SENSORIMOTOR MECHANISMS OF TIME PERCEPTION: INVESTIGATING TEMPORAL BINDING EFFECT THROUGH PREDICTIVE MECHANISMS

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2023

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Thesis submitted to the

Institute for Graduate Studies in Social Sciences

in partial fulfillment of the requirements for the degree of

Master of Arts

in

Cognitive Science

by

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Boğaziçi University

2023

Sensorimotor Mechanisms of Time Perception: Investigating Temporal Binding Effect through Predictive Mechanisms

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DECLARATION OF ORIGINALITY

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- this thesis contains no material that has been submitted or accepted for a degree or diploma in any other educational institution;
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ABSTRACT

Sensorimotor Mechanisms of Time Perception: Investigating Temporal Binding Effect through Predictive Mechanisms

Temporal binding refers to the perception that two events, which are related in terms of their cause and effect, occur closer together in time than they actually do. This effect not only creates a perceived cause-and-effect relationship but also compresses the time interval between events. Since the influential article on the intentional binding effect was published by Haggard, Clarke, and Kalogeras in 2002, researchers put forth several necessary conditions for the explanation of the effect. While proximity in time and predictability play a crucial role, it is primarily causality that determines the outcome rather than intentional action. According to Buehner (2012), causality is the fundamental factor behind the effect. Despite the productive work done in this area, there is still much to be discovered about the mechanisms that underlie temporal binding. In this thesis, we aim to investigate two main aspects of temporal binding. Firstly, we aim to determine whether the act of performing an action alone is sufficient to induce temporal binding or if outcome prediction plays a critical role. To achieve this, we conduct a series of experiments to compare congruent and incongruent outcomes, with the aim of uncovering the underlying mechanisms that cause this intriguing time distortion. Secondly, we examine the various factors that contribute to temporal binding. In addition to outcome prediction, we investigate the role of temporal control, which is the ability to dictate timing, in shaping our perception of time. We aim to understand how different factors affect temporal binding by analyzing each component.

ÖZET

Zaman Algısının Duyusal Motor Mekanizmaları: Öngörü Mekanizmaları Üzerinden Bir Zamansal Kısalma İncelemesi

Zamansal kısalma, nedensel olarak ilişkilendirilmiş olayların, ilişkisiz olaylara kıyasla daha yakın bir zaman aralığında algılanma fenomenini ifade eder. Bu etki, sadece bir neden ve sonuç arasında algılanan bir çekim yaratmakla kalmaz, aynı zamanda olaylar arasındaki zaman aralığını daraltır. Zamansal kısalma üzerine temel bir makale yayımlandığından beri (Haggard, Clarke ve Kalogeras., 2002), araştırmacılar etkinin meydana gelmesi için gerekli koşulları belirlemişlerdir. Öngörülebilirlik ve ardışıklık kritik unsurlar olmasına rağmen, sonuç olarak niyetli eylem değil, neden-sonuç ilişkisi başlıca sonucu belirler. Buehner (2012)'e göre, etkinin temel faktörü nedenselliktir. Bu alandaki üretken çalışmalara rağmen, zamansal kısalmanın mekanizmalari hakkında hala keşfedilmeyi bekleyen çok şey bulunmaktadır. Bu tezde, zamansal kısalmanın iki temel yönünü araştırmayı amaçlıyoruz. İlk olarak, bir eylemi gerçekleştirmenin tek başına zamansal kısalma yaratmak için yeterli olup olmadığını veya sonuç öngörüsünün kritik bir rol oynayıp oynamadığını belirlemeyi amaçlıyoruz. Bu amaçla, uyumlu ve uyumsuz sonuçları karşılaştırmak için bir dizi deney gerçekleştiriyoruz, bu ilginç zaman bozulmasına neden olan ve altında yatan mekanizmaları ortaya çıkarmayı umuyoruz. İkinci olarak, zamansal kısalmaya katkıda bulunan çeşitli faktörleri incelemekteyiz. Sonuç öngörüsüne ek olarak, zamanı belirleme yeteneği olan zamansal kontrolün, zaman algımızı şekillendirmedeki rolünü araştırıyoruz. Hedefimiz, her bir bileşeni analiz ederek farklı faktörlerin zamansal kısalma üzerindeki etkisini anlamaktır.

