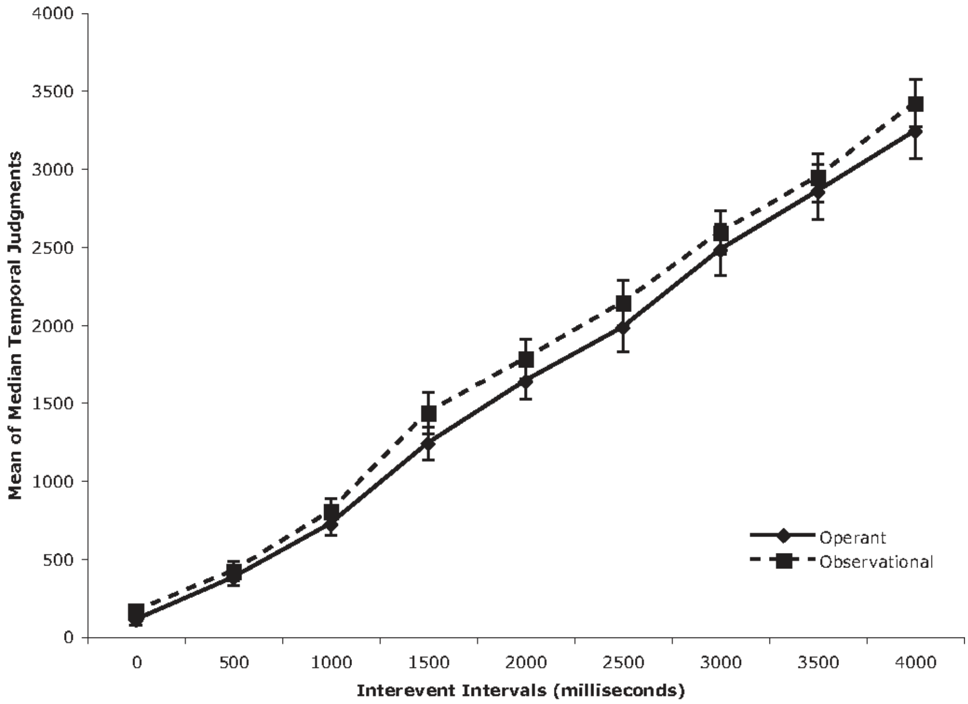


Fig. 24: Mean of the median magnitude estimations provided by participants in experiment 1e (interval estimation). Image sourced from (Humphreys & Buehner, 2009)

Humphreys et al. attribute this observation to the design of the experiment and the specific components of the intentional binding effect that the methodology targeted. Since participants were instructed to estimate the delay between the action and outcome only after experiencing the entire sequence, it is conceivable that they were mainly activating the inferential components linked to the intentional binding effect. This contrasts sharply with the approach employed in the Libet Clock method, where participants primarily utilize predictive processes associated with the binding effect, as the temporal estimate is coupled with immediate motor activity.

As noted in the previous sections, the dual-component system underlying the binding effect is well-established in the intentional binding literature. In particular, as outlined by Moore and Haggard (Moore & Haggard, 2008), the intentional binding effect is a result of both predictive and inferential components, and they proposed that these components are integrated in a Bayesian manner. Given that participants consistently estimate the interval inferentially (i.e., only after witnessing the entire action-outcome cycle) in this methodology, the observed results may indicate a predominant reliance on inferential processes over predictive components.

A critical inference drawn from investigating the use of the magnitude estimation task for gauging the action-outcome delay under voluntary or intentional conditions is the increased reliance on inferential components during the estimation of the intentional binding effect. This finding implies the possibility of a divergent impact on sensitivities to action-outcome delay depending on the methodology employed.

3.5.2 Method of Constant Stimuli / Temporal Bisection

The method of constant stimuli is a psychophysical approach employed in experimental investigations to gauge perception thresholds or establish the correlation between a stimulus's intensity and a participant's perception or response (Gescheider, 2013; Lapid et al., 2008). This technique is commonly utilized in studies focusing on sensory perception, such as vision or audition. In this approach, participants are exposed to a sequence of stimuli varying in intensity or magnitude presented in a random sequence. The spectrum of stimuli typically spans a broad range from very low to very high intensities, covering both subthreshold and suprathreshold levels. The specific values and quantity of stimuli within this range are predetermined based on the experimenters' objectives. Generally, participants are instructed to detect, discriminate, or evaluate the stimuli in various ways. For instance, they may be tasked with identifying whether they perceive a stimulus (detection task), distinguishing between different stimuli (discrimination task), or rating the intensity or magnitude of the stimulus.

By exposing participants to various stimuli and recording their responses, we can establish a psychometric function that outlines the correlation between the intensity of the stimulus and the participant's reactions. Typically depicted as a curve, the psychometric function uses the x-axis for stimulus intensity and the y-axis for the proportion of correct or corresponding responses (Fig. 25). This psychometric function enables the determination of perceptual thresholds, marking the points at which participants can accurately detect or differentiate stimuli. The 50% point on the x-axis is commonly identified as the point of subjective equality (PSE), or the bisection point in the case of temporal bisection (BP), indicating that, given a specific stimulus value, there is a 50% probability that the participant can discern the value accurately. This approach provides a more accurate assessment of the perception-response relationship by incorporating multiple stimulus levels and randomizing their presentation to mitigate potential response biases.

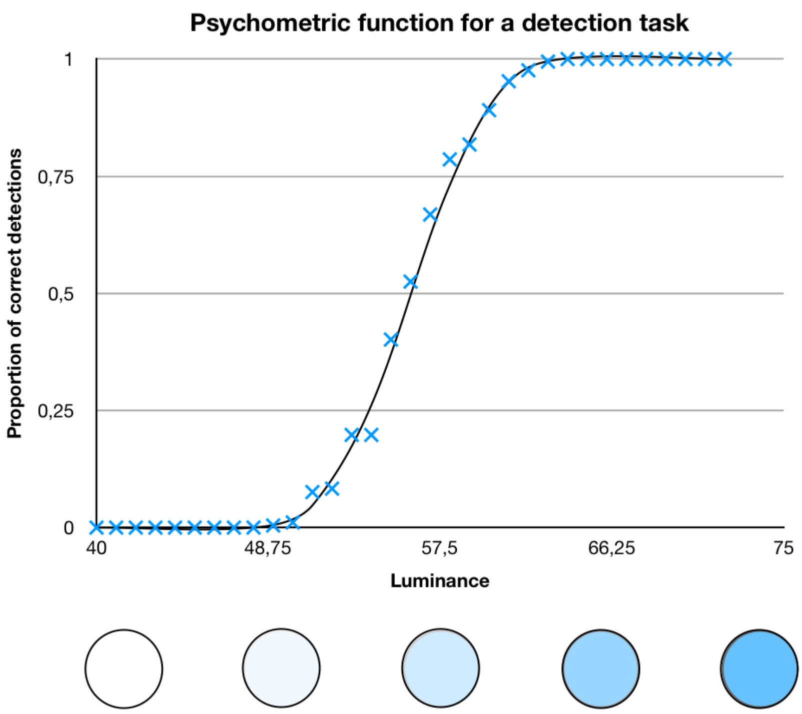
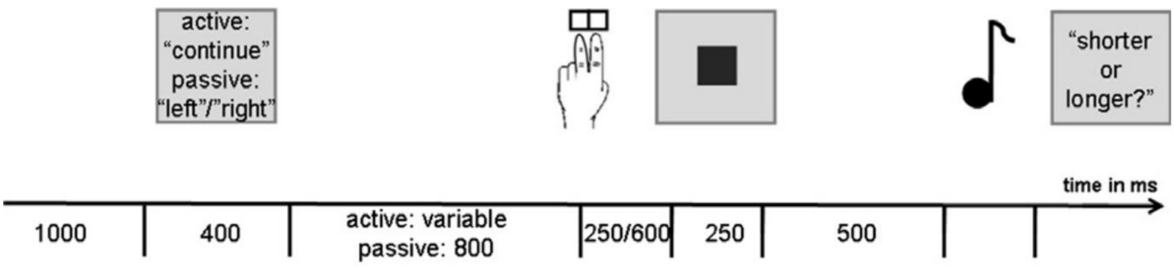


Fig. 25: An illustrative instance of a psychometric function. It demonstrates how the accuracy of detections can rise as the luminance of the stimulus increases. Image sourced from Psychometric function. (2022, May 31). In Wikipedia. https://en.wikipedia.org/wiki/Psychometric_function

An inherent benefit of employing this approach to assess the intentional binding effect is the capacity to compute Weber fractions. The Weber fraction denotes the percentage or proportion of the original stimulus necessary for detecting a perceivable difference. Weber's law posits that the just noticeable difference (JND) between two stimuli is linked proportionally to the magnitude of the initial stimulus. Essentially, it quantifies the relative sensitivity of the human sensory system to alterations in stimulus magnitude. This enables a comparison regarding whether the intentional binding effect influences participants' consistent estimation of the interval between the voluntary key press and the resulting outcome.

Another benefit of employing the constant stimuli method to gauge the intentional binding effect, particularly concerning the magnitude estimation task mentioned in the preceding section, is its ability to address challenges inherent in methods such as magnitude estimation. For instance, magnitude estimation tasks necessitate participants to encounter different action-outcome delays in various trials, introducing an element of unpredictability that could influence the dynamics of the intentional binding effect (Hughes et al., 2013; Tanaka et al., 2019). Through the method of constant stimuli, we can introduce both consistent and predictably varying action-outcome delays. Additionally, magnitude estimation has demonstrated susceptibility to response biases, wherein participants may alter their estimations influenced by beliefs and other factors (Cravo et al., 2011; Poulton, 1979).

Nolden et al. (Nolden et al., 2012) employed this methodology in two experiments (Fig. 26), utilizing two distinct action-outcome delays (250ms and 600ms) and incorporating two action conditions (active and passive). Participants deliberately pressed one of two keys in the active scenario, choosing between action-outcome delays. Conversely, the keys spontaneously popped up against the participants' resting fingers in the passive scenario.



standard interval (ms)	intervals of comparison (ms)												
250	40	57	110	145	180	215	250	285	320	355	390	425	460
600	96	180	264	348	432	516	600	684	768	852	936	1020	1104

Fig. 26: Trial structure of the method of constant stimuli experiment as an alternative way to measure the intentional binding effect as conducted by Nolden et al. In the active condition, participants are signalled with "continue," indicating they can press one of two keys. In the passive condition, "left" or "right" indicate the key that will be triggered against the participants' fingers. Key presses, whether active or passive, signify the start of the action–outcome delay (standard interval), and the onset of a coloured square marks its conclusion. The square's duration (250ms or 600ms) and colour (red or blue) correspond to the keys. Participants must compare the action–outcome delay to a randomly varying tone (comparison interval) on each trial. The time course below details the different tone durations for each action–outcome delay. Image sourced from (Nolden et al., 2012)

Within the active condition, each trial involved the participant pressing a key, followed by the corresponding action-outcome delay. Subsequently, a black square appeared for 250ms, indicating a visual outcome of the voluntary action. This visual outcome was succeeded by a 500ms white screen, followed by a variable tone lasting between a range of pre-specified comparison durations.

- In the 250ms action-outcome delay condition: 40, 57, 110, 145, 180, 215, 250, 285, 320, 355, 390, 425, and 460ms.
- In the 600ms action-outcome delay condition: 96, 180, 264, 348, 432, 516, 600, 684, 768, 852, 936, 1020, and 1104ms.

Following the tone exposure, participants were tasked with judging whether the tone duration was shorter or longer than the previously experienced action-outcome delay.

The passive condition closely resembled the active one, with a key popping up without voluntary participant action. Subsequent steps in the experiment mirrored those of the active condition, with participants judging whether the observed tone duration was shorter or longer than the pop-outcome interval they had experienced before.

In terms of the findings, it was noted that in the 250ms condition, participants perceived no difference between the action-outcome delay in the active condition and that in the passive condition. However, intriguingly, in the 600ms condition, participants perceived the action-outcome delay to be shorter in the active condition compared to the passive condition (Fig. 27). This replication of the intentional binding effect deviates from the conventional Libet Clock method, as it indicates a perceived shortening of the interval at longer action-outcome intervals rather than shorter ones. This outcome stands out as unique among various intentional binding methods, with the method of constant stimuli revealing the intentional binding effect primarily after extended action-outcome delays.

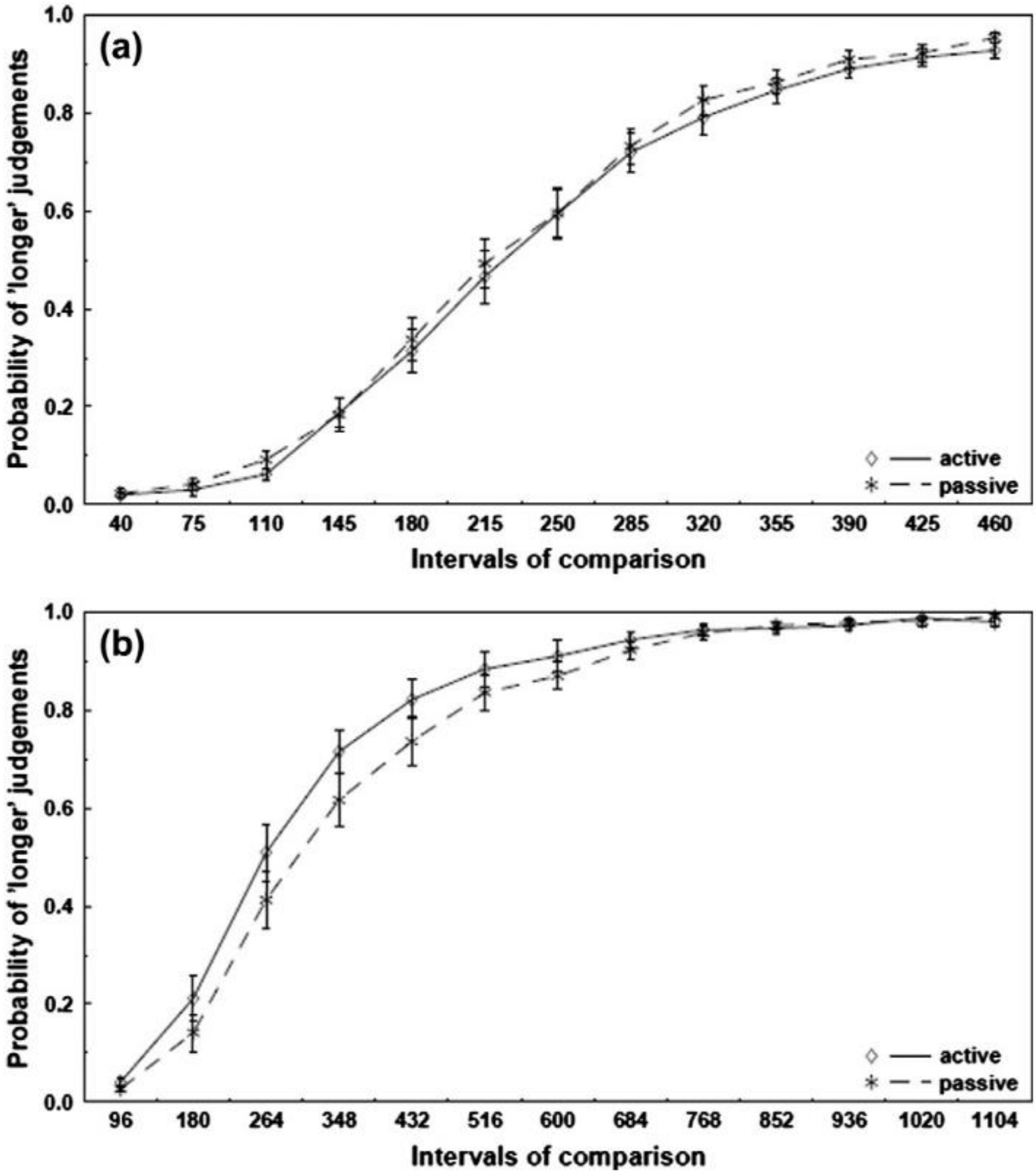


Fig. 27: The psychometric fits of the results observed by Nolden et al. using the method of constant stimuli to measure the intentional binding effect. Mean and standard error of the probability that participants perceived a comparison interval as longer than the standard interval when the method of constant stimuli was employed to measure the intentional binding effect. (a) shows the data for the 250ms action–outcome delay, and (b) shows the data for the 600ms action-outcome delay. Image sourced from (Nolden et al., 2012).

In a supplementary analysis, it was observed that there were no discernible distinctions in the calculated Weber fractions across all conditions, suggesting uniform steepness in the psychophysical functions. This confirmation supports the idea that participants faced comparable challenges in all conditions, and any observed differences in

Point of Subjective Equality (PSE) were not a result of varying difficulty levels among the conditions.

Subsequently, the experiment was repeated as a follow-up experiment with a single alteration. Unlike the first experiment, where a different action-outcome delay followed one key, both keys were now associated with the same delay—the only observed contrast in results pertained to a comparison between the two experiments. Weber fractions in the first experiment were more significant than those in the second, signifying a shift in difficulty where duration estimations in the initial experiment proved more demanding than in the subsequent one. This discrepancy can be attributed to differing task demands between the two experiments (Fig. 28).

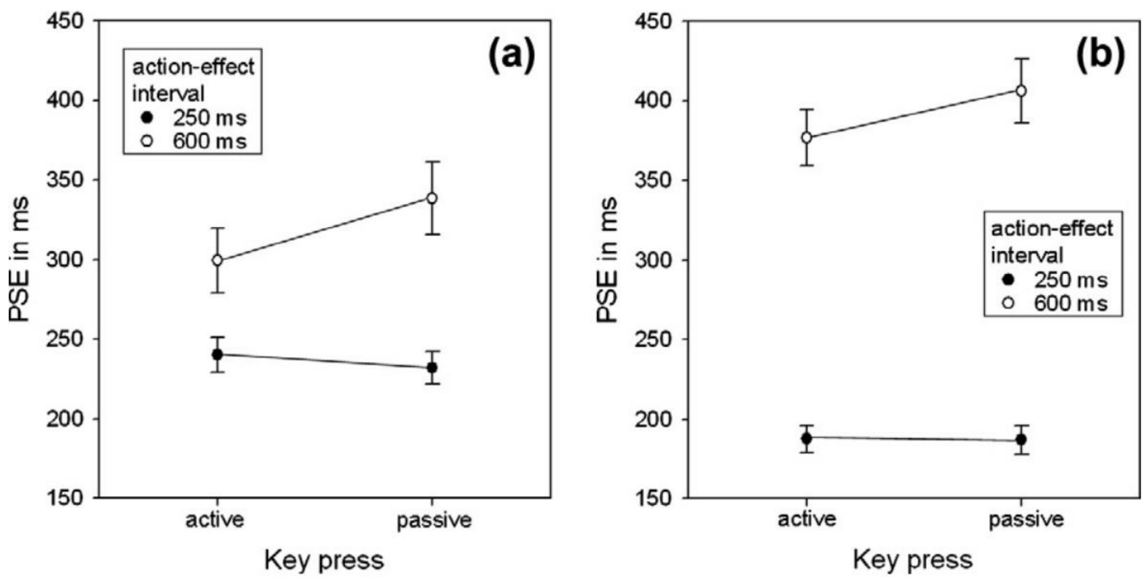


Fig. 28: Comparison of the points of subjective equality obtained from employing the method of constant stimuli to measure the intentional binding effect. Mean and standard error of the points of subjective equality between the active and passive conditions for both the 250ms and the 600ms action-outcome delay. (a) shows the results of Experiment 1, and (b) shows the results of Experiment 2. In both experiments, the action-outcome delay of 600ms is perceived as shorter in the active than passive condition. Image sourced from (Nolden et al., 2012).

Based on the findings, Nolden et al. suggest that employing the method of constant stimuli for measuring the intentional binding effect is somewhat more straightforward than the Libet Clock method. This is because it directly assesses the perceived duration of the action-outcome interval instead of separately estimating the points in time of the voluntary action and outcome. Not only does it surpass the Libet Clock method in this regard, but Nolden et al. also contend that it outperforms the magnitude estimation method. This is particularly noteworthy as the method utilized by Humphreys et al. requires some degree of variability in the observed action-outcome intervals (Humphreys & Buehner, 2009).

Interestingly, this is the only method where the binding effect becomes apparent specifically for longer action-outcome delays. Notably, the effect appears absent for shorter action-outcome delays, as utilized in methods like the Libet Clock or magnitude estimation. The authors propose that the method of constant stimuli employed in their study shares more similarities with the magnitude estimation approach used by Humphreys et al. (Humphreys & Buehner, 2009). They emphasize that the sensitivity of the intentional binding effect at various action-outcome delays depends on the specific methodology employed. In the method of constant stimuli, participants are tasked with recalling the observed action-outcome delay and then comparing it with either an internally generated representation of time or an externally presented comparison stimulus. Since this relies on a more inferential comparison process, as advocated by Moore and Haggard (Moore & Haggard, 2008), it is plausible that this particular methodology is relatively more attuned to these specific components.

3.5.3 Magnitude Reproduction

The magnitude reproduction task is employed in experimental psychology to evaluate the perception of temporal magnitudes (Block et al., 2018; Block & Zakay, 1997; Zakay, 1993). This method involves a prospective estimation task where participants are presented with a reference duration and then tasked with reproducing it based on their time perception. In a typical magnitude reproduction task, participants are initially exposed to a duration to be encoded, often presented visually or auditorily. They are then instructed to replicate the encoded duration by indicating how long they believe it lasted. Various response methods

(Fig. 29) can be used, such as pressing a button to mark the interval's start and end or holding down a key to recreate the experienced interval (Mioni et al., 2014). The magnitude reproduction task allows us to understand how individuals perceive and mentally represent temporal magnitudes. It consists of two phases: the initial encoding phase and the subsequent reproduction phase.

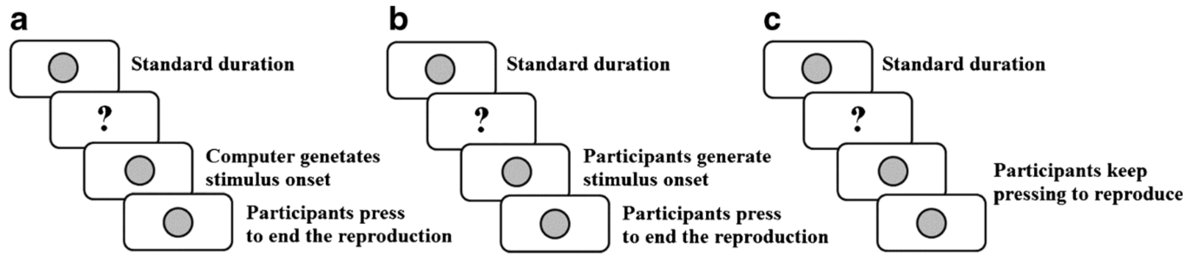


Fig. 29: Various methods which are employed to observe magnitude reproduction variations. a) Press at the end, (b) Press to start and press to stop the reproduction, or c) Press continuously (the beginning and ending of pressing mark the interval). Image sourced from (Mioni et al., 2014)

This specific approach was adapted and utilized by the research team led by Humphreys et al., who had previously employed the magnitude estimation paradigm to assess the intentional binding effect (Humphreys & Buehner, 2009). They employed the same modified version of the procedure from their estimation study. In this modified procedure, participants encountered temporal intervals between their actions and a subsequent outcome (the operant condition) or between two tones to assess an unintended condition (the observational condition, which contrasted with the operant condition). Subsequently, participants were required to replicate the perceived interval between the action and outcome by holding down a key.

They conducted two experiments to examine the intentional binding effect using this novel paradigm for reproducing magnitudes, termed interval reproduction. Their hypothesis posited that the reproductions by participants in the operant condition would be notably shorter compared to those in the observational conditions. In the first experiment, random intervals between 1200ms and 1600ms were employed. These random intervals were initiated immediately after a voluntary button press in the operant trials or after a pre-recorded click stimulus lasting 120ms in the observational trials. A 1kHz pure tone, presented for 100ms, served as the outcome stimulus. The operant and observational trials were organized into blocks, and the sequence of these blocks was counterbalanced.

In the operant trials, participants were instructed that pressing a green button on a button box after the trial began would lead to a tone after a specific interval. Subsequently, they were tasked with depressing and holding a yellow button on the button box for a duration corresponding to the interval between the voluntary button press and the outcome they had observed. In contrast, observational trials began with a green cross displayed on the screen for a random duration ranging from 1500ms to 2000ms before initiating the first auditory click, signalling the commencement of the interval. Following this auditory click, there was an interval, succeeded by the presentation of the tone. Participants were then required to reproduce the duration of the observed interval between the auditory click and the tonal outcome by pressing and holding the yellow button on the button box.

The analysis focused on a reproduction error measured in ms, calculated by subtracting the actual inter-event interval from the participants' reproduced interval. Consequently, a null value from the difference indicated an accurate reproduction, while negative and positive errors signified underestimation and overestimation, respectively. The results of the initial experiment aligned with the authors' hypothesis: operant intervals were underestimated and reproduced as shorter than observational intervals, which were only slightly underestimated (Fig. 30). Nevertheless, the significant difference between the two conditions led to the conclusion that the intentional binding effect was observable and robust by using the interval reproduction procedure. Furthermore, the authors asserted that these findings supported their earlier experimental results (Humphreys & Buehner, 2009), suggesting that the intentional binding effect extended beyond the millisecond level to longer super-second intervals. However, it remains unclear why the authors chose the interval range of 1200ms to 1600ms and did not consider sub-second ranges, as they had in their previous study involving magnitude estimation.

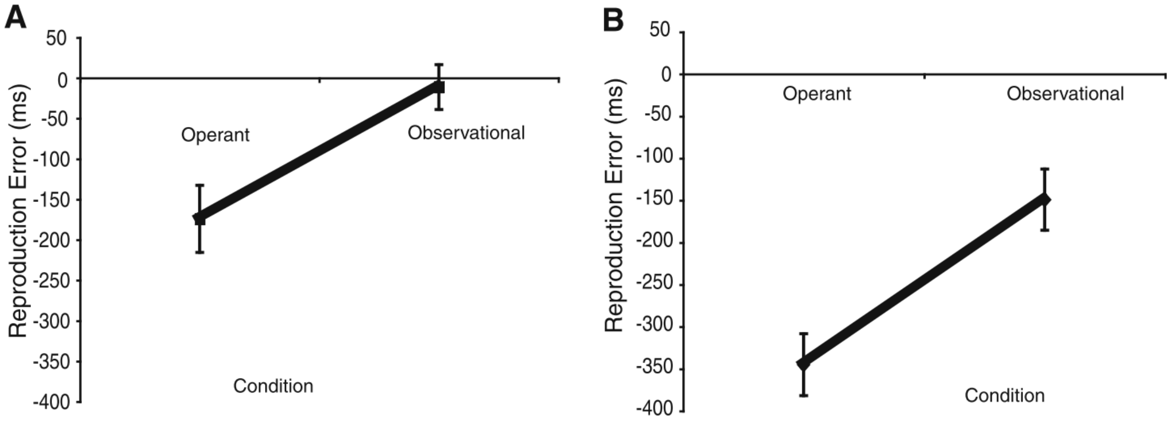


Fig. 30: Mean reproduction errors gathered from the interval reproduction task. A) Experiment 1's results, and B) Experiment 2's results. The reproduction error was calculated by subtracting the actual action-outcome delay from the participants' reproduced durations. Image sourced from (Humphreys & Buehner, 2010)

The second experiment closely resembled the first, with a minor variation. In the observational trials, participants were instructed to assess the interval between the first auditory click's conclusion and the outcome tone's initiation. However, it was conceivable that participants might have initiated their judgment at any point during the presentation of the first auditory click stimulus, potentially introducing bias when comparing observational and operant trials. The second experiment adopted a more cautious approach to test the binding hypothesis to address this. In this case, the observational interval was measured from the beginning of the auditory click rather than the end. This adjustment was expected to result in an increased negative reproduction error in the observational trials compared to the operant trials.

Nevertheless, the outcomes persisted without alteration, with the reproduction durations in operant trials being notably underestimated in comparison to the reproduction durations observed in observational trials (Fig. 30). The authors assert, based on these experiments, that temporal binding is not restricted to the artificial context of the Libet Clock method. Instead, interval reproduction methods facilitate research in a direction that allows for more direct observation of the subjective contraction of voluntary action-outcome delays instead of implying this solely through the alteration of individual events. The authors draw on a similar rationale as employed in their previous interval estimation task to explain most of the results they had observed while implementing the interval reproduction task.

The intentional binding results observed in studies utilizing the Libet Clock method (Haggard et al., 2002b) are attributed to a matching pattern between the predicted and experienced outcomes, reinforcing the connection between voluntary action and outcome. This explanation aligns with the efferent binding hypothesis, emphasizing the activation of predictive elements within the intentional binding effect. However, in the interval reproduction method employed by Humphreys et al., the absence of predictability is notable due to the variable random inter-event interval (ranging from 1200ms to 1600ms). Consequently, it is improbable that the interval reproduction paradigm facilitates precise efferent-based predictions. The authors appear to favour a postdictive and causal interpretation of the results, suggesting that the apparent compensatory shortening of operant intervals is induced to maintain the qualitative binding relationship between a causal action and its effect through temporal contiguity (Buehner & Humphreys, 2009).

3.6 Methodological Differences in Measuring the Intentional Binding Effect

In light of the evidence presented in the previous sections regarding the various methodologies to measure the intentional binding effect, a fundamental query emerges: Does the determination of the specific category of action-outcome delay (short or long) for measuring intentional binding rely on the chosen methodology? The discussed methodologies for assessing intentional binding seem to point in that direction. When employing the Libet Clock method, the sensitivity of the binding effect seems confined to shorter action-outcome delays, as this method emphasizes temporal accuracy and time point estimates requiring a more predictive approach. Conversely, inferential methods, where participants judge the duration of the action-outcome interval post-hoc, consistently demonstrate greater sensitivity to longer action-outcome delays, whether through judgment or estimation.

However, a recent study by Reuss et al. challenges this notion (Ruess et al., 2018). Contrary to expectations, the sensitivity of the intentional binding effect to action-outcome delay appears not to be strictly tied to the methodology used. In a comparative study of the Libet Clock method to measure binding effects (Fig. 31), significant binding effects were observed at around the 250ms mark, aligning with expectations from a typical intentional binding experiment using the Libet Clock method (Haggard et al., 2002b; Ruess et al., 2017). As the action-outcome delay increased beyond 250ms, the binding effect diminished, reaching a minimum at around 650ms delay. Intriguingly, as this delay extended to 850ms, the binding effect began to recover. This is quite an unexpected observation since previous literature suggests the binding effect should not have existed at this long a delay. The specific recovery in binding magnitude is attributed to the inferential components behind the intentional binding effect acting as a fallback measure, where the binding effect primarily arises due to these components.

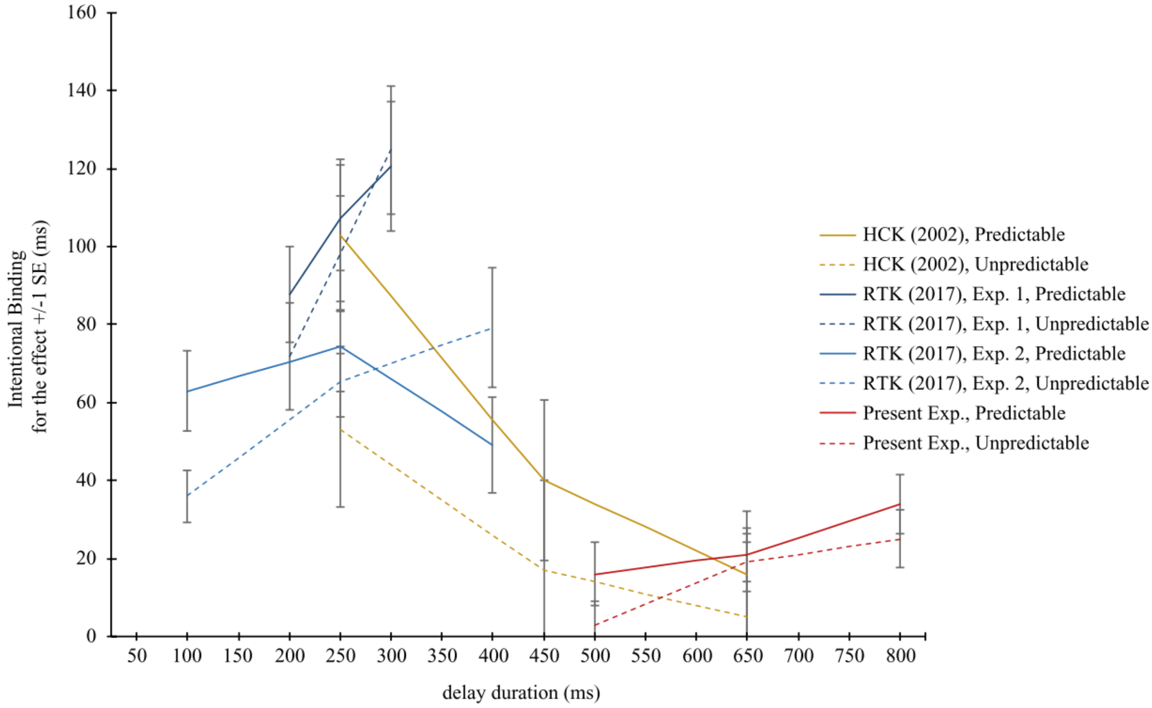


Fig. 31: Comparison of intentional binding magnitudes across studies. The various binding magnitudes are based on the effect delay duration (x-axis) and temporal predictability of the effect (shown by separate lines). This comprehensive representation encompasses studies investigating the impact of delay duration on time point measures of intentional binding using the clock paradigm. Studies included are: (Haggard et al., 2002b) with delay durations of 250ms, 450ms, and 650ms (depicted in yellow); (Ruess et al., 2017) with delay durations of 200ms, 250ms, and 450ms (Experiment 1; depicted in light blue) and 100ms, 250ms, and 650ms (Experiment 2; depicted in dark blue); and (Ruess et al., 2018) with delay durations of 500ms, 650ms, and 800ms (depicted in red). Image sourced from (Ruess et al., 2018)

This study challenges the assumption that the methodology is inherently tied to the action-outcome delay sensitivity of the intentional binding effect. Consequently, the consistent disparities in results based on the chosen methodology prompt us to question whether divergent findings across studies stem from tapping into distinct cognitive processes, especially considering the acknowledged dual components in the formation of the intentional binding effect—namely, a predictive sensory-based component and a postdictive inferential component (Moore & Haggard, 2008; Synofzik et al., 2008, 2013).

Specific to the alternative methodologies, the literature indicates that the binding effect relies on a broader causal inference concerning the voluntary action-outcome pairing. This observation extends to the methodologies discussed earlier and the broader body of literature on the subject (Desantis et al., 2011, 2012; Fereday et al., 2019; Suzuki et al., 2019). This proposition is grounded in the notion that most studies using alternative methodologies to measure intentional binding share a common stance regarding the sensitivity of the binding effect to longer delays, a sensitivity not well-supported by the Libet Clock method.

3.7 Temporal Dynamics of Intended Outcomes Within the Intentional Binding Effect

By now, we understand the intentional binding effect, an implicit method for gauging the sense of agency or determining whether a particular action or observed outcome was intentional. In the context of an intentional binding episode, an individual voluntarily performs an action and then experiences the sensory outcome after an artificially introduced delay between the action and outcome. This leads to the perception that the action-outcome pairing occurred closer in time than when they were physically separated. A pertinent question can arise in the context of the intentional binding effect: when the outcome shifts towards the action during intentional binding, does it expand in time, or does it shift forward in time as a whole, thereby compensating for the perceived compression in time between the voluntary action and the sensory consequence.

Research in this domain was taken up by Makwana et al. in a recent study (Makwana & Srinivasan, 2017). Their investigation involved a modified version of the temporal bisection task (Fig. 32), where participants selected one of two coloured circles with the understanding that they might encounter the chosen object later. This selection of a visual stimulus was deemed a proxy for intention. After the outcome selection, an action-outcome delay occurred, and participants then experienced either the initially chosen object or the other one for a randomly determined duration. The scenario was considered intentional when the experienced object aligned with the initial choice and unintentional when it did not. Participants were tasked with judging whether the observed duration of the object was closer to a short or long anchor they had encountered earlier. The authors hypothesized that if an outcome shifted in time rather than expanded, there would be no distinction in how participants perceived an intended outcome versus an unintended one. This hypothesis and the authors' focus on exploring temporal expansion justified their use of the temporal bisection task.

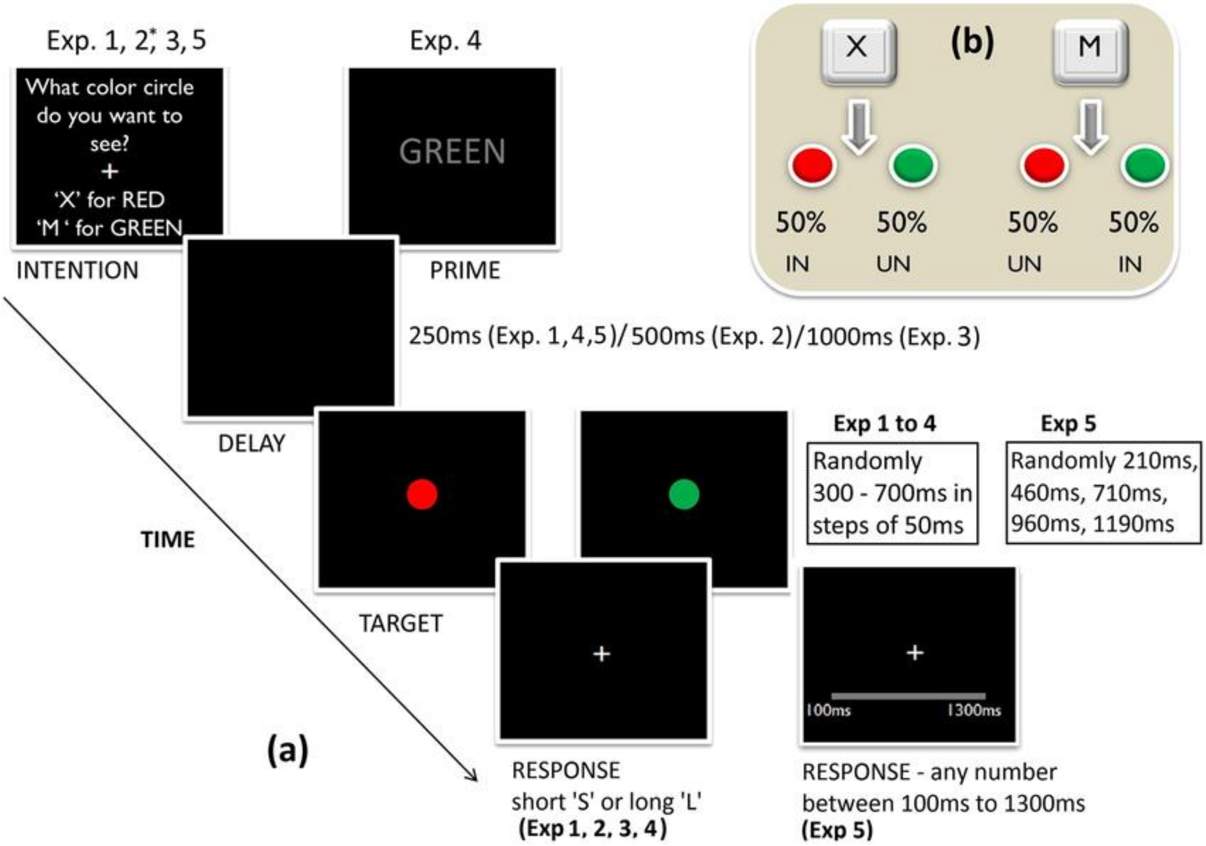


Fig. 32: Trial structure of the modified version of the temporal bisection task to measure outcome expansion due to intentions. a) Trial structure employed in all experiments. The '*' indicates using yellow and blue circles instead of red and green. Before each trial, participants chose the colour circle they wanted to see by pressing pre-assigned keys. The outcome was presented after a fixed delay, varying across experiments [250ms in Exp. 1, Exp. 4, Exp. 5; 500ms in Exp. 2; 1000ms in Exp. 3]. Half of the trials randomly presented the intended outcome, while the other half presented the unintended outcome. In Exp. 4, participants were compelled to press the key based on the displayed word; on half the trials, the word matched the circle colour (congruent), and on the other half, it did not match (incongruent). In Exp. 1, 2, 3, and 4, a temporal bisection task was utilized, where the target circle appeared for a variable duration (ranging from 300 ms to 700ms in 50ms steps), and participants categorized it as close to a short duration (press 's') or long duration (press 'l'). In Exp. 5, a verbal estimation task was employed, with the target circle appearing for variable durations (210ms, 460ms, 710ms, 960ms, 1190ms), and participants used a computer mouse to estimate the duration within the range of 100ms to 1300ms. b) Distribution of intended and unintended outcomes. Image sourced from (Makwana & Srinivasan, 2017)

The collected data underwent fitting to a psychometric function, and the bisection points were extracted. Results indicated that participants judged the duration as longer when they observed an intended object. Therefore, the study concluded that outcomes tend to expand in time rather than shifting as a whole within the intentional binding effect, as evidenced by participants perceiving intended outcomes as longer than unintended ones.