ACKNOWLEDGMENTS

Firstly and most importantly, I would like to give many thanks and sheer gratitude to my thesis advisors, Dr. Inci Ayhan and Dr. Lucas Thorpe. Throughout this process, even before starting my master's program here at Bogazici University, Dr Ayhan shared my enthusiasm for coming here and working with her. She helped me in more ways than one and was understanding and considerate at all stages. And thank you to Dr. Thorpe for assisting me from start to the very end, for sharing your two pennies with me on everything and all the improvements that we made.

My sincerest appreciation goes out to all my dear mates and colleagues at the lab, for engaging rather enlightening conversations with me and supporting me in any way possible. I would like to give special thanks to Aylin and Hasnun, who gave their time to contribute to the data collection process and meetings. I would also like to thank Elif Kaplan for answering my questions and giving great recommendations on data analyses.

To my mum

and my long-lost mate newton

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CHAPTER 1

INTRODUCTION

Temporal binding is a phenomenon where two subsequent events- initiated by action or inferred to be the result of causal relations- are perceived as closer together in time. The effect was first dubbed as 'intentional binding' since the initial experiments involved voluntary vs involuntary conditions to measure the action-outcome shifts (Haggard, Clark, and Kalogeras., 2002). Over 20 years, much research has been done to replicate the binding effect utilising different designs and methodologies (see chapter 2); however, the underlying mechanisms of temporal binding are still in question. The general framework for explaining the effect was initially claimed to be the forward action mechanisms (Moore and Haggard 2008; Moore et al. 2009) and action-specific predictions (Haggard & Clark. 2003; Kilner et al. 2007). When an intentional action produces a highly contingent and predictive outcome, we experience the onset of action occurring later than it actually is and the outcome earlier. Additionally, temporal contiguity (i.e., temporal proximity of the action and its effects) keeps the predictions' calculated discrepancy minimal, contributing to the binding effect. In one aspect, this thesis aims to examine if action is sufficient for the effect and if action-outcome-specific predictions are necessary by comparing both self-triggered with externally triggered stimuli and predicted and unpredicted action effects.

While Haggard et al. (2002) propose the binding effect as a consequence/derivative of intentional movements, there is an alternative explanation to be considered, which concerns itself with causal vs non-causal conditions. Haggard et al. (2002) did not find a binding effect when unintentional actions are performed, which indicated the role of intentional actions, therefore concluding that the binding effect occurs as a function of intentional action. However, the causality framework could be seen as superimposed on intentionality, connected to a copious extent, which implies that the causality principle drives temporal binding rather than intentionality (Buehner & Humphreys, 2009; Buehner, 2012). By removing intentional action from the temporal binding equation, the causality account establishes that if event one is perceived as the cause of event two, then the time between these events compresses.

By this reasoning, the causality account asserts that:

(1) Intentional action is not necessary for temporal binding to occur.

(2) Establishing causal relations between events is necessary for the binding effect to occur, as intentional action alone is insufficient.

Regarding these two accounts, however, they need not be mutually exclusive. Changing the name of the effect from intentional binding to causal binding would not disregard the role of intentional action altogether. Intentional binding can be put under causal binding as a respective case of causal binding if it includes the apparent perception of perceiving the first event as causing the second event, which is almost always the case. An exception of a broken link between intentional action and its effect would contain a condition that the experimenter explicitly informs the participant that their action did not cause the effect they had been presented, despite the participant's belief that it did. In situations where people have control over the outcome via intentional actions, binding is more potent because the cause-and-effect relationship is less ambiguous. However, when observing the actions of others, especially machines, there is more uncertainty about the causal associations. This account regards intentionality as a boost effect within the causality and claims that if an experimental design includes an intentional action condition, this condition's binding effect magnitude will be more considerable than other causal conditions (Shiloh et al., 2017).