Across their investigation, the researchers conducted four experiments employing the temporal bisection task, each with distinct parameters (Fig. 32).

1. In Experiment 1, an action-outcome delay of 250ms was utilized, and participants encountered red or green circles as objects.
2. Experiment 2 featured a longer action-outcome delay of 500ms, with participants encountering yellow or blue circles as objects.
3. Experiment 3 maintained the action-outcome delay of 1000ms, using the same objects as in the first experiment.
4. Experiment 4 retained the 250ms action-outcome delay but with a variation in the nature of the action. Instead of an intentional action, participants were primed with the object they would see. In this scenario, there was no action to choose the desired outcome; instead, participants were primed with the object.

In all experiments, the presented objective durations were randomly selected from 300ms to 700ms in increments of 50ms.

Interestingly, the effect of intention-induced temporal expansion was observed exclusively in the first and second experiments. In contrast, the third experiment did not demonstrate any expansion effects induced by intention, nor did the fourth experiment. The reason for the absence of an expansion effect in the fourth experiment is evident. Since the objects functioned as primes, lacking intentional involvement, intention induced no expansion effects (Fig. 33).

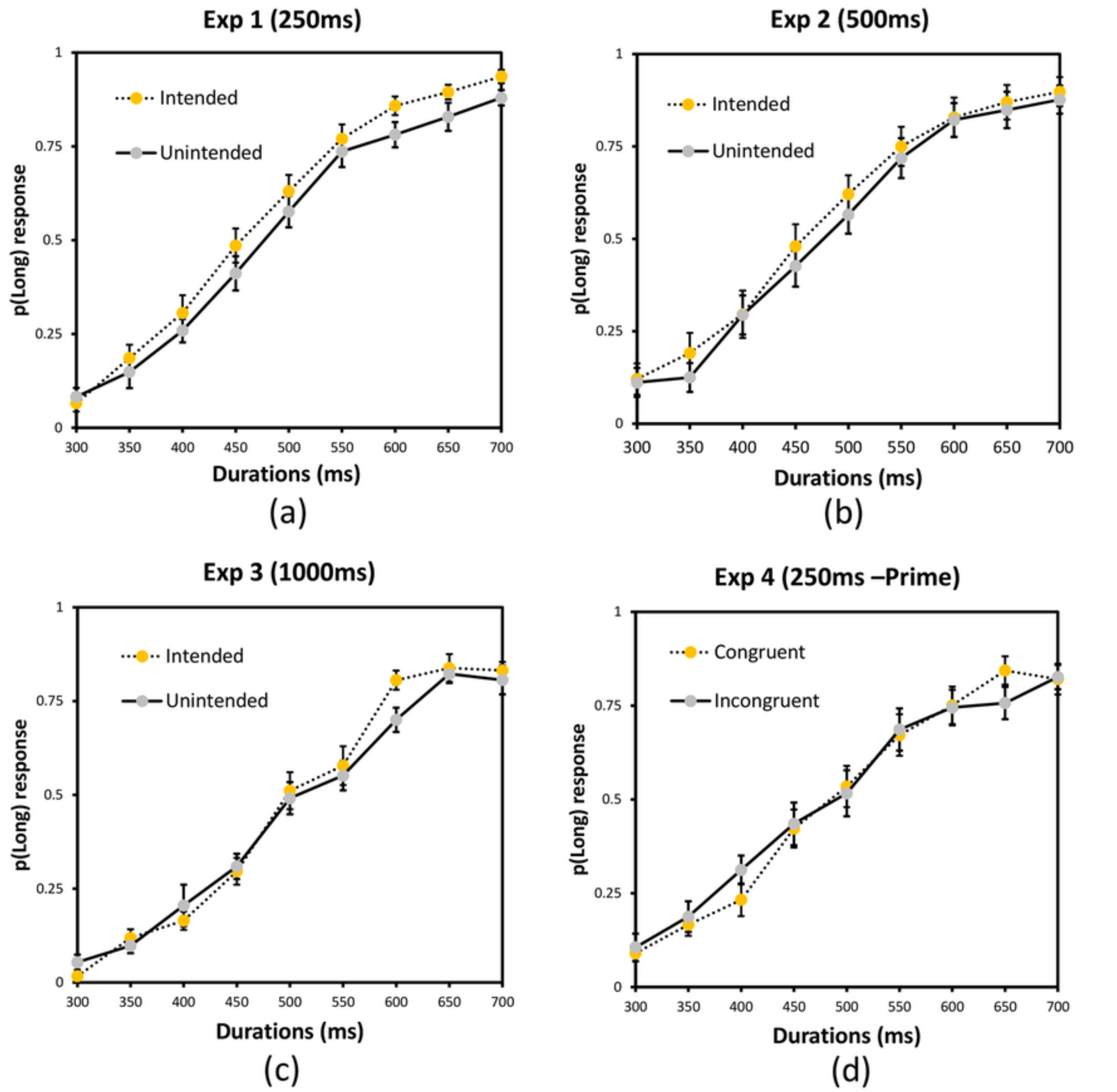


Fig. 33: Graphs illustrating the probability of long responses along with the standard error for each stimulus duration, comparing intended and unintended conditions. (a) Exp. 1 (250ms action-outcome delay), (b) Exp. 2 (500ms action-outcome delay), and (c) Exp. 3 (1000ms action-outcome delay). The graphs in (d) also represent congruent and incongruent conditions in Experiment 4 (250ms action-outcome delay). Image sourced from (Makwana & Srinivasan, 2017)

The authors argue that the results align with the two criteria outlined in the intentional binding literature regarding the other three experiments.

1. The intentional binding effect typically diminishes as the delay between the action and its outcome increases (Eagleman & Holcombe, 2002; Haggard et al., 2002b).
2. The intentional binding effect is observable solely for intention-based actions, not stimulus-based ones (Haggard et al., 2002a).

The authors contend that the four experiments precisely meet these conditions. The first three experiments satisfy the initial criterion, while the fourth experiment adheres to the second criterion, emphasizing the intentional nature of the actions involved (Fig. 33).

Having said that, an essential point behind the derivation of these two conditions from the intentional binding literature relies on measurements conducted through the Libet Clock method. In contrast, the study in question utilized the temporal bisection task, a methodology aligned with the method of constant stimuli (Nolden et al., 2012), as discussed in earlier sections. Given this distinction in methodologies, it is reasonable to anticipate expansion effects following longer delays (Fig. 27), potentially extending beyond the conditions specified rather than being exclusive to them.

3.8 Our Interest in the Temporal Dynamics of Intended Outcomes Within the Intentional Binding Effect

Considering all that has been discussed up to this conjecture, with respect to the preceding sections concerning the examination of intentional outcomes' temporal expansion using a modified temporal bisection task, we posit that the dissociation may stem from how the elements of the intentional binding effect were defined operationally based on the evidence gathered from Ruess et al.'s study (Ruess et al., 2018). It is conceivable that, due to the employed methodology, participants activated components closely resembling those utilized during the execution of the Libet Clock method instead of those utilized in inferential methods like the method of constant stimuli.

The forthcoming chapters of this thesis (Chapter – 4 and Chapter – 5) will foray into exploring the significance of the action-outcome delay and its association with the two components of the intentional binding effect in the context of the temporal expansion of outcomes under intention.

Chapter – 4

Differential Effect of Action-Outcome Delays on the Temporal Expansion of Intended Outcomes

4.1 Introduction

The sense of agency is the subjective feeling of control of one's actions. To measure the sense of agency, one of the methods employed in literature is the idea of intentional binding (Fig. 9, Fig. 14), where it is understood that if an action is committed by an agent voluntarily, then the subjective interval between the committed action and its effect is perceived to be temporally shorter than the physical interval at which they are separated at (Haggard, 2017; Haggard et al., 2002b; Haggard & Tsakiris, 2009; Moore & Obhi, 2012). One of the mechanisms behind such subjective attraction is the bi-directional relation between voluntary action and its sensory consequence (Eagleman & Holcombe, 2002). A few models have tried to explain the idea of intentional binding, as previously discussed (Buehner, 2012; Hughes et al., 2013; Wenke & Haggard, 2009). One of them is the sensory recalibration model (Stetson et al., 2006) (Fig. 15), in which the brain recalibrates the temporal interval between a voluntary action and its outcome such that it shifts the outcome towards the action. However, a question arises whether the entire outcome shifts in time towards the action during such recalibration or is just the outcome onset that shifts, leading to an expansion of the outcome.

To commence our discussion on this question, it is imperative to present a summary of the study that has been previously discussed, albeit with additional technical insights into the methodology employed. The study in question is from 2017 by Makwana et al., who found that it is indeed the outcome onset that expands, therefore causing an expansion of the intended outcome (Makwana & Srinivasan, 2017) (Fig. 32). In the study, the authors implemented a modified version of the temporal bisection task wherein participants chose which coloured circle they would like to see as an outcome. The outcome selection is followed by an action-outcome delay before the outcome is displayed, where either the intended/selected outcome or the other (unintended) is observed. The participants then had to judge whether the observed outcome was closer to a "SHORT" or "LONG" anchor (300ms and 700ms, respectively), which they had learned before the experiment. Although the study consisted of four experiments, we will be dealing with the first three experiments within the context of our discussion. The three experiments had varying action-outcome delays (250ms, 500ms, 1000ms). The results revealed that the outcome expanded toward the action when the delay was 250ms, and as the delay increased, the effect became less pronounced. To establish a link between intentional binding and the perceived duration of the outcome, the authors sought their results to align with two conditions under which the intentional binding effect is well established.

1. The intentional binding effect tends to decrease as the delay between the action and outcome increases (Eagleman & Holcombe, 2002; Haggard et al., 2002b) and
2. The intentional binding effect is present only for intention-based or voluntary actions, not stimulus-based ones (Haggard et al., 2002a).

Their experiments satisfied these two conditions, grounding the results in intentional binding literature (Fig. 33).

However, the task used in the study raises concerns about the operationalization of intention (free will) due to the way participants selected outcomes representing their intentions. The experimental design included a bar-like cue that indicated how frequently participants had chosen a specific colour during the outcome selection phase. This bar was introduced to prevent participants from repeatedly choosing the same outcome (by pressing a single key all the time) and to encourage them to consider all options equally. According to long-standing philosophical traditions dating from figures like Aristotle to Kant and Hegel, if someone was not "free" when they did something, their actions might not be considered intentional (Carafides & Feinberg, 1972). The purpose of the bar was explained as a loose constraint, serving as a cue to prompt participants to think about the colour they desired to see in each trial. However, such a bar in the participants' visual periphery, guiding their outcome selections, could potentially introduce complications or complexities to the concept of intention itself (Chambon & Haggard, 2012; Wegner & Wheatley, 1999) ("prior conscious thought").

Prioritizing information is fundamental to human perception, and it is conceivable that the temporal processing of attended information (in this case, outcome monitoring due to the visual cue) is heightened and accelerated while irrelevant information is suppressed (Bundesen, 1990; Correa et al., 2006; Nobre, 2001; Treisman, 1969). It is plausible that the bar acted as a prior cue, leading participants to enhance their attention toward choosing between the two possible outcomes (Wen & Haggard, 2018) instead of focusing on the outcome. This, in turn, might have allowed the intended outcome to reach the threshold of consciousness faster, similar to the prior entry phenomenon (Hilkenmeier et al., 2012; Spence et al., 2001), where attending an event could make it appear earlier than a simultaneous unattended event. Since the processing for the intended outcome, elicited by the peripheral cue, starts earlier, the intentional activity triggered by the attended stimulus could add to the activity already triggered by the cue (Scharlau, 2007).

Furthermore, intentional binding, in addition to external cues, has been demonstrated to be intrinsically dynamic in terms of how prior and posterior information are distributed, as proposed by the cue integration theory (Jagini, 2021; Klaffehn et al., 2021; Moore & Fletcher, 2012; Wolpe et al., 2013) (Fig. 19). According to this theory, the intentional binding effect is developed through two components (Haggard & Cole, 2007; Moore & Haggard, 2008; Wen et al., 2015b): a predictive component based on prior information and a postdictive component based on posterior information. Depending on the available information, intentional binding might rely more on one component than the other, resulting in variations in overall binding as well as in the relevant action bindings (perceptual shift of the action towards the outcome) and outcome bindings (perceptual shift of the outcome towards the action). The presence of an external cue during action selection could potentially influence the temporal dynamics of the intentional binding effect (Yamamoto, 2020).

Therefore, considering the influence of external information on intentional binding and the potential mechanisms of faster processing based on available cues, it is plausible that the bar-like prior cue during the intention selection phase could have impacted the observed outcomes in Makwana et al.'s study, resulting in the expansion of the intended outcome within shorter time frames (250ms and 500ms) (Fig. 33). Additionally, the authors invoke pre-activation theory (Cardoso-Leite et al., 2010; Haggard, 2005; Kühn & Brass, 2010; Press et al., 2014; Waszak et al., 2012) to explain the expansion of an outcome following the shorter action-outcome delay conditions (250ms and 500ms). However, based on the arguments presented, removing the bar-like cue that facilitated outcome selection tracking might lead to a difference in how the pre-activation of an intended outcome can affect its temporal expansion.

To address this issue, we implemented a modified version of the temporal bisection task by having a set of six immediately recognizable 2D geometric shapes (Circle, Triangle, Square, Rhombus, Parallelogram, and Pentagon) (Fig. 34). We used random pairs of these shapes on the intentional selection slide. This approach circumvented the confounding factor of the bar-like visual cue used to track the two alternative forced choices. With this modification, participants were presented with a random pair of objects on each trial, allowing them to independently and freely choose either outcome without being influenced by any external information that might impact their free will.

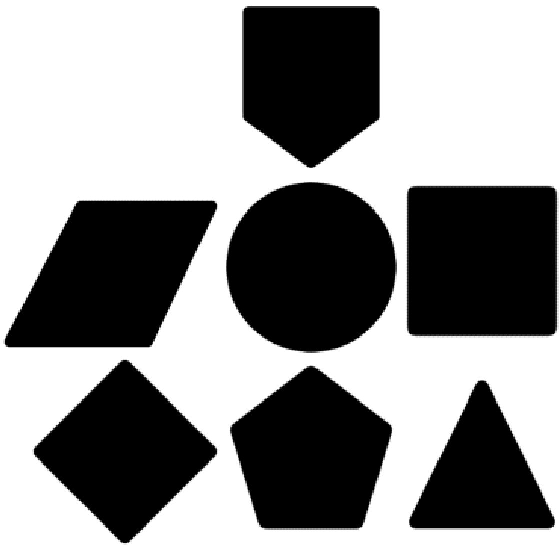


Fig. 34: Set of six solid 2D geometric shapes used as selectable outcomes in the testing phase of the experiment (Parallelogram, Circle, Square, Rhombus, Pentagon, Triangle) along with a badge-shaped object for training and feedback phases of the experiment.

We conducted our version of the temporal bisection task to assess the effect of intention on the temporal expansion of the outcome, using action-outcome delays of 250ms and 1000ms as a within-subject factor in experiment 1 and a between-subject factor in experiment 2. Additionally, this design allowed us to investigate the pre-activation account reported in previous studies. We hypothesized that if the expansion of an intended outcome resulted from intention being pre-activated rather than the effect of the bar-like cue, we would observe a similar if not more significant expansion of the intended outcome under the 250ms action-outcome delay condition, but not under the 1000ms action-outcome delay condition, just like in the earlier study (Makwana & Srinivasan, 2017) (Fig. 33).

4.2 Method

4.2.1 Participants

A total of 23 participants in experiment 1 (mean age: 24, 5 female) and 46 participants in experiment 2 (mean age: 22, 15 female) (24 participants in the 250ms delay group and 22 participants in the 1000ms delay group) were recruited from the International Institute of Information Technology, Hyderabad, India. All participants were healthy and naïve as to the purpose of the study. They had normal or corrected-to-normal vision, and the study was approved by the Institute Review Board (IRB), International Institute of Information Technology, Hyderabad, India. All the experimental procedures and methods were performed per the relevant guidelines and regulations. Informed consent forms were obtained from all the participants, and remuneration was paid for their participation.

4.2.2 Stimuli and Apparatus

All experiments were designed using Psychtoolbox (Ver. 2.0.18) on MATLAB(R2021b) and run on a CRT monitor (1024x768 resolution) at a refresh rate of 100Hz. Participants sat 60cm from the monitor screen in a dimly lit experimental room. Stimuli consisted of six solid black 2D, each sized 150x150 pixels, with a visual angle of 3.82 degrees against a white background. During both experiments' training and feedback phases, an additional badge-shaped 2D object was used in addition to the main six objects (Fig. 34). To analyse the data; the psychometric curve was fitted using the Psignifit toolbox (Ver. 2.5.6) in MATLAB. All other analyses were performed using JASP (Ver. 0.16).

4.2.3 Procedure

We employed a modified version of the temporal bisection task for all experiments (Fig. 35). The trial structure consisted of three phases: training, feedback, and testing. In the training phase, participants encountered a flashing badge-shaped 2D object ten times for a SHORT duration of 250ms and ten times for a LONG duration of 850ms. They were instructed not to use counting strategies but to develop a mental representation of the learned temporal anchors. During the feedback phase, participants were required to identify the SHORT or LONG anchor durations they learned in the training phase with an accuracy above 95%.

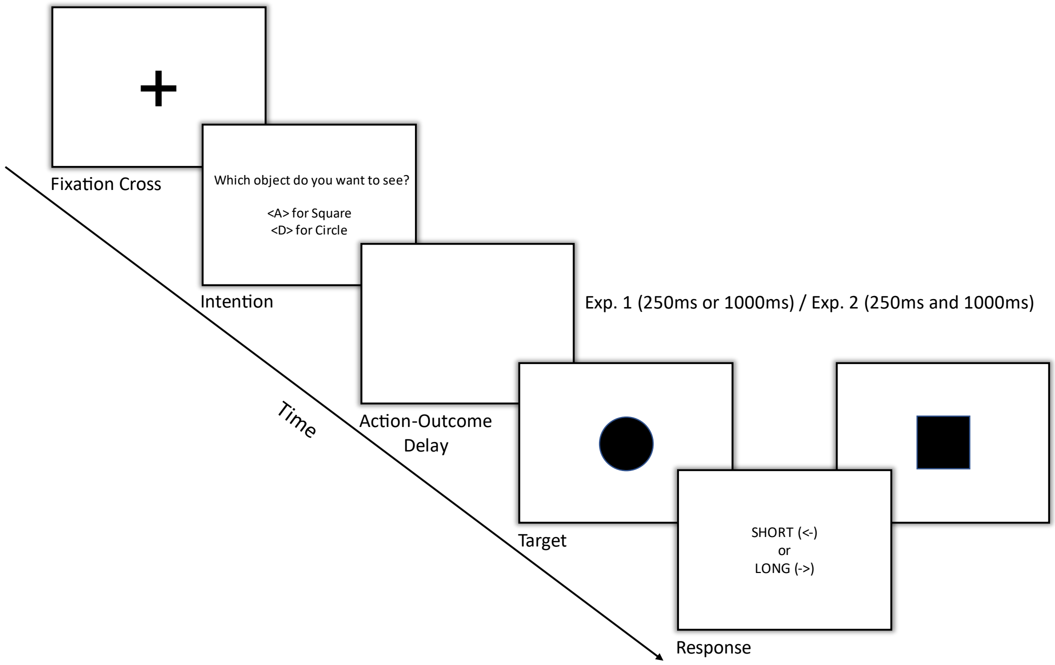


Fig. 35: Experimental design employed in both experiments. Before each trial, the participants select the object they want to see by pressing the pre-assigned keys. Outcome selection was followed by either a 250ms or 1000ms action-outcome delay in experiment 1 (delay as a within-subject factor) and experiment 2 (delay as a between-subject factor). The target stimulus would randomly be either the intended or unintended selection. This target was flashed for a random objective duration between 250ms to 850ms in steps of 100ms, after which the participants reported whether the target stimulus was closer to the LONG (850ms) anchor or SHORT (250ms) anchor by pressing the relevant arrow keys.

In each self-paced trial of the testing phase, participants were presented with a fixation cross, followed by two objects labelled "Object 1" and "Object 2." They had to choose between the two objects by pressing a designated key corresponding to the word representing the pair of objects in that particular trial. Words were used instead of shapes to allow quick assessment and activation of the representation of the shape before making a selection (Noorman et al., 2018). To ensure participants recognized the 2D shapes, they were asked to match the shapes on the screen with their corresponding names before the experiments. Participants were explicitly instructed to base their key press on the object represented by the key, not the key itself.

Once the participant selects an object, one of the two action-outcome delays was followed by either the intended selection or the other for one of seven objective durations ranging from 250ms to 850ms in steps of 100ms increments. The probability of getting the intended outcome was set at chance (50%) to prevent accurate prediction of the target object, thereby ensuring that any observed effects were attributed to intention rather than prediction. Participants reported the duration of the object as closer to the SHORT (250ms) or LONG (850ms) anchor they learned in the training and feedback phases of the experiment by pressing the corresponding key. Four breaks were incorporated between the trials, corresponding to each experiment's total number of trials. Participants' intention response, i.e., what object they wanted to see, and their duration judgment response (SHORT/LONG) were recorded.

In experiment 1, the target stimulus appeared either after a 250ms delay or a 1000ms delay, interspersed in a within-subjects design, resulting in 420 trials. There were 210 trials under each delay condition (250ms and 1000ms), half of which were intended selections and the rest unintended. Each objective duration (250ms to 850ms) had 15 trials. The six objects were paired based on a 6x6 arrangement, with repetitions removed, resulting in 30 combinations repeated seven times, leading to 210 object pairs per action-outcome delay. All factors were completely randomized.

In experiment 2, the action-outcome delays of 250ms and 1000ms were considered a between-subjects factor, meaning participants belonged to either the 250ms or 1000ms delay group. Each participant underwent 210 trials, of which 105 were intended, with 15 trials per objective duration. The 210 object pairings were randomized within each group.

4.3 Results

4.3.1 Experiment 1 (Within Subject Design – Intermixed Action-Outcome Delays)

In this experiment, we tested whether intention influences the perceived duration of an outcome under different action-outcome delays of 250ms and 1000ms as a within-subject factor. Under the temporal bisection task, participants underwent initial training using two anchor durations, labelled as "SHORT" (250ms) and "LONG" (850ms). Subsequently, during the testing phase, participants engaged in object selection, followed by an action-outcome delay, and finally, the presentation of the outcome (Fig. 35). The participants were tested with seven objective durations, ranging from 250ms to 850ms in 100ms increments, which served as comparison stimuli. Their task was to judge whether the observed target stimuli were closer in duration to the "SHORT" or "LONG" anchor. The outcome being intended or unintended, and the action-outcome delay was set at a chance level across all trials. The collected data were then organized based on each participant's two outcome conditions (intended and unintended) and the two action-outcome delays (250ms and 1000ms). To analyse the data, we fitted each participant's responses to a logistic psychometric function (Fig. 36). We estimated the bisection points (BPs) and the difference limen (DL) from this function. The bisection point represents the duration at which the probability of perceiving the observed outcome as "long" is 50%. On the other hand, the difference limen is a measure of precision, also known as the "just noticeable difference", corresponding to half the difference between the values at 75% and 25% probabilities of responding "long". We considered an outcome expansion when the intended outcome showed a leftward shift in the bisection point compared to the unintended outcome.

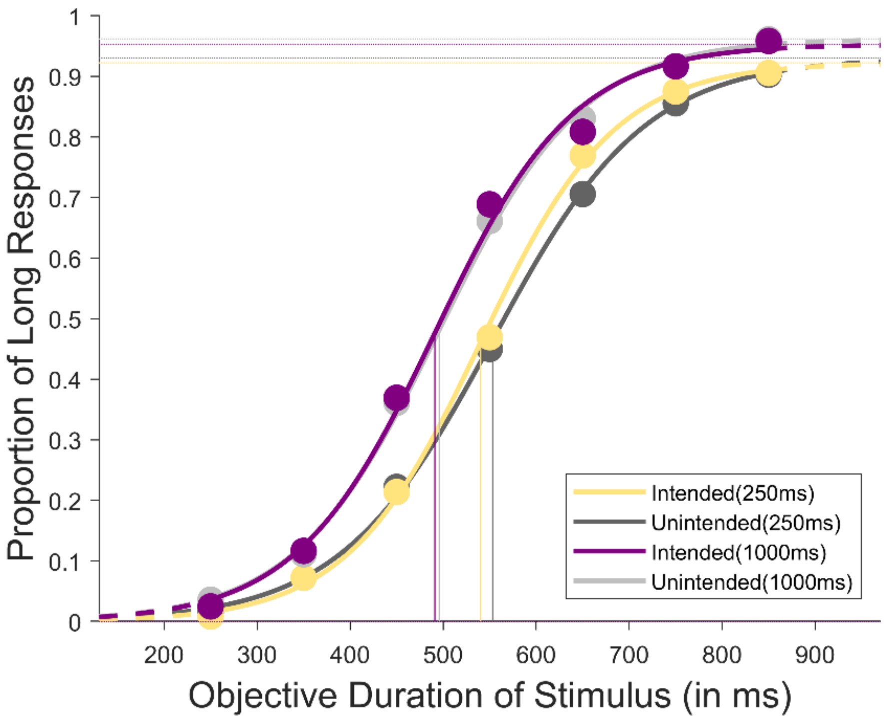


Fig. 36: Average psychometric fit for the results of all participants between intended and unintended conditions at an action-outcome delay of 250ms and 1000ms from Exp. 1.

A 2 (Outcome: Intended and unintended) × 2 (Action-Outcome Delay: 250ms and 1000ms) within-subject repeated measures ANOVA on BP values showed no significant effect of intention [$F(1,22) = 0.608$, $p = 0.444$, $\eta_p^2 = 0.027$] as well as intention × delay interaction [$F(1,22) = 0.036$, $p = 0.852$, $\eta_p^2 = 0.002$], indicating that participants did not perceive the intended event as longer than the unintended event (Fig. 37). However, the delay seemed to have a significant effect [$F(1,22) = 32.87$, $p < 0.001$, $\eta_p^2 = 0.599$]. A similar ANOVA on the DLs showed no significant effect of intention [$F(1,22) = 0.825$, $p = 0.373$, $\eta_p^2 = 0.036$], delay [$F(1,44) = 2.398$, $p = 0.136$, $\eta_p^2 = 0.098$], and intention × delay interaction [$F(1,44) = 0.263$, $p = 0.613$, $\eta_p^2 = 0.012$].

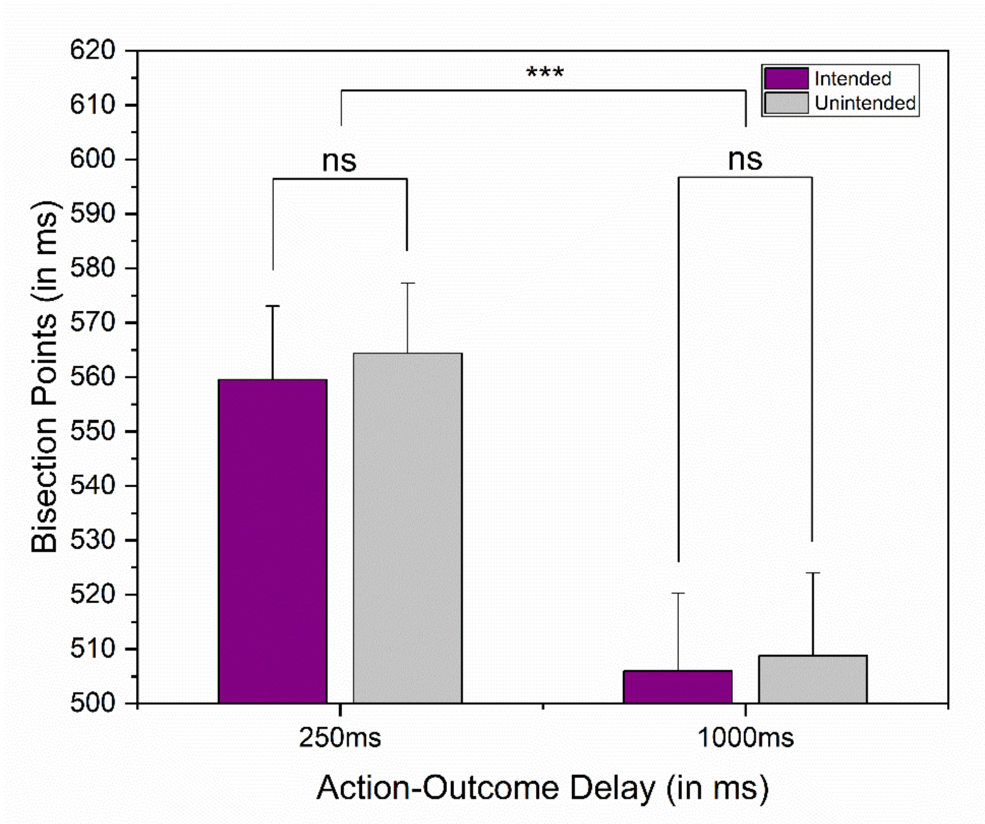


Fig. 37: Results of Experiment 1. Comparison of average BPs (Bisection Point) under the intended and unintended conditions across the two action-outcome delays as a within-subject factor. The error bar represents the standard error of the mean, *** indicates $p<0.001$, and ns indicates $p>0.05$.

We also subjected the observed bisection points (BPs) to a Bayesian paired sample t-test to assess the strength of the null effect of intention in both the action-outcome delay conditions. The calculated Bayes factor indicated that the data were 3.66 times more likely to align with the null hypothesis than the alternative hypothesis under the 250ms action-outcome delay condition. Similarly, under the 1000ms action-outcome delay condition, the data were 4.32 times more likely to support the null hypothesis than the alternative hypothesis. This provides moderate evidence for the absence of a significant effect of intention in both delay conditions.

The findings indicate that participants did not perceive any difference in the outcome duration between the intended and unintended trials across the two delay conditions. However, it appears that the action-outcome delay itself has an influence. Specifically, when the delay was set at 1000ms, participants tended to overestimate the outcomes consistently, regardless of whether they were intended or unintended (Fig. 37).

The predictability and timing of events play a role in intentional binding (Cravo et al., 2011; Darriba & Waszak, 2018; Hughes et al., 2013; Ruess et al., 2017; Sato & Yasuda, 2005; Tanaka et al., 2019), and the lack of significant intentional effects in Experiment 1 could be attributed to the erratic timing variations between actions and outcomes. Nevertheless, there have been experimental instances where intentional binding was observed even in situations with unpredictable action-outcome delays (Humphreys & Buehner, 2010; Imaizumi & Tanno, 2019; Morioka et al., 2018; Muth et al., 2021). However, considering the context of the study, where we are trying to probe the pre-activation account, it is reasonable to explore this phenomenon under consistent action-outcome delays in our research.

4.3.2 Experiment 2 (Between Subject Design)

Like experiment 1, the participants in this experiment also performed the temporal bisection task (Fig. 35). However, in contrast, we implemented the action-outcome delay as a between-subject factor for this experiment. This allowed us to examine the effect of action-outcome delay on intention independently. The participants were divided into two groups, and each group was tested with one of the two action-outcome delays (250ms or 1000ms). The collected data were first organized based on the two outcome conditions (intended and unintended). Each participant's data was fitted to a logistic psychometric function (Fig. 38 and Fig. 39), and the BPs were estimated along with the DLs.

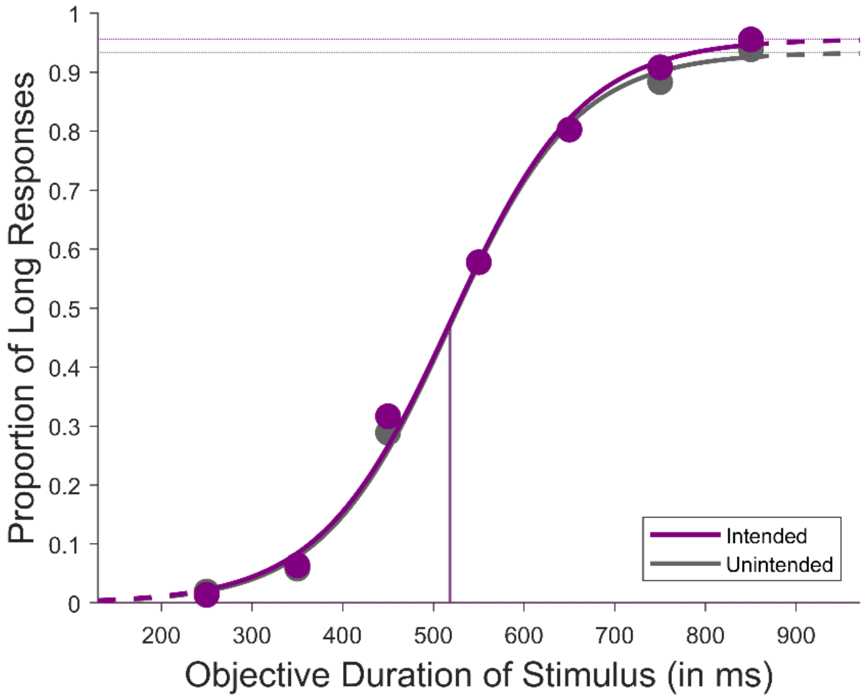


Fig. 38: Average psychometric fit for the results of all participants between intended and unintended conditions at an action-outcome delay condition of 250ms from Exp. 2.

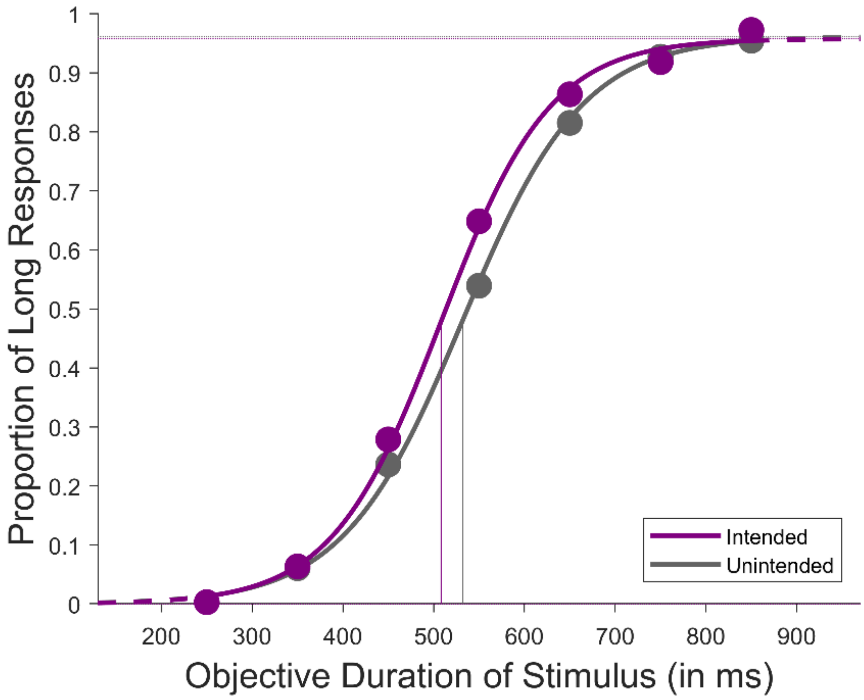


Fig. 39: Average psychometric fit for the results of all participants between intended and unintended conditions at an action-outcome delay condition of 1000ms from Exp. 2.

Repeated measures 2 (outcome: intended and unintended) × 2 (action-outcome delay: 250ms and 1000ms) mixed ANOVA with the action-outcome delay being a between-subject factor and the outcome being a within-subject factor, showed a significant effect of intention [$F(1,44) = 8.096$, $p = 0.007$, $\eta_p^2 = 0.155$] and a significant effect of intention × delay interaction [$F(1,44) = 4.906$, $p = 0.03$, $\eta_p^2 = 0.100$]. However, there was no significant effect of delay [$F(1,44) = 0.037$, $p = 0.849$, $\eta_p^2 = 8.374e^{-4}$]. Tukey corrected post hoc tests show that there was an effect of intention under the 1000ms action-outcome delay condition [$p = 0.006$] only (519.578±60.161ms under intended and 543.862±58.563ms under unintended) and not in the 250ms action-outcome delay (527.093±61.42ms under intended and 530.119±48.875ms under unintended) (Fig. 40). A similar mixed ANOVA on the DLs showed no significant effect of intention [$F(1,44) = 2.196$, $p = 0.145$, $\eta_p^2 = 0.048$], delay [$F(1,44) = 1.567$, $p = 0.217$, $\eta_p^2 = 0.034$], and intention × delay interaction [$F(1,44) = 1.59$, $p = 0.214$, $\eta_p^2 = 0.035$]. To evaluate the strength of the null effect of intention under the 250ms delay condition, we performed a Bayesian paired sample t-test on the observed BPs. The calculated Bayes factor indicated that the data were 4.22 times more in favour of the null hypothesis, providing moderate evidence for the absence of a significant effect of intention.