1.1 The perception: shifts of events or time compression?

Although various methods could be implemented to study temporal binding (interval estimation, reproduction, stimulus anticipation, simultaneity judgments, to name a few), the prevailing method remains the clock-face rotation method (Libet et al. 1983). Many researchers have observed that time perception can be influenced by how we perceive events and intervals. However, a more effective way to study the contraction of intervals is by investigating interval timing itself. This can be done in a number of ways, for example, verbal or categorical estimation tasks, interval reproductions tasks, or comparison tasks such as the method of constant stimuli. This is because methods that rely on perceived events, like the Libet clock method, may not be as accurate due to the given presupposition of compressed interval assumption beforehand. Looking at a clock face and reporting the start and the end of one event brings extra attentional load to the experimental blocks. Also, interval estimation and reproduction methods are in use, albeit in scarcity, especially interval reproduction.

Seemingly, the binding effect manifests itself in both event shift and interval estimation methods; be that as it may, there are two standpoints to choosing the Libet clock or other psychophysical methods:

(1) If the objective is to explain the effect as shifts in perception, therefore, events moving to or away from each other, one should favour the Libet clock method.

(2) However, if the inter-event interval compression brings about temporal binding, one should expect to see the effect when using other methods like estimation or reproduction.

Whether it be the shifts of events or temporal compression of an interval, both explanations could accurately describe the temporal binding effect.

Further, the events in question are infrequent in everyday life, so we cannot easily construct causal or prediction-based relations between them based on their naturality. Keypresses, pressing nobs to auditory, visual, or tactile sensory events combination, require pre-learning or adaptation phases to acquire said relations. Previous research has rarely used interval reproduction as a method and adaptation phases for abstract sequential events. As we are interested in the discussion of the compression of time and whether prediction-based inferences contribute to the binding, this thesis aims to provide supplemental evidence of the observation of the effect using interval reproduction and adaptation phases (top-up or training trials to learn event mappings prior to experimental phases) to actualise the relationship between abstract events.

1.2 Is binding the result of forward action mechanisms?

An alternative explanation is that temporal binding is not dependent upon forward action mechanisms or action-outcome prediction (Hughes et al., 2013). Rather than predicting action-outcome contingencies, the involvement of other predictive processes like temporal control and temporal prediction should suffice for the effect to occur. In their review paper, Hughes et al. (2013) propose four predictive factors influencing the binding effect: motor identity prediction, temporal control, temporal prediction, and non-motor identity prediction. The hypothesis was that temporal control should be solely enough for an underlying process of temporal binding.

Hughes et al. (2013) defined said processes as:

Table 1. Predictive processes defined by Hughes, et al., (2013), p.3.

Concept	Description
Temporal Prediction	The ability to predict the specific point in time at which a sensory event will occur.
Temporal Control	Using one's actions to control the timing of a stimulus, often involving precise temporal prediction.
Non-Motor Identity Prediction	Predicting the specific identity of a sensory stimulus without any direct involvement of actions.
Motor Identity Prediction	Predicting the identity of a sensory event based on an action or motor behavior performed by the individual.

According to the review paper by Hughes et al. (2013), there are four predictive factors influencing the binding effect: motor identity prediction, temporal control, temporal prediction, and non-motor identity prediction. The hypothesis was that temporal control should be solely enough for an underlying process of temporal binding. In the hopes of shedding some light on this hypothesis, this thesis aims to find the contrast between temporal control, prediction, and identity control and whether temporal control without temporal prediction is a strong predictor for binding using a new learning-based experimental design. A novel feature of this thesis is that we introduce an experimental paradigm in which we disentangle temporal prediction from temporal control in two blocks employing random intervals within a range as well as fixed intervals. In four temporal control blocks, we used both fixed and random delays between the action and the effect, changing the definition of temporal control to the expectation of observing an effect at some point in time as a function of performed action, therefore dissociating temporal prediction from temporal control. As stated above, we conceptually made use of the temporal prediction definition as the power to anticipate the exact timing of a second external stimulus after the occurrence of the first stimulus or event. Identity prediction, on the other hand, was defined similarly to Hughes et al. (2013) but with the exclusion of the action term. In our study, identity prediction referred to predicting which sensory outcome would result from both a participant's action in a specific block and an external event as the initiator in another.