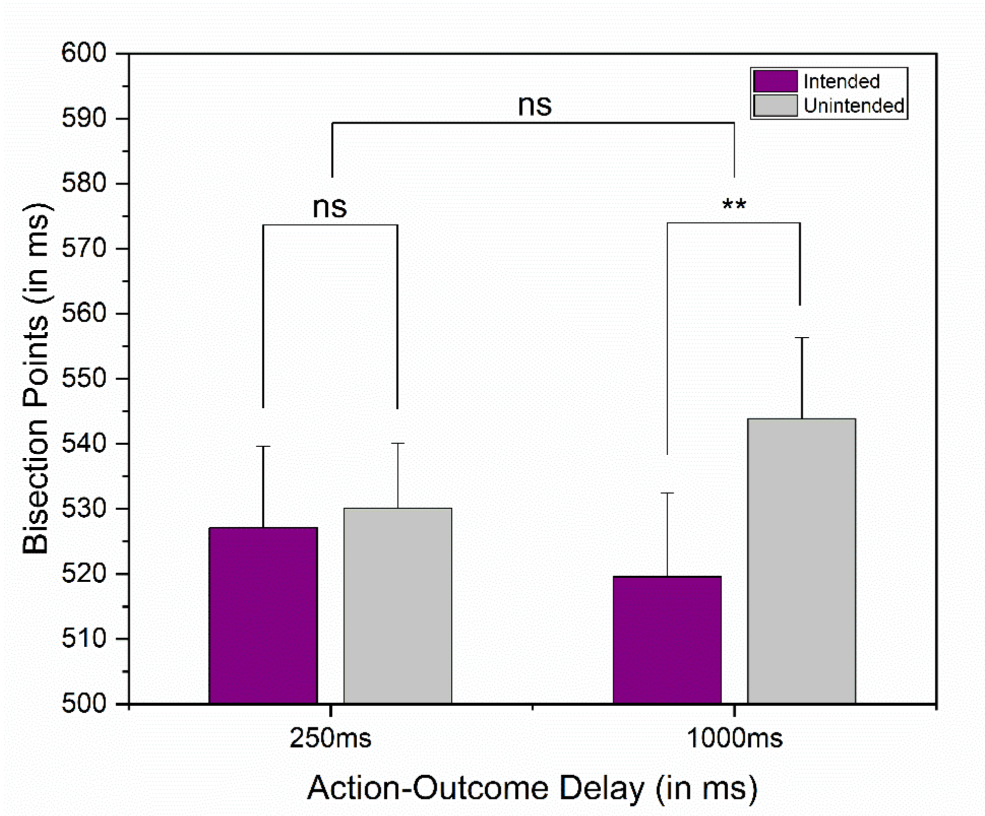


Fig. 40: Results of Experiment 2. Comparison of average BPs (Bisection Point) under the intended and unintended conditions across the two action-outcome delays as a between subject-factor. The error bar represents the standard error of the mean, ** indicates p<0.01, and ns indicates p>0.05.

4.4 Discussion

In a prior investigation by Makwana et al., they demonstrated a temporal expansion of intended outcomes within a unique temporal bisection task. However, concerns regarding the reliability of results concerning the impact of prior information on participants prompted us to modify the task by removing the bar-like cue to track outcome selections. Our study sought to explore the influence of intention on temporal expansion while addressing this potential confounding factor associated with the voluntary selection of actions. Participants were tasked with selecting a 2D object as an outcome, monitoring its duration, and then comparing it to memorized temporal anchors (250ms labelled as SHORT, and 850ms labelled as LONG) following either a short (250ms) or longer (1000ms) delay. Experiment 1 employed a within-subject design for action-outcome delay, while Experiment 2 utilized a between-subject design for our investigation.

The results from the initial experiment, where the action-outcome delay was a within-subject factor, did not reveal any intention-induced expansion of the outcome in either of the action-outcome delay conditions. Nonetheless, it is worth noting that there was a general tendency to overestimate the outcome under the 1000ms delay condition, regardless of whether the outcome was intended or not. This indicates that participants experienced an expansion effect for the outcome in the 1000ms delay condition, irrespective of their intention (Fig. 37). On the other hand, the results from the second experiment revealed a different outcome. Here, an effect of intention on the temporal expansion of the outcome was observed. However, this effect was explicitly seen in the context of the 1000ms action-outcome delay condition (Fig. 40).

4.4.1 Would the Pre-Activation of Intention Explain the Observed Results?

Makwana et al.'s earlier study demonstrated an intention-induced expansion effect for shorter delays (250ms and 500ms) but not for longer delays (1000ms) (Fig. 33). They attributed these findings to a pre-activation account of intended outcomes, which suggests that self-generated expectations cause a form of pre-activation (Cardoso-Leite et al., 2010; Haggard, 2005; Kühn & Brass, 2010; Press et al., 2014; Waszak et al., 2012) of the representation of an intended outcome. This pre-activation leads to a faster accumulation of its awareness threshold, resulting in these outcomes being experienced earlier. According to this account, pre-activations of self-generated expectations are more substantial than cue-induced expectations (Gaschler et al., 2014; Kemper et al., 2012; Kemper & Gaschler, 2017). However, the results of the current study contradict this explanation. Suppose the expansion of an intended outcome was solely due to the pre-activation of intention. In that case, an expansion effect should have been observed even for the 250ms action-outcome delay in either of the experiments (Fig. 37 and Fig. 40). However, that was not the case; the expansion effect was evident only after a substantial delay (1000ms) (Fig. 39 and Fig. 40). This suggests that the expansion observed in this study is not attributable to a pre-activation account but rather to other factors.

4.4.2 Why there was no effect of Intention at Shorter Action-Outcome Delays

A shorter delay between stimuli can result in rapid succession, potentially hindering the encoding of intentions. The immediate presentation of stimuli may challenge the cognitive processes in forming stable intentional representations, making it difficult to retrieve intentions effectively. Shorter delays could also impede the development of the intentional representation of the outcome and impose an increased cognitive load and demands on working memory, further disrupting the stable representation of intentions and compromising intention recognition. Conversely, a longer delay gives individuals more time for intentional processing and representation (Block, 2009). Intentional encoding may occur more accurately during longer delays as individuals have sufficient time to form and maintain intentions. This temporal spacing of stimuli may facilitate intentional representation, leading to improved intention recognition. Hence, the dependence on the delay can explain why we only observe an effect of intention after a longer action-outcome delay.

4.4.3 An Attentional Account of the Observed Results

In addition to the effect of intention after a longer delay, the outcome expanded when it aligned with participants' intentions. Studies on time perception suggest that when participants concurrently perform a non-temporal task (such as recognizing intention) during prospective timing, they tend to overestimate duration judgments when prioritising timing as the main task (Block et al., 2018). This is consistent with established models of prospective timing (Zakay & Block, 1997), where focusing on time can lead to overestimating prospective duration judgments. However, the choice of what to focus on during prospective duration judgments can be influenced by the cognitive system's needs in relation to the current task's goal (Henderson et al., 2009).

In our case, when the participants chose an outcome, it was in line with their goal of encountering the chosen outcome later. As a result, the relevance they assigned to a specific outcome selection determined the depth of information processing and the amount of resources allocated to its prospective judgment (Billings & Scherer, 1988). Hence, it is possible that when participants experienced an intended outcome, temporal relevance played a role in directing attentional resources toward its judgment, making the event feel longer.

According to the temporal relevance model of prospective time judgments (Zakay, 2015), the level of temporal relevance influences the amount of attention allocated to a particular duration judgment. When temporal relevance surpasses a certain threshold, attentional resources are directed toward the duration judgment, while minimal allocation occurs when temporal relevance is not significant (below the threshold). This attentional allocation based on temporal relevance enhances temporal information processing. Since participants in our study were actively anticipating an intentional outcome, it is plausible that their judgments were overestimated when they experienced it. Therefore, the observed expansion effect resulting from intention in the second experiment may be attributed to the retrieval of intention from memory and the engagement of attention during the task due to its temporal relevance.

4.4.4 Additional Results from Experiment 1

Apart from our primary exploration of the effect of intention on the temporal expansion of an outcome, we made two intriguing observations in the first experiment (Fig. 37). (a) the significant effect of delay on the BPs, and (b) the non-significant effect of intention.

The Significant Effect of Delay on the Bisection Points. Recent research on the intentional binding effect has raised concerns about a potential confounding factor in its measurement. Some studies have criticized the binding effect, suggesting it might be a by-product of the experimental task design (Buehner, 2015; Desantis et al., 2012; Gutzeit et al., 2023; Kirsch et al., 2019). Binding effects are compared based on the presence or absence of overt actions, which can lead to a confounded attribution of the binding effect solely to intention. This is especially true as there have been experimental studies where the mere execution or even the resemblance of an action could cause a temporal binding effect similar in magnitude to what is observed in traditional intentional binding studies, even without any semblance of intention present (Poonian & Cunnington, 2013; Ruess et al., 2020; Suzuki et al., 2019).

Studies that have observed a binding effect regardless of intention tend to explain the effect arising from the perception of a causal association between the action and the outcome (Haering & Kiesel, 2014; Hoerl et al., 2020; Ruess et al., 2020). The significant effect of delay and the absence of intentional effects observed in experiment 1 (Fig. 37) could also be attributed to such a causal association between the action and the outcome, and the lack of significance in the difference limens (DLs) supports this interpretation. According to a recent study by Fereday et al. (Fereday et al., 2019), the temporal acuities (precision or DL) should remain consistent across causal conditions when comparing two causal conditions (Fig. 41). The results from our first experiment align with the suggestion made by Fereday et al. This could indicate that the observed results in our experiment 1 might be attributed to causal multisensory integration rather than solely to intentional factors. Even though we had attributed the expansion of the outcome in the second experiment as due to intention, this does not negate the role of causality in this context.

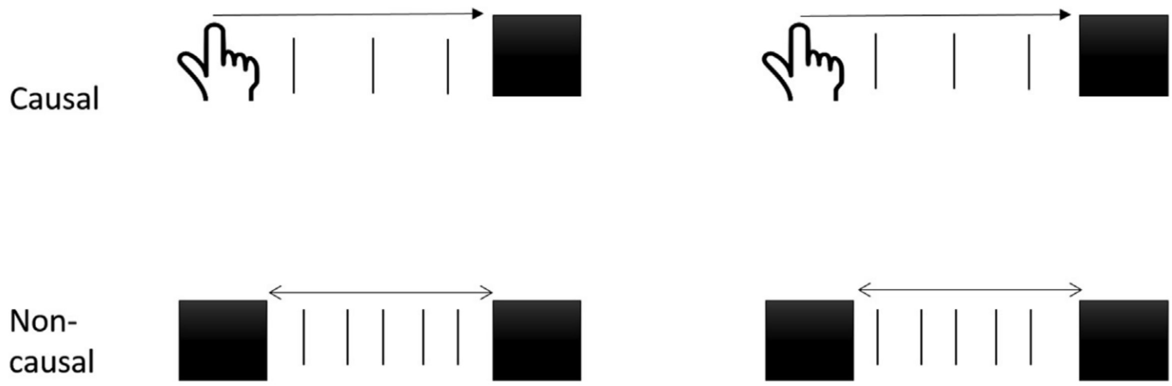


Fig. 41: Illustration showing hypothesised internal clock pulses in causal and non-causal intervals. According to Fereday et al., The pulse rate within causal conditions should remain unaffected during a causal episode but should vary between causal and non-causal conditions. The fewer pulses in the causal condition are due to a slower pacemaker during causal episodes. Image sourced from (Fereday et al., 2019)

Subsequently, it is also plausible that the results we observe in experiment 2 could be interpreted as temporal binding relying on causality and intentions serving as a mechanism to establish causal congruency. Experimental evidence also supports this notion as it indicates that temporal binding in the context of causal events produces a more substantial binding effect when participants believe they are the ones who performed the action (Desantis et al., 2011; Lush et al., 2017). Consequently, intentional binding may be a part of a broader phenomenon of causal multisensory integration, where an event's cause is intentional. Nevertheless, additional experimentation is necessary to probe the causal role in intentional binding further.

The Non-Significant Effect of Intention. The non-significant effect of intention in experiment 1 (Fig. 37) may also be attributed to the nature of the task. The continuous recalibration of outcome anticipation (Stetson et al., 2006) or learning of contingencies (Cravo et al., 2011; Haggard & Clark, 2003) might have overshadowed intentional binding due to the unpredictable nature of action-outcome delays. While some studies have demonstrated significant binding even with unpredictable action-outcome delays (Humphreys & Buehner, 2010; Imaizumi & Tanno, 2019; Morioka et al., 2018; Muth et al., 2021), meta-analytic reviews suggest that temporal predictability plays a crucial role in intentional binding (Hughes et al., 2013; Tanaka et al., 2019), particularly in the context of the Libet Clock method. However, considering that the Libet Clock method engages different processes than inferential methods (Siebertz & Jansen, 2022), we need to be careful while considering this.

Previous studies that used the interval estimation task also indicated some influence of temporal predictability on temporal estimates. For instance, research conducted by Imaizumi et al. (Imaizumi & Tanno, 2019) and Humphreys et al. (Humphreys & Buehner, 2009) differed in how action-outcome delays were manipulated. In the former, delays varied within a block of trials. Though they found a significant binding effect, further analysis showed that the binding weakened as the action-outcome delay increased. In contrast, the latter study demonstrated a significant interaction between action-outcome delay and the amount of observed binding, with binding increasing as the action-outcome delay increased. Moreover, a follow-up experiment by Imaizumi et al. using visual outcomes instead of auditory ones resulted in the disappearance of the binding effect. Another study by Nolden et al., which measured intentional binding using the method of constant stimuli, found more significant Weber fractions when participants experienced different action-outcome delays within the same block of trials, suggesting reduced performance under changing action-outcome delays (Nolden et al., 2012).

While the evidence from these studies is not entirely conclusive, the presented data leads us to believe that the temporal predictability of outcome onsets may have influenced the results observed in our first experiment. This aligns with the findings of the meta-analyses mentioned above, which emphasized that the temporal context, specific characteristics of the action and outcome context, and the type of outcome modality (visual, haptic, auditory) can induce different modulation of binding. Alternatively, it could be possible that another factor might be interfering with the intentional representation. Selecting a response and recognizing its congruence with the chosen object involves a conscious and controlled process. Consequently, this process could be influenced by cognitive factors such as attention, task requirements, or a shortage of cognitive resources (Elgendi et al., 2018). It is possible that the unpredictability of the action-outcome delay heightened attentional demands, leading participants to focus more on calibrating for the outcome's timing rather than recognizing the intentional connection, akin to a form of choice blindness (Johansson et al., 2005, 2008).

4.4.5 The Differential Impact of Action-Outcome Delay and Component Operationalization

Our experiment showed an interesting outcome related to the impact of intention following longer delays. This aligns with the binding dynamics commonly observed in inferential paradigms used to measure the intentional binding effect (Engbert et al., 2007; Fereday et al., 2019; Humphreys & Buehner, 2009; Kühn et al., 2013; Nolden et al., 2012; Wen et al., 2015a). These paradigms typically show significant binding effects after longer action-outcome delays (Wen, 2019). In our study, the absence of an external cue may have caused participants to focus more on the outcome and its connection to the committed action or intention rather than on the action selection process. Conversely, when external cues are present, participants may become more action-specific in their focus, leading to results that align with sensory-based paradigms like the Libet clock method (Haggard et al., 2002b; Moore & Obhi, 2012; Ruess et al., 2017), where binding effects tend to be short-lived and operate within a strict time window (Shimada et al., 2009).

The differential impact of delay on intentional binding is commonly linked to the methodology employed as well as what components of the intentional binding effect are engaged (Haggard & Cole, 2007; Moore & Haggard, 2008; Siebertz & Jansen, 2022; Wen et al., 2015b). Sensory paradigms show significant binding effects under shorter action-outcome delays, while inferential paradigms reveal such effects under longer delays (Imaizumi & Tanno, 2019; Wen, 2019). However, studies like Ruess et al.'s experiment indicate that the same methodology can demonstrate varying sensitivities of the binding effect depending on the action-outcome delay (Ruess et al., 2017, 2018) and other external factors (Klaffehn et al., 2021). The differential sensitivity to components of the intentional binding effect across the studies may be explained by the Bayesian cue integration theory (Jagini, 2021; Klaffehn et al., 2021; Moore & Fletcher, 2012; Wolpe et al., 2013). According to this theory, the observed temporal binding between an action and its outcome results from an optimal Bayesian integration of information (Hillis et al., 2002; Körding & Wolpert, 2004). Based on the limited evidence, we can speculate that Makwana et al.'s study engaged the processes relevant to the Libet clock method. In our study, inferential processes were given priority.

4.4.6 Possible and Speculative Operationalization of Different Intentions

While our experimental design did not directly assess this aspect, recent research suggests that intentional operationalization through experimental design could influence the binding effect (Vinding et al., 2013, 2015). The philosophical literature on the phenomenology of intention (Pacherie et al., 2010) discusses a distinction between proximal and distal intentions (Fig. 42). Proximal intent focuses on the mechanics of performing an action, while distal intention involves the broader purpose beyond the action's execution.

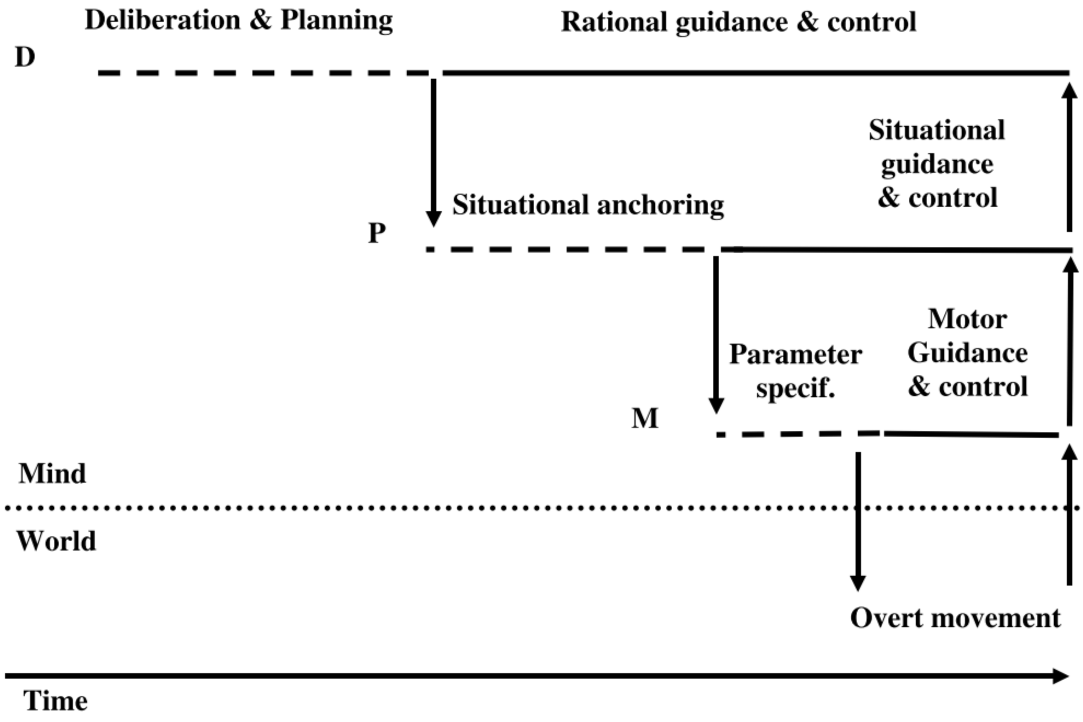


Fig. 42: The intentional cascade of distal intentions (D), proximal intentions (P), and motor intentions (M).

The PIDI framework (proximal intent distal intent) suggests that one form of intent can be more prominent than the other (Plaks & Robinson, 2017), similar to the dual component theory underlying the intentional binding effect. Proximal intentions align with the Libet method for measuring the intentional binding effect, whereas distal intentions align with inferential methods. The observed expansion of outcomes in our second experiment, specifically at the 1000ms action-outcome delay (Fig. 40), may be attributed to a stronger emphasis on distal intention since distal intentions require the establishment of intention in working memory (Gilbert, 2011), and it is understood that proximal intentions characterize the Libet method for measuring the intentional binding effect (Mele, 2010; Zhu, 2003). The variation in delay effects across the studies (Makwana et al.'s and ours) could be linked to the specific operationalization of intention and the engagement of components underlying the intentional binding effect. Sensory-based proximal intention may cause outcome expansion at shorter delays but decays for longer delays. On the other hand, inference-based distal intention causes outcome expansion at more prolonged delays.

However, the application of this interpretation is highly speculative and contingent. Additional research and experimentation are imperative to thoroughly explore and validate this specific explanation for the differential impact of action-outcome delay. Consequently, it is crucial to approach the PIDI framework with great caution. For more details on the dissociation of intentional contexts, please refer to the information provided in the Appendix of this thesis.

The following chapter further explores the operationalizability of the components related to the intentional binding effect in the context of a temporal reproduction task. If the determination of action-outcome delay ranges to assess the intentional binding effect is contingent on how actions and outcomes are processed rather than the specific methodology employed, it can be asserted that, depending on how we define intentional outcome processing, there may be no necessity for reliance on the action-outcome delay.

Chapter – 5

Outcome Processing Drives Action-Outcome Delay Sensitivities over the Temporal Expansion of Intended Outcomes

5.1 Introduction

In alignment with our earlier research, our subsequent study deals with the temporal dynamics of an intended outcome. However, in this investigation, we challenge the notion proposed by Makwana et al. that the temporal expansion of an intended outcome relies on the action-outcome delay. Instead, our prior study introduces uncertainty regarding the consensus that the sensitivity of the intentional binding effect to the action-outcome delay is contingent on the chosen methodology. The key factor is that we have observed expansion tendencies reflecting both predictive methods for assessing the intentional binding effect (as seen in Makwana et al.'s study) and inferential methods (employed in our previous study). The only disparity between implementing the temporal bisection task in Makwana et al.'s experiment and ours lies in including and excluding a bar-like cue in the action selection phase. This suggests that the reliance on the binding effect's sensitivity on the action-outcome delay may be influenced by how actions or outcomes are processed.

Therefore, given the current literature on the intentional binding effect, as discussed, it is evident that the action-outcome delay, influenced by task demands, plays a crucial role in developing the binding effect. Subsequently, this factor can potentially influence the temporal processing of outcomes when intentional actions are involved. Building upon these principles, it seems that the influence of the action-outcome delay on the temporal expansion of intended outcomes could be contingent upon how the outcome is mentally processed. Consequently, the interaction between action-outcome delay and intention remains ambiguous, impacting the perceived duration of intended outcomes.

A potential solution to address these questions could be found in the context of using temporal reproduction. The temporal reproduction task has been previously implemented and validated to measure the intentional binding effect (Humphreys & Buehner, 2010). The methodology entails a prospective task of estimating a duration, where the initial step typically involves encoding a target duration and then storing it in memory for later reproduction through a motor action to convey the temporal magnitude (Fortin & Rousseau, 1998; Mioni et al., 2014). In our context, during the encoding phase, participants are presented with a range of objective durations associated with intentional or unintentional outcomes. In the subsequent reproduction phase, participants are instructed to reproduce the durations they encountered during the encoding phase.

The primary rationale behind employing this dual process paradigm is to solely evaluate the impact of the action-outcome delay on outcome expansion due to intention. Prior studies have consistently involved participants making some form of judgment about the outcome duration while experiencing it. This manner of processing the outcome could explain the observed dependence between the action-outcome delay and temporal expansion in previous studies. By segregating the encoding phase from the reproduction phase, our objective is to exclusively assess how intention influences the temporal expansion of an outcome, as what is encoded is meant to be faithfully reproduced by the participant during the later reproduction phase of the task.

Therefore, in the present study, we employ a modified version of the temporal reproduction task to investigate whether the expansion of outcomes triggered by intentions would interact with the delay between action selection and its outcome. In the task, participants must first choose the object they want to see within a trial. This object selection would be considered a proxy for intention as, according to the content argument of intention (Wittgenstein, 1953), when someone decides to do A rather than B, they may develop an intention whose specific content will relate to A rather than B. An action-outcome delay then follows the outcome selection. Afterwards, the participant would observe the chosen or the other outcome for an objective duration and then reproduce that duration when prompted. Suppose the reproduced durations of the outcome are affected by intention; we should see an intention-induced expansion in the reproduction durations when the outcome they observe is congruent with their intention.

We hypothesize that we would not detect any disparities in outcome expansion among various action-outcome delays. This is because, unlike previous studies, we are not affecting the encoding process through other forms of outcome processing besides encoding the temporal duration and whether it is intended or unintended.

5.2 Methods

5.2.1 Participants

27 participants (Mean Age: 22, 4 Female) under the 250ms condition and 29 participants (Mean Age: 21.6, 9 Female) under the 1000ms condition were recruited from the International Institute of Information Technology, Hyderabad, India. All participants were healthy and naïve as to the purpose of the study. They had a normal or corrected-to-normal vision, and the Institute Review Board (IRB), International Institute of Information Technology, Hyderabad, India, approved the study. All the experimental procedures and

methods were performed per the relevant guidelines and regulations. Informed consent forms were obtained from all the participants, and remuneration was paid for their participation.

5.2.2 Stimulus and Apparatus

The experiment was designed using Psychtoolbox (Ver. 2.0.18) on MATLAB (R2022b) and run on a CRT monitor (1024x768 resolution) at a refresh rate of 100Hz. Participants sat 60cm from the monitor screen in a dimly lit experimental room. Regarding the stimuli, the testing phase featured four filled black 2D shapes (circle, triangle, square, and rhombus) measuring (size: 150x150 pixels) (Visual Angle: 3.82) set against a white backdrop. In the training phase, an additional 2D object with a badge-like shape was introduced alongside the primary four objects.

5.2.3 Design

We employed a modified version of the temporal reproduction task for our study (Fig. 43). In this task, participants selected an object they wished to observe, which served as a proxy for their intention. To facilitate this process, we utilized words instead of shapes in the intention selection phase, allowing participants to rapidly assess their desired choice by mentally activating the shape's representation before making their selection (Noorman et al., 2018). Subsequently, the chosen or alternate object would appear on-screen after an action-outcome delay (250ms or 1000ms) lasting for an objective duration (300ms, 450ms, 600ms, or 750ms). Participants were then required to reproduce the duration by pressing and holding a designated key upon seeing a "NOW" prompt on the screen. This keypress was presented with an object throughout the reproduction, congruent with the target object shown in that trial. Participants were instructed to match their reproduced durations to the original observed ones as closely as possible. The combination of four objective durations and two types of outcomes (intended or unintended) resulted in eight conditions. There were 20 trials in each condition, for 160 trials per action-outcome delay. The action-outcome delay served as a factor between groups.

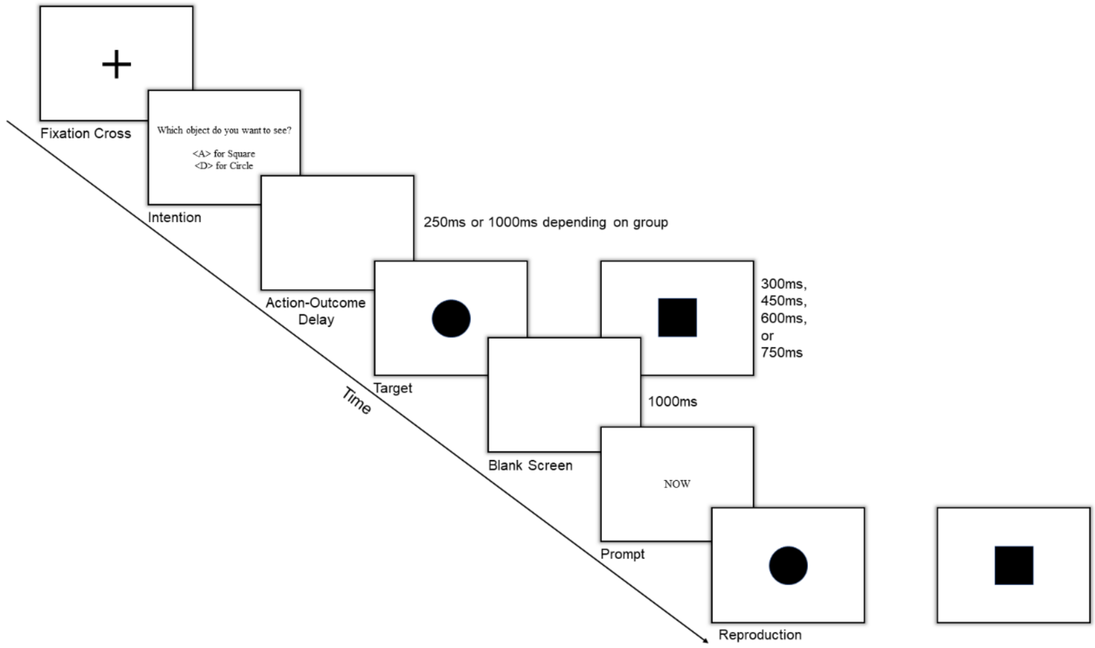


Fig. 43: The design employed in the temporal reproduction experiment. Before each self-paced trial, the participants select the object they want to see by pressing the pre-assigned keys. Outcome selection was followed by a 250ms or 1000ms action-outcome delay (between-subject factor) depending on the participant group. The target stimulus would randomly be either the selected or other object. This target was flashed for a random objective duration (300ms, 450ms, 600ms, or 750ms), after which the participants reproduced the observed target duration, following an on-screen prompt, by pressing and holding a pre-designated key.

5.2.4 Procedure

Before the participants proceeded with the experimental session, they underwent five temporal reproduction task practice trials. These practice trials were conducted to acclimatize the participants to the reproduction task as well as to assess whether the participants were able to reproduce the durations accurately enough as per the instructions given to them. Each self-paced trial in the practice session started with a fixation cross, followed by a 1000ms blank screen. The participants were then exposed to a badge-shaped 2D object (Fig. 34) for 1000ms. This target stimulus was again followed by a 1000ms blank screen, after which the participants were asked to reproduce the duration as accurately as possible by pressing and holding the corresponding designated key upon seeing a “NOW” cue on the screen. Participants were instructed to refrain from using counting techniques and instead rely on their internal representation of the observed duration (Rattat & Droit-Volet, 2012).

As for the main experimental session, within each self-paced trial of the testing phase, participants were presented with a choice between two objects labelled as “Object 1” or “Object 2” (randomly selected from a set of shapes: circle, triangle, square, and rhombus) (Fig. 34). They indicated their choice by pressing the corresponding key associated with the pair of objects in that trial. To ensure participants were familiar with the 2D shapes, they were required to match them on-screen with their respective linguistic counterparts before the experiment. Participants were explicitly instructed to base their key press on the object represented by the key rather than the key itself. Once an object was selected, it was followed by one of two action-outcome delays (250ms or 1000ms, depending on the participant group), leading to the appearance of either the intended selection or the alternative object. These appearances occurred for one of four predefined objective durations (300ms, 450ms, 600ms, and 750ms). The probability of the intended outcome was set to chance (50%) to prevent participants from accurately predicting the target object, thereby ensuring that any effects observed were linked to intention rather than prediction. A 1000ms blank screen followed the target stimulus presentation, after which participants were prompted with a “NOW” cue to reproduce the duration of the target stimulus by pressing and holding the appropriate key. The participants’ intended object choice and their reproduced duration were both recorded.

5.3 Data Analysis and Results

In this experiment, we examined how the reproduction of outcome durations for a predefined set of standard durations (300ms, 450ms, 600ms, and 750ms) is influenced by intention, considering different action-outcome delays of 250ms and 1000ms as a factor varying between groups.

Before analyzing the recorded data, we identified and removed outliers. Instead of using the outlier removal method proposed by Chang et al. (Chang et al., 2011), which was based on standard deviation and might unintentionally exclude non-outlier data, we adopted a comparable trimming approach from Cai et al. (Cai & Wang, 2014). We treated as outliers reproduced durations shorter than half of the objective duration or longer than two times the objective duration. Using this method, we removed 790 out of 8960 trials, which accounted for 8.82% of the total trials. This trimming strategy was chosen to avoid including accidental key presses, which could distort standard deviation values.

To evaluate the effect of intention and action-outcome delay on the temporal expansion of an outcome under intention, the average duration that participants reproduced under different conditions was subjected to repeated measures 2 (Intention/Outcome: Intended or Unintended) × 2 (Action-Outcome Delay: 250ms or 1000ms) × 4 (Objective Duration: 300ms, 450ms, 600ms, or 750ms) mixed ANOVA with the action-outcome delay being a between-subject factor and the intention, objective duration was considered as within-subject (Fig. 44). When the sphericity assumption for ANOVA was violated, Greenhouse-Geisser correction was applied to the degrees of freedom. The results revealed a significant main effect of intention [$F(1,54) = 15.960$, $p < 0.001$, $\eta_p^2 = 0.228$], indicating that intended outcomes showed a larger magnitude of reproduction than unintended (481.65ms under the intended condition and 471.08ms under the unintended condition averaged across all objective durations and action-outcome delays) (Fig. 45). There was also a significant main effect of objective duration [F(1.55, 83.73) = 527.249, $p < 0.001$, $\eta_p^2 = 0.907$] demonstrating that participants could proportionally differentiate and reproduce the objective durations (Fig. 46). Additionally, an interaction effect was observed between intention and objective duration [F(2.69, 145.32) = 4.472, $p = 0.007$, $\eta_p^2 = 0.076$], which suggests that the degree to which intention affected the expansion of perceived outcomes during reproduction varied based on the objective duration used (Fig 4). Tukey corrected post hoc analysis showed that the effect of intention was not significant at the 300ms and 400ms levels [p = 1] but was significant at the 600ms [p = 0.016] and 750ms [p = 0.002] levels.

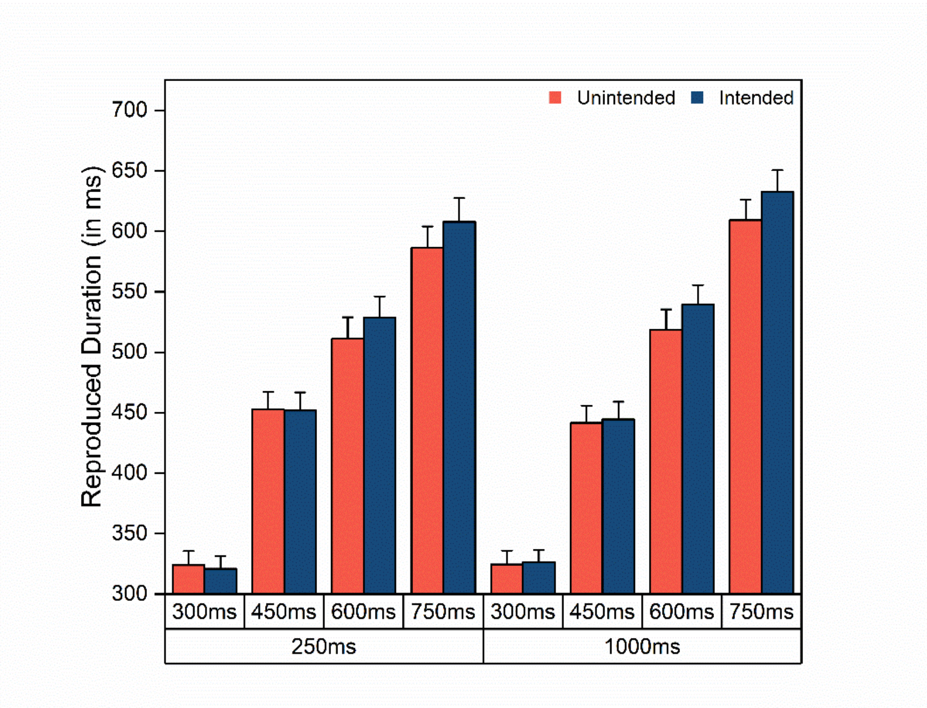


Fig. 44: Average reproduced durations across all conditions. The error bar represents the standard error of the mean. The blue column indicates reproduced durations of intended outcomes, whereas the coral column indicates unintended outcomes. The top row on the X-axis represents the objective duration, and the bottom represents the action-outcome delay. The difference between the intended and unintended duration reproductions was evident at objective durations of 600ms and 750ms only.

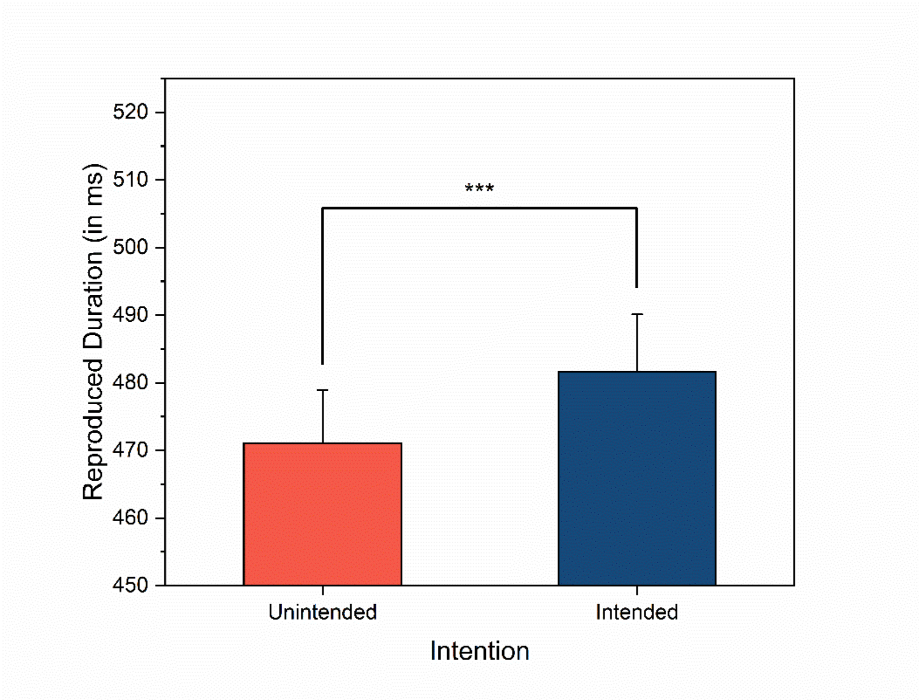


Fig. 45: Average reproduced durations across the intended and unintended conditions, aggregated across both the 250ms and 1000ms action-outcome delays and all the objective durations. The error bar represents the standard error of the mean, and *** indicates p<0.001. The blue column indicates reproduced durations of intended outcomes, whereas the coral column indicates unintended outcomes.