In this case, we could attribute the result of the effect to either the action being performed or the causality between the two events or maybe both these processes are relevant cues in the context of experimental design. How is it that when an action causes an effect, we perceive the interval between them as shorter compared to seeing or listening to two externally triggered sensory events? In another aspect, this thesis aims to differentiate and contrast individual processes, namely identity prediction, temporal control, and temporal prediction, whether temporal control- it also possesses temporal prediction- is at the top of the underlying mechanism suspected list. Our goal is furthermore to look into the definition of these processes, in particular, de-couple temporal prediction from temporal control and gain insight into the individual forces of temporal binding.

The research questions and hypothesis for this thesis can be stated as follows:

I). The predictive process of temporal control alone would be sufficient to cause the binding effect (Hughes et al. 2013). Ultimately, by changing the concept of temporal control to dissociate it from temporal prediction in our experimental design, we hypothesize that temporal control without fixed interval prediction is still going to be the root cause for binding to occur.

II) Precise identity prediction between the two events will not influence the binding effect, yet reaction times might be affected, thus telling a different story (Haering & Kiesel, 2014).

III) Contrary to what Haggard et al. (2020) expected from predictive forward mechanisms, learning that there is a 100% event identity mapping in the acquisition phases of experimental blocks will not affect the magnitude of binding in the test phases when incongruency is introduced (Desantis et al., 2012).

IV) As for the novelty of the study, learning the interval between the two events in the acquisition phases and then manipulating or keeping the interval the same in the test phases might reveal some newfound effect on binding and something new to be added to the research in general.

We think that the usage of catch trials, gathering reaction times data as manipulation checks, and changing the design from fully randomised to controlled in terms of keeping some variables constant across experiments can boost the strength of the hypotheses above.

We start by describing the temporal binding effect, how it is considered to be coming from different frameworks, and methodologies used in search of its discoveries in Chapter 1. In Chapter 2, we provide detailed descriptions of various frameworks that explain the binding effect and identify their similarities and differences. Additionally, in Chapter 2.4, we introduce the methods that have been used to date, and in 2.5, the experimental designs that are close to us in comparison and what particular concepts or components we changed. The depiction of the design, procedure and results of the experiments is reserved in Chapter 3. We discuss the findings and implications of the thesis and introduce a new philosophical framework of temporal binding in Chapter 4.

CHAPTER 2

BACKGROUND

2.1 … Binding?

2.1.1 Intentional binding

In 2002, Haggard et al. conducted a study where they discovered the intentional binding effect, which is a perceptual illusion of compression of the time interval between self-made actions and their outcomes. The researchers used the Libet clock method (Libet et al. 1983) to conduct the study. In three experimental conditions, participants were asked to estimate the time between their actions and the outcomes by observing a clock face that rotated at a speed of 2,560ms per rotation. Before the experimental conditions, participants judged the onset of action and outcome events to mark the baseline measurements. In four types of baseline trials, first, participants made a voluntary press at a time of their choosing and marked the onset time of their action on the clock, second, transcranial magnetic stimulation (TMS) via motor cortex twitched their finger involuntarily, and they judged the time of the twitch, third, they heard a TMS-induced click and received a sham-TMS over parietal cortex which did not end in involuntary muscle twitch, and participants reported the time of the click noise, lastly, without any voluntary or involuntary action they listened a 100ms tone and marked the time when they heard it.