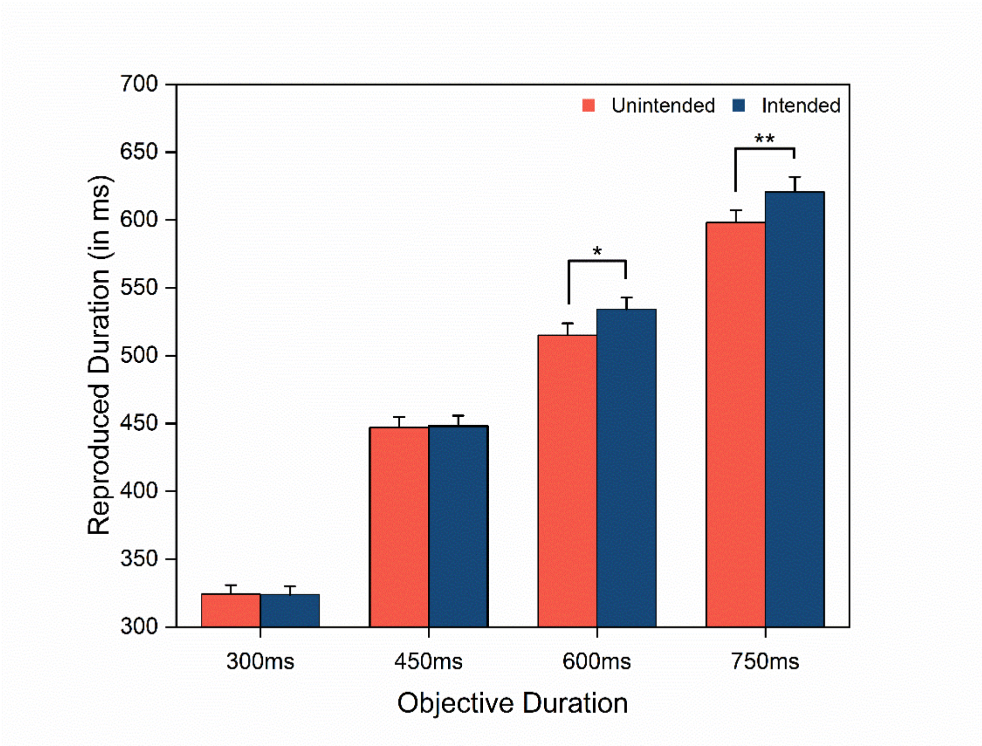


Fig. 46: Average reproduced durations across the two intention conditions, and all the objective durations collapsed across the action-outcome delays (250ms and 1000ms). The error bar represents the standard error of the mean, ** indicates p<0.01, and * indicates p<0.05. The blue column indicates reproduced durations of intended outcomes, whereas the coral column indicates unintended outcomes.

The rest, intention × action-outcome delay interaction [F(1,54) = 328.44, p = 0.517, η_p^2 = 0.008], objective duration × action-outcome delay interaction [F(1.55, 83.73) = 1.693, p = 0.196, η_p^2 = 0.03], intention × objective duration × action-outcome delay interaction [F(31.42, 144640.36) = 0.012, p = 0.997, η_p^2 = 2.172e^{-4}] were insignificant. Notably, the effect of the action-outcome delay was not significant [F(1,54) = 0.264, p = 0.609, η_p^2 = 0.005], which suggests that the different action-outcome delays did not lead to significant differences in how intention influenced the perceived expansion of outcomes across all objective durations.

In addition to our primary analysis, we computed the coefficients of variation based on the average reproduced durations in all experimental conditions to assess the variability or precision of reproduced durations. The coefficient of variation is defined as the ratio of the standard deviation to the mean of the reproduced durations. To evaluate the effect of our independent variables on the coefficients of variation, we conducted a similar 2 × 2 × 4 repeated measures mixed ANOVA on them. In cases where the assumption of sphericity for the ANOVA was violated, Greenhouse-Geisser correction was applied to the degrees of freedom. The results indicated a significant main effect solely for the objective duration [F(2.6, 140.416) = 84.575, p < 0.001, η_p^2 = 0.61], indicating that the objective duration influenced participants' task performance in each trial.

The rest, intention [F(1,54) = 0.058, p = 0.810, η_p^2 = 0.001], action-outcome delay [F(1,54) = 0.264, p = 0.609, η_p^2 = 0.005], intention × action-outcome delay interaction [F(1,54) = 0.275, p = 0.602, η_p^2 = 0.005], objective duration × action-outcome delay interaction [F(2.6, 140.416) = 0.759, p = 0.502, η_p^2 = 0.014], intention × objective duration [F(2.851, 153.973) = 0.864, p = 0.457, η_p^2 = 0.016], and the intention × objective duration ×

action-outcome delay [$F(2.851, 153.973) = 0.856$, $p = 0.461$, $\eta_p^2 = 0.016$] did not yield statistically significant results.

5.4 Discussion

Considering the information gathered from existing intentional binding effect literature, it is crucial to highlight that the action-outcome delay, as determined by the chosen methodology, is a relatively underexplored yet significant variable that shapes one's perception of the intentional binding effect. Therefore, a more comprehensive investigation is warranted to understand better how intention impacts an outcome's temporal expansion. We conjecture that the influence of action-outcome delay on the temporal processing of outcomes may be contingent on the specific outcome-related processing involved. Consequently, we adopted a modified version of the temporal reproduction task to probe the interaction between action-outcome delay and the expansion of an intended outcome. The two-phase structure of this task allows us to independently examine whether the encoding of an intended outcome is affected by the action-outcome delay without the interference of additional processing, which could be pertinent in other methodologies, such as the temporal bisection task used in prior studies.

We anticipated that the reproduced durations of intended outcomes would show no differences in reproduced durations, regardless of whether the action-outcome delay is short or long.

5.4.1 Preliminary Exploration of the Results

In line with our hypothesis, the action-outcome delay had no discernible impact on how intended outcomes were encoded. Our findings indicate a significant expansion in the temporal reproductions of intended outcomes, regardless of whether the action-outcome delay was short or long (Fig. 44). These results lead us to believe that the temporal expansion of an intended outcome may not solely depend on the action-outcome delay, as previously suggested (Makwana & Srinivasan, 2017). Instead, it seems to hinge on some other differential system related to how outcomes are processed within the intentional binding effect.

One potential aspect related to the specific processing of outcomes within the intentional binding effect might be associated with how its components are operationalized, as mentioned previously in the introduction. Methods like the Libet method emphasize the predictive aspect, while methods like constant stimuli and interval estimation are more inference-based. This distinction in component operationalization based on the methodology also extends to the sensitivity of action-outcome delays. Methods that operationalize predictive components tend to be more sensitive to shorter delays, while methods that operationalize inferential components are sensitive to longer delays (Humphreys & Buehner, 2009; Ruess et al., 2018; Wen et al., 2015a).

In our task design's reproduction phase (Fig. 43), two simultaneous processes occur: reproducing the estimated duration and comparing durations stored in memory. This dual processing during the reproduction phase is well-established in the temporal reproduction literature (Droit-Volet, 2010). The preparatory motor process for reproducing the duration could involve predictive mechanisms similar to those found in the Libet Clock methods. In contrast, the inferential processes are akin to those associated with psychophysical or temporal estimation methods when comparing and assessing the accuracy of the reproduced duration against the encoded duration.

As a result, the lack of an action-outcome delay effect may be connected to how the task's demands operationalized the components underlying the intentional binding effect during the reproduction phase. This observation challenges the presupposed notion that the temporal expansion of an intended outcome is mainly noticeable for shorter action-outcome delays and diminishes as the delay increases (Makwana & Srinivasan, 2017) (Fig. 33). Instead, it appears that the nature of the employed task plays a pivotal role, particularly in how the predictive and inferential components are operationalized within the context of the intentional binding effect.

In addition to our main findings, we also examined the coefficients of variation for each objective duration and intention condition. Our results showed no significant effects, except for differences associated with the objective duration. Specifically, we observed decreased coefficients as the objective duration increased. While this may contradict the scalar property of time (Gibbon, 1977), the results suggest that participants consistently adjusted their reproduced durations proportionately to the presented target durations (Fig. 44). Similar coefficient of variation patterns have been observed in other tasks involving the reproduction of temporal intervals, further supporting the validity of our reproduced durations (Chang et al., 2011; Lewis & Miall, 2009; Wearden, 2003; Wearden & Lejeune, 2008).

5.4.2 Could Pre-Activation of Intention Explain Outcome Expansion?

When considering the root causes of the observed expansion effect resulting from intention, it is essential to emphasize that overestimation in reproduction occurs precisely when the results align with the participants' intended choices (Fig. 44 and Fig. 45). Some might argue that this behaviour could be attributed to a mechanism of pre-activation, as earlier studies have suggested (Haggard et al., 2002b; Press et al., 2014; Waszak et al., 2012), a notion also supported by Makwana et al. (Makwana & Srinivasan, 2017) in their experiments. However, the concept of pre-activation as an explanation may not apply to our findings. There are two main reasons for this.

1. If pre-activation is valid within our context, it should also apply to shorter objective durations and
2. Pre-activation as a concept is generally understood to work for shorter action-outcome delays only.

Addressing the first reason, we observe overestimation when reproducing objective durations of 600ms and 750ms. However, this overestimation is absent for 300ms and 450ms (Fig. 44 and Fig. 46). It might be possible that the perception of intention was diminished specifically for shorter objective durations. Previous research has demonstrated that pre-activation (Bompas & O'Regan, 2006; Cardoso-Leite et al., 2010; Kok et al., 2012; Roussel et al., 2013) and intention (Blakemore et al., 1999a; Roussel et al., 2014; Waszak et al., 2012) tend to attenuate the impact of outcomes. This attenuation is particularly relevant in our context since the task involves motor activity, and pre-activation is inherently action-specific (Bays et al., 2005; Chapman et al., 1987; Stenner et al., 2014). However, it is also worth noting that the attenuatory effect does not apply to the visual domain (Schwarz et al., 2018), and since our task deals with objective durations as visual stimuli, attenuation, in turn, pre-activation of intention may not be a suitable explanation.

Secondly, prior literature on pre-activation suggests it to be regarded as a low-level process with a limited time window (Horváth, 2015; Hughes et al., 2013; Wen, 2019). In fact, previous research on the expansion of intended outcomes has found no significant effect of intention after longer delays (Makwana & Srinivasan, 2017). Taken together, it is reasonable to conclude that pre-activation is not the underlying cause of outcome expansion resulting from intention.

5.4.3 Exploring Attentional Mechanisms as an Alternative

If we cannot rely on the pre-activation of intention to account for our findings, it becomes necessary to explore alternative explanations. One possible avenue worth exploring is the role of attention. The psychological literature has extensively documented the influence of attention on time perception (Block & Gruber, 2014; Brown, 1985; Tse et al., 2004; Zakay & Block, 1996). Within our study, attention may have played a role in the expansion of intended outcomes through two plausible mechanisms based on prospective duration estimation literature.

1. Within accumulation/interruption timing models of estimation and
2. In the context of attentional models for time estimation.

Models assuming accumulation/interruption timing of estimation are defined as an accumulation of temporal information (as pulses) within an internal clock model (Church, 1984; Hicks et al., 1976; Treisman, 1963, 2013) (Fig. 16). According to these models, the to-be-reproduced events correspond to the total number of units in an accumulator that would be transferred to memory for later comparison. During reproduction, temporal information accumulates again, reflecting what was previously stored in memory. This accumulation process is generally believed to be under the control of attention (Meck, 1984; Rousseau et al., 1984; Tse et al., 2004; Zakay & Block, 1996). It is conceivable that the accumulation process could be momentarily interrupted due to the recognition of intention, causing a prolonged perception of duration. The accumulated pulses then contribute to extended reproductions proportional to the observed objective duration.

On the other hand, as per attentional models of time estimation, attention is a cognitive resource that needs allocation between a temporal and non-temporal processing component (Block et al., 2018; Brown, 1997, 2008; Hicks et al., 1976; Thomas & Weaver, 1975). The temporal processing aspect pertains to duration reproduction, while the non-temporal aspect relates to intention recognition. The term “intention” itself derives from the Latin verb “intendere”, meaning “to direct attention”. Here, conscious attention defines a target for the visuomotor system, specifically anticipating the experience of an intended outcome (Campbell, 2009). When attention is split between these two processes, it necessitates a longer duration to accumulate the units corresponding to the intended duration during the reproduction phase.

Consequently, this allocation of attention results in an expanded perception of time in proportion to the level of attention dedicated to it. However, based on the coefficients of variation we obtained, applying these time estimation models to explain our results may be challenging, as we did not observe significant effects beyond those associated with objective durations, particularly concerning intention manipulation. Instead, our observed temporal expansion may relate more to a broader attentional mechanism. Previous studies on time perception have suggested that when individuals concurrently engage in non-temporal tasks, such as recognizing intentions, during prospective timing, they tend to overestimate duration judgments when timing is prioritized as the primary task (Block et al., 2018). This aligns with established models of prospective timing (Zakay & Block, 1997), where focusing on timing can lead to overestimating prospective duration estimates. Furthermore, the choice of what to emphasize during prospective duration estimation can be influenced by the cognitive system's requirements with the current task's objective (Henderson et al., 2009).

In our experiment, when participants select an outcome, they choose an object to encounter later. Consequently, the significance they attach to the specific object they select becomes higher regarding the allocation of resources for prospective duration estimation and the depth of information processing (Billings & Scherer, 1988). This assumed relevance regarding an intended outcome may contribute to redirecting attentional resources toward its estimation, ultimately leading to the observed overestimation (Zakay, 2015).

5.4.4 Why was there no Outcome Expansion due to Intention for Shorter Objective Durations?

Considering attentional processes as a possible mechanism behind the expansion of an intended outcome would call for an account for the non-significant effect of intention at the shorter objective durations (Fig. 44 and Fig. 46). A possible explanation for this could be related to the cognitive demands of the task in question. Mental operations that are consciously performed, like intentional expectation, are understood to rely on a shared cognitive resource pool, where the involvement of multiple mental tasks can interfere with one another (Arnell & Duncan, 2002; Castellotti et al., 2022). In our study, the task involves reproducing a stimulus by pressing and holding a key while striving for accuracy aligned with the observed objective duration. This reproduction can be viewed as the primary task participants are directed to carry out. Additionally, participants recognize whether the observed target stimulus is congruent with their intentional selection.

It is plausible that pressing and holding the key to replicate the observed duration during temporal reproduction could have reduced the proportion of cognitive resources available for the retrospective memory retrieval of intention (Block et al., 2010). This is particularly significant concerning temporal estimation studies since duration judgments rely more on recall than recognition (Block, 2009). Owing to this competition for resources, it is conceivable that the representation of intention might not have reached the level of conscious awareness during shorter objective duration reproductions.

Furthermore, imposing a concurrent working memory load is a common approach for limiting the overall conscious cognitive resources accessible for a primary task (Lavie, 2005), which in this context is temporal reproduction. Conversely, intention becomes the cognitive load, as the representations need to be compared in memory during reproduction. Research has also demonstrated that a concurrent working memory load can diminish the sense of agency (Hon et al., 2013). Given that the intentional binding effect is often taken as an indicator of the sense of agency, it is reasonable to hypothesize that the lack of a significant impact of intention for shorter objective durations could be attributed to insufficient cognitive resources available for the complete recognition of the intention's representation.

Chapter – 6

Conclusion and Future Directions

6.1 Summary of the Conducted Studies

We started this thesis with the importance of measurement methodologies within the field of cognitive science, particularly in utilizing time perception to gauge various perceptual and cognitive processes. The central focus of this thesis revolves consistently around a specific cognitive measurement, namely the assessment of conscious processing through the lens of time perception. The methodological exploration of measuring consciousness via time perception commenced with the introduction of the Libet Clock method by Haggard et al. In this approach, the authors employed mental chronometry and reaction times to devise a straightforward yet sophisticated means of evaluating the perception of agency, building upon Benjamin Libet's conceptualization of the Libet Clock. This perceptual phenomenon has been identified and termed as the intentional binding effect.

The intentional binding effect serves as an implicit measure of the sense of agency. During an intentional binding episode, there is a perceptual phenomenon wherein a temporal gap between a voluntary action and the anticipated sensory consequence is perceived as shorter than its actual duration. However, a question could be posed here: when the expected sensory consequence is moved closer to the voluntary action in such an episode, does this shift represent an overall advancement in time, or does it extend temporally, counterbalancing the perceived compression in temporal perception?

The question at hand appears to find an answer through experimental studies, indicating that in an intentional binding scenario, the intended outcome undergoes temporal expansion rather than an entire event shifting in time. Nevertheless, the outcomes of these experiments appear to support only a superficial interpretation. A crucial insight derived from this experimental inquiry highlights the correlation between the action-outcome delay and the temporal expansion of the intended outcome. Specifically, the effect of intentionality on temporal expansion is observed primarily for shorter action-outcome delays, diminishing as the delay increases. Despite this, considering insights from various literature on time perception and intentional binding, it would have been expected, based on the methodology employed, to observe expansion effects for shorter delays and following longer delays, if not exclusively.

This speculation guides us to our initial experimental investigation, employing a modified version of the temporal bisection task (Chapter – 4). We conducted two experiments to explore intention's impact on an outcome's temporal dynamics. Notably, we observed a significant outcome expansion effect resulting from intention. However, this effect manifested solely in the condition with a 1000ms action-outcome delay and when the outcome onset was predictable. This finding contrasts sharply with the conclusions drawn in the study by Makwana et al. The disparate effects of action-outcome delays in the two studies can be elucidated by considering the operationalization of different components of the intentional binding effect through the cue integration theory. We also speculate that there may be variations in the operationalization of intentions. Based on the presented evidence, we contend that the study by Makwana et al. may have emphasized the predictive components associated with the intentional binding effect, given the action-guiding bar-like cue on the outcome selection slide. Conversely, our study, lacking such a cue, may have focused more on the inferential components of the binding effect, aligning with the nature of the temporal bisection task, which resembles the method of constant stimuli in measuring the intentional binding effect.

If it holds that the sensitivity of intentional binding to the action-outcome delay is contingent on how actions and outcomes are processed rather than the particular methodology utilized, then, by concurrently operationalizing both components of the intentional binding effect, we need not be reliant on the sensitivities to action-outcome delays for measuring the intentional binding effect.

In pursuit of this objective, we incorporated the temporal reproduction task in our subsequent study (Chapter – 5) to gauge the temporal expansion of outcomes under intentional conditions. The goal was to investigate whether the sensitivity of the temporal expansion of an intended outcome is tied to the action-outcome delay or the processing of outcomes. Our results unveiled a significant influence on outcome expansion resulting from intention, regardless of whether the action-outcome delay was short or long. This result indicates that the perception of intentional outcomes remains unaffected by the delay, supporting the argument that defining the sensitivity of the binding effect to the action-outcome delay need not be contingent on the methodology used.

The absence of significance in the impact of action-outcome delays on the temporal expansion of intended outcomes may be ascribed to aligning the operationalization of components of the intentional binding effect with our explanation regarding the differing effects observed in our study compared to Makwana et al.'s. More precisely, the motor act of reproduction may have elicited predictive components. In contrast, inferential components could have been engaged during the reproduction processing to ensure accuracy in aligning with the encoded duration.

The existing body of literature holds divergent views on whether the methodology dictates the employed delay in measuring the intentional binding effect (Humphreys &

Buehner, 2009; Ruess et al., 2018; Wen, 2019). Our research advocates for an operational perspective on the components associated with the intentional binding effect, thereby enhancing our comprehension of methodological influences on its measurement. Beyond our primary investigation into the significance of action-outcome delay in the intentional binding effect, specifically regarding the temporal expansion of intended outcomes, our study yielded various noteworthy secondary findings. For instance, we discovered evidence supporting intentional binding as part of a broader array of factors contributing to temporal binding, including causality. With the incorporation of causality, intentional binding, traditionally characterized as an expression of general temporal linkage, could now be viewed as a potential bi-directional mechanism for reducing ambiguity.

The findings derived from our conducted studies hold significant implications for understanding the generation of the intentional binding effect, particularly concerning the temporal dynamics of intended outcomes. In contrast to a prior study that delved into the temporal dynamics of intended outcomes, our investigation addresses the critique of free will (Gallagher, 2006). This is because our study on intention focused more on the outcome than on action selection, enabling us to measure the expansion of a genuinely endogenous and internally generated intention. It also encompasses descriptive and abstract levels of intention beyond mere motor processes. Thus, our results suggest the importance of considering relevant perceptual cues, task methodology, and action-outcome delays, as they can influence the development of intentional binding dynamics.

6.2 Limitations and Future Directions

While the studies in this thesis offer valuable insights, it is crucial to recognize certain limitations. Our inquiries predominantly focus on the temporal dynamics of the outcome within the intentional binding context rather than addressing intentional binding comprehensively. Future research is essential to solidify the understanding of outcome expansion concerning voluntary actions and integrating voluntary actions with sensory consequences. Additionally, the fixed specificity of short and long action-outcome delays at 250ms and 1000ms in both studies restricts our observations to limited perspectives. To ensure the robustness of the observed results, broader ranges of action-outcome delays are necessary for testing and validation.

Subsequent research in this field could delve deeper into the operationalization of intention as well as component operationalization and delve into the underlying reasons for this subjective expansion, utilizing established time perception models such as the clock model (Treisman, 1963, 2013; Wearden et al., 2007). It would be valuable to explore which component, whether the pacemaker or switch/gate, contributes to the temporal expansion of an intended outcome instead of attributing the observed expansion effects solely to a general attentional process to explain intention-related outcomes. Moreover, a better understanding of the interplay between causality and intention could offer more profound insights into the mechanisms underlying intentional binding.

6.3 Conclusion

In conclusion, this thesis constitutes a substantial contribution to comprehending the diverse facets of the intentional binding effect, particularly the temporal dynamics of outcomes within this perceptual phenomenon. It underscores the significance of methodological factors and emphasizes the need to carefully examine how they can influence the development of intentional binding and, consequently, the sense of agency. Reflecting on the research journey undertaken for this thesis, we encountered challenges related to collecting and analyzing behavioural data, gaining valuable insights into the critical importance of employing proper methodologies to measure cognitive processes. As demonstrated in our examination of Makwana et al.'s study, inadequate methodological approaches can potentially obscure conclusions regarding phenomenologically thin concepts like the sense of agency or intricate perceptual processes like the intentional binding effect. In summary, this research advances our comprehension of the intentional binding effect and time perception and paves the way for future exploration and innovation in the field. The speculative evidence for causality and the proximal-distal intent framework offers a philosophical perspective on operationalising intentions within the intentional binding effect or the sense of agency.

Appendix

Intentions refer to the mental states or processes that precede and accompany our actions. They involve a conscious decision to perform a particular action with a specific goal in mind. Intentions play a crucial role in the sense of agency, which is the feeling of being in control of one's actions and their consequences. The sense of agency involves the perception that one's actions are purposeful and that they have an impact on the external world. Intentions are a crucial component of this sense, representing the individual's conscious choice to engage in a particular behaviour. When we form intentions, we commit to a specific action, contributing to our perception of agency.

Although the philosophical and phenomenological aspects related to the idea of intention are outside the scope of this thesis, we have found evidence for a categorical distinction across studies in chapter – 4, in line with previous literature who have properly operationalized various intentions within the intentional binding effect (Vinding et al., 2013, 2015). Therefore, it felt necessary to allow ourselves to be at least accompanied by the ideas related to the philosophy of intentions for a broader perspective on intentionality, intentional binding, and the sense of agency, which are the core discussions in this thesis.

What are Intentions?

The causal theory of action asserts that behaviour qualifies as an action when it stems from a specific psychological cause or involves a particular psychological causal process (Davidson, 1963). Intentions, within this framework, are considered distinctive and sui generis mental states with complex functional roles, playing a crucial part in the causal sequence of actions. These intentions can be understood as mental states encapsulating conscious desires and motivations to achieve specific outcomes, characterized by purpose and goal orientation. Unlike fleeting thoughts or wishes, intentions involve a conscious commitment and determination to act in pursuit of a desired outcome. Their unique features underscore their pivotal role in human agency and decision-making processes, encompassing key components such as goals or outcomes, deliberation and planning, motivation, action initiation, and flexibility. Intentions are generally understood to involve several key components (Brand, 1982):

- Goal or Outcome: Intentions are directed toward specific goals or desired outcomes, representing the envisioned end state that individuals aim to achieve.
- Deliberation and Planning: They often involve a process of deliberation and planning arising from either conscious decision-making or unconscious automatic processes.
- Motivation: Intentions reflect a person's motivation or drive to engage in a particular action and provide the impetus for initiating and sustaining behaviour towards the intended goal.
- Action Initiation: They play a crucial role in initiating actions, serving as mental states that prompt the initiation of behaviour towards the intended goal.
- Flexibility: intentions exhibit flexibility, allowing for adjustments based on changing circumstances or new information, and they can be revised, abandoned, or modified as needed.

The specificity and strength of intentions can vary, ranging from vague aspirations to well-defined plans with clear timelines and action steps. Furthermore, intentions differ in conscious awareness, with some being explicitly known and articulated while others operating more subconsciously. In summary, intentions, as conscious mental states driving actions, are central to human agency and decision-making, serving as a bridge between thoughts and behaviour, shaping actions, and guiding individuals towards specific goals. The study of the nature and significance of intentions has been a focal point in philosophy, psychology, and cognitive science, and this appendix explores the multifaceted nature of intentions, delving into their defining characteristics, the concept of intentional action, and the intriguing duality inherent in them. Although a few of these concepts are broadly relevant to the context of this thesis, they are speculative and not the focus of this thesis.

How an Intentional Action is Defined

Intentions are essential to human existence and are commonly considered the foundation of conscious thought (Bratman, 1987; Searle, 1979, 1983). They play a role in various complex tasks, such as when I intend to write this thesis or decide to return to my room after a day's work. Defining an intention does not involve describing its sensory qualities; instead, it is defined based on the action it aims to accomplish, like the specific goal towards the completion of this thesis. Therefore, intentions are closely tied to actions or the events and states they seek to bring about. When an agent voluntarily commits an action, it can be categorized as intentional. The key components of intentional actions include the occurrence of a movement, the internal generation of behaviour through goal-directed thought, and the exclusive origin of this generated behaviour from within the agent, denoted as the 'I'.

Intentions are mental states internally generated by this 'I'; subsequent actions that change the external world are regarded as intentional actions. It is important to note that intentions need not be exclusively conscious, as seen in cases like the alien or anarchic hand syndrome (Della Sala et al., 1991). However, in the context discussed here, regular intentional action involves first-order consciousness (consciousness of intention) and second-order consciousness (self-consciousness, 'I').

This dual order of intentions aligns with the dominant neuroscientific perspective on the consciousness of intentional action, known as the central monitoring account (Frith, 1992). According to this account, when an event occurs, it is crucial to determine whether the conscious agent caused it or if it was an external event by chance or caused by another agent in the environment. The central monitoring process involves monitoring intentions and comparing the predicted consequences of those intentions with perceptual events in the environment (Fig. 4). This process plays a critical role in distinguishing internally generated events from external events, separating perceptual awareness from the self-generated mental states associated with willed action.

Generative and Constructive Accounts of Intention in Action

Elaborating on the central monitoring process related to conscious intention, consciousness has at least two distinct contributions to the intentional action process (Baldwin & Baird, 2001).

- The Generative Account: This account, prevalent since Descartes and his famous statement "I think, therefore I am" (Cogito, ergo sum), asserts that all conscious states initiate a sequence of events culminating in movement (Newman, 2023). According to this perspective, conscious states have a causal influence over the material body, leading to purposeful actions.
- The Constructive Account: In contrast, the constructive account has received less scientific attention. However, it posits that consciousness provides a foundational set of conditions against which intentional action unfolds. In other words, conscious

awareness of our intentions and the resulting bodily and environmental consequences is essential to construct the possibility of intentional action.

In summary, the generative and constructive views of conscious intention diverge in their emphasis on the roles of consciousness. The generative perspective underscores how conscious states causally influence the physical body, emphasizing their role in generating actions. On the other hand, the constructive viewpoint highlights how conscious representations contribute to the sense of 'I' as an agent, emphasizing the role of consciousness in constructing the foundation for intentional actions and ultimately leading to the sense of agency, shaped by consciousness, as a crucial factor motivating individuals to engage in intentional actions.

Conceptual Framework of Intentions

According to the causal theory of action (Davidson, 1963), an action qualifies as such only if it possesses a specific psychological cause or involves a particular psychological process. Causalism can manifest in various forms, depending on the interpretation of an action-relevant causal sequence or which part of the causal sequence is identified as the action. Therefore, intention can play a dual role in a causal action sequence, with some functions between the initial formation of intention and the initiation of action and others involved in guiding and monitoring action from initiation to completion. This dual nature has led many philosophers, such as John Searle, Michael Bratman, Myles Brand, and Alfred R. Mele, to adopt a dual approach to intentions in action.

- John Searle (Searle, 1983) distinguished between prior intentions and intentions in action.
- Michael Bratman (Bratman, 1987) distinguished between future-directed and present-directed intentions.

- Myles Brand (Brand, 1984) distinguished between prospective and immediate intentions.
- Alfred R. Mele (Mele, 1992) distinguished between distal and proximal intentions.

Based on the theories proposed by the philosophers above, when we consider a duality of intentions in action, according to Pacherie, there are two implicit problems associated with them (Pacherie, 2008).

- The two forms of intention are mutually exclusive. i.e., the role of one intention is over when another is in place.
- Action guidance and monitoring are generally assumed to be the sole responsibility of the second intention. i.e., the second intentional form is considered more abstract and higher order than the first.

Pacherie proposes a conceptual framework in which intentions are organized hierarchically in cognitive processes. Each intention has a specific role but is not mutually exclusive with other intentional forms during a causal action sequence. This hierarchical structure offers a holistic approach to understanding the phenomenology of intention in action. Pacherie introduces three action stages, each corresponding to a different level of intention, and each level of intention plays a distinct role in guiding and monitoring action.

When we think about intentions, it is not a system where we exclusively decide what intention is required for an action. Instead, it is an ordered hierarchy. For example, my intention to finish writing this thesis involves many sub-intentions to be satisfied. However, I do not do so independently when I consider these sub-intentions. I still consider my overarching intention to finish writing along with other sub-goals I intend to complete. In the same way, Pacherie suggests that the idea of intentions is, in fact, a hierarchy with macro-level dynamics between each form of intention. The threefold distinction among intentions in

Pacherie's framework includes Distal Intentions (Global), Proximal Intentions (Local), and Motor Intentions (Action-Specific).

Pacherie suggests that this three-tier hierarchy is based on analysing their complementary functional roles, the content they hold, and their temporal scales within a causal action sequence. The framework emphasizes that intentions are not momentary, isolated events but are embedded within a broader context of meaning and purpose. By distinguishing between distal, proximal, and motor intentions, the framework highlights that immediate and overarching intentions, long-term goals, desires, and motivations influence actions.

Distal Intent

Distal, long-term or ultimate intentions are comprehensive and overarching objectives that steer behaviour over an extended duration. These intentions are future-oriented, encompassing the aspiration to achieve specific outcomes or states that may necessitate multiple steps and actions for realization. Distal intentions imbue individuals with a sense of purpose and direction, influencing their behaviour and decision-making over time.

Pacherie's concept of distal intentions closely aligns with Bratman's idea of future-directed intentions (Bratman, 1987). Distal intentions serve as endpoints for practical reasoning concerning goals, means, plans, and interpersonal coordination. In essence, they are involved in the high-level rational guidance and monitoring of actions. This rational guidance, characterized as tracking control, ensures the successful implementation of each successive step before progressing to the next. Importantly, distal intentions are not bound by specific temporal constraints; they are context-free and not heavily contingent on an agent's present situation. This characteristic allows them to, in principle, remain detached from the current circumstances of the agent. The content of distal intentions comprises both conceptual and partly descriptive elements.

Proximal Intent

Proximal intentions, as described earlier, denote immediate or short-term goals and intentions that direct behaviour within a specific context. These intentions encompass the immediate steps or actions necessary to achieve a larger goal or outcome. They are situated within a particular situation involving cognitive, perceptual, or social aspects and motor actions.

As outlined by Pacherie, the primary functions of proximal intentions revolve around generating an intention to commence action immediately. The temporal duration of these intentions is understood to span from the initiation of action to its completion. The specific content of proximal intentions is derived from distal intentions, which serve as overarching guiding plans. This content inheritance allows proximal intentions to embed themselves within the context of the action. The temporal anchoring property of proximal intentions (Barresi & Moore, 1996) distinguishes them from distal intentions. In contrast to distal intentions, which are concerned with the overall goal and adhere to global consistency and coherence constraints, proximal intentions exert control over the immediate goal. For instance, when playing a musical piece, handling the current note corresponds to proximal intentions while maintaining a constant tempo and rhythm is governed by distal intentions.

Motor Intent

Motor intentions pertain to specific plans or mental representations of movements or actions that an individual intends to execute. They focus on the immediate implementation of physical actions and are closely linked to the motor system. Motor intentions are more concrete and specific, directly related to the physical execution of behaviours. Unlike proximal and distal intentions, which handle high-level forms of action guidance and monitoring, with the former having a temporal anchoring aspect, motor intentions involve what is referred to as motor representations.

Motor representations are basic, sub-conscious systems that carry out the immediate goals set by proximal intentions. However, for the purposes of this thesis, the concept of motor intentions is not considered extensively because it deals more with the dynamics of the motor system and is not immediately associated with conscious intentions, which is the focus of this thesis. Research by Pisella et al. (Pisella et al., 1998) indicates that motor intentions are typically self-correcting and may have their dynamics not entirely governed by proximal intentions. Additionally, the motor system may have limited access to information from other cognitive systems, including those underlying conscious perception (Bridgeman & Graziano, 1989; Haffenden & Goodale, 1998; Marcel, 2003). Since the intentional binding effect is generally considered prone to such conscious perceptions, we will not deal with the specificity of motor intentions.

In summary, while motor intentions specifically address motor actions and involve the planning and execution of movements, being a subset of proximal intentions, the latter can encompass a broader range of goals or intentions beyond just motor actions. Proximal intentions may include cognitive processes, perceptual goals, or intentions related to social interactions, depending on the specific context. A critical distinction between proximal and motor intentions is that intentions are traditionally directed at actions, whereas motor intentions are directed at mere movements. Consequently, the discussion in this thesis will focus solely on proximal and distal intentions, excluding the consideration of motor intentions.

General Dynamics of Proximal and Distal Intent

According to Pacherie's conceptual framework, the three levels of intention—distal, proximal, and motor—do not operate in isolation, as suggested by earlier philosophies. Instead, they coexist and collectively form an intentional cascade, each level exerting specific control over the action. Distal intentions are identified as the causal initiators, triggering proximal processes and providing them with a general action plan. Proximal processes ground this plan in the current context, refining the action representation to align with the situation.

Building on Searle's componential view of action (Searle, 1979, 1983), which posits that an action comprises both movement and the intention guiding it, and drawing insights from Frankfurt's argument that the key distinction between action and mere bodily movement lies in the person's relation to the body's movements (Frankfurt, 1978), Pacherie proposes that an action, in its minimal sense, is an intentional movement. This intentional movement consists of the bodily movement and the M-intention that causes and guides it. In this context, intentional actions involve intentional movements directed by proximal intentions, which are, in turn, regulated in the comprehensive sense by distal intentions. Pacherie contends that distal intentions align with the traditional understanding of intentions as mental states directed at actions.

Pacherie notes that the dynamics of the three-level cascade do not imply the presence of the entire intentional cascade for every action. Some actions may occur spontaneously without distinguishing between distal and proximal intentions. For instance, distal intentions continue to guide and control the action even after giving rise to a corresponding proximal intention. Similarly, the proximal intention persists even after the generation of the corresponding motor intention.

Categorical Difference of Intentions in the Intentional Binding Effect

In the intentional binding effect context, "operationalized intention" refers to how intention is defined, measured, or manipulated in empirical studies. It involves translating the abstract concept of intention into observable variables or experimental conditions that can be objectively assessed or controlled.

Recent research by Vinding et al. (Vinding et al., 2013, 2015) suggests that the operationalization of intention in studies may inadvertently capture different levels of intention. They conducted experiments recognizing that researchers often contrast voluntary and non-voluntary actions when exploring the sense of agency and the experience of action. However, they rarely investigate how different types of intention may influence this experience. Building on Pacherie's conceptual framework, they distinguished between two types of intention: proximal and delayed. This operationalization involved varying the delay between the formation of intention and the execution of the corresponding action.

The researchers hypothesized two potential outcomes. First, if proximal and delayed intentions involve distinct cognitive processes, the results should show apparent differences based on the type of intention. Second, if both types of intentions represent the same cognitive process extended in time, any distinction between them would be conceptual rather than functional.

The observed results indicated that delayed intentions and proximal intentions had different impacts on the experience of action. Notably, there were significant differences in the intentional binding effect based on the operationalized intention. The binding effect was notably increased when there was a delay between the intention to act and the actual execution of the action, compared to scenarios where there was no delay between intention and action.

Possible Operationalization of Intentions Based on Methodology

Considering the research conducted by Vinding et al., it is reasonable to suggest that the methodology used to measure the intentional binding effect allows for a categorical distinction in operationalizing the type of intention employed. Our studies on the temporal expansion of intended outcomes (refer to chapters 4 and 5 on pages 78 and 103, respectively) provide speculative support for this idea. This evidence complements the dual component theory of intentional binding discussed earlier (refer to page 70).

Furthermore, integrating the proximal intent distal intent framework into the study of intentional binding offers a more nuanced comprehension of human agency and decision-making processes (Plaks & Robinson, 2017). Examining both the immediate and overarching aspects of intentions allows researchers to investigate how immediate actions are influenced by broader intentions and how these intentions, in turn, shape subsequent actions. This approach facilitates a deeper understanding of the interplay between immediate goals, long-term motivations, and the overall sense of agency.

Additionally, the framework bridges the gap between the subjective experience of agency and the objective analysis of behaviour. Recognizing the dual nature of intentions provides a more comprehensive explanation of the diverse aspects of intentionality, encompassing both the subjective feeling of agency associated with immediate actions and the broader cognitive processes that underlie our goal-directed behaviour. Therefore, guiding research on the intentional binding effect in this direction is crucial.

Related Publications

Donapati, R. R., Shukla, A. and Bapi, R. S. (2024) 'Action-outcome delays modulate the temporal expansion of intended outcomes', *Scientific Reports*, 14(1). doi: 10.1038/s41598-024-52287-x.
(Accepted and Published)

Donapati, R. R., Shukla, A. and Bapi, R. S. (2024) 'Outcome Processing Drives Action-Outcome Delay Sensitivities over the Temporal Expansion of Intended Outcomes', *PLoS ONE*.
(In Submission)

Donapati, R. R., Shukla, A., & Bapi, R. S. (2023). Intended Outcomes Expand In Time: Evidence from the Temporal Reproduction Task. *Proceedings of the Annual Meeting of the Cognitive Science Society*, 45. Retrieved from https://escholarship.org/uc/item/0d02z417
(Accepted and Published)

Donapati, R. R., Shukla, A. and Raju, B. S. (2022) 'Differential Effects of Delay on Intended Outcome: Evidences from Temporal Processing', *Annual Conference of the Association for Cognitive Science (ACCS-9)*. IIT Delhi.
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