Three experimental conditions were voluntary, involuntary (TMS-induced), and sham-TMS movement. In three conditions, the first event was followed after 250ms by a tone. Participants reported either the first or second event in separate blocks in the experimental conditions. Compared to the single-event baseline conditions of action or the tone, Haggard et al., 2002 discovered that in the voluntary action condition, the events became closer together bi-directionally; thus, the action was perceived later and the tone earlier. Contrasting voluntary and involuntary conditions, they reported a repulsion effect in the TMS-induced condition where the interval grew longer, or the two events shifted away. The sham-TMS condition did not differ significantly from the baseline conditions.

In a second experiment, they added temporal interval manipulation conditions using three intervals: 250, 450, and 600ms. Participants marked the onset of their actions and tones in fixed intervals or randomized combinations of all three interval conditions in six new operant blocks. They found that the binding effect was downsized both after 450ms and also in randomized blocks where the intervals were varied.

Haggard et al. (2002) dubbed the effect as intentional binding, and the implications of this study were:

I.) When an intentional action triggers an event, they attract toward each other, which taps into the forward action mechanisms and motor control. The awareness of action made the action-outcome causal link coherent through intentionality and feedback of afferent-efferent copies of motor control.

II.) If the action is induced involuntarily, the repulsion effect ensues between the two events in which there could be a broken causal link in the event perception.

III) The forces underlying the effect could be temporal contiguity and temporal predictability.

What was the running cause behind the intentional binding effect? Haggard et al. (2002) proposed that the forward action mechanisms (Blakemore et al., 2000) and motor control (Wolpert et al., 1995; Wolpert & Miall., 1996; Wolpert, 1997) are behind these results. According to the forward action theory, when an action is being performed, the brain sends an efference copy of the predicted signal of a consequence of that action. If the postdictive sensory feedback matches the predicted signal, the calculated discrepancy will be reduced to approximately zero. We are looking for a concordance between our predictions which comes with voluntary action and the effect of the action. In the TMS-induced condition, a mismatch is detected by the discrepancy calculator, namely the comparator in the forward action model. When the comparator informs back that the action predictions fit the outcome prediction, two events become closer, transpiring into the intentional binding effect, whereas a mismatch results in the repulsion effect. If there is no intention to plan and execute an action, the body will not send a motor command coupled with an efference copy to be matched with an outcome; consequently, muscle twitch alone will not be enough to produce the binding effect. Before being challenged (Hughes et al., 2013), temporal predictability and forward action/comparator models were at the top of the list for explaining the binding effect.

Another support for the intentionality account comes from Cravo et al. (2011). They reported that the combination of action, temporal predictability, and temporal contiguity is required to modulate temporal binding, which are also necessary conditions, and singling out one of these will not be sufficient for the effect. In the experiments, participants were presented with a tone at fixed or random intervals after lifting their finger and in between the two events, a temporally independent flash appeared at different SOAs. Then, they judged whether the tone and flash occurred at the same time or not, and they contrasted these active conditions with the no-action conditions. In no-action conditions, the first event was the disappearance of the fixation point after between 1 and 2 seconds. They used 250ms as the fixed interval and random intervals between 250-750ms as the random interval in experiment 1. However, both 300 and 600ms were used as fixed intervals; in other conditions, the randomised order of the two intervals was delivered after the action. The results show that the tone was perceived earlier when there was a short interval between the events only in action conditions. In agreement with Haggard et al. (2002), longer intervals were considered not contiguous even with intentional actions, and the binding effect is sensitive to both predictability and contiguity conditions. On the other hand, temporal predictability alone is not sufficient to modulate the compression between events.

Overall, Cravo et al. (2011) notes that:

i) temporal binding requires the presence of action as a necessary condition.

ii) simply having a fixed interval between two events is not enough to cause the desired effect.

iii) temporal predictability and contiguity play a significant role only in the presence of voluntary action.

2.1.2 Causal Binding

Alternatively, to the intentional binding account, some researchers have suggested that intention is not a necessary condition for the binding effect to occur, recognising a causal relationship between events is sufficient, and this top-down effect on the sensory events is the reason behind the illusion of time compression. Intentional binding can be considered a subset under the parent term of causal binding. Compared to being a result of forward action models, causal binding emerges under the principles of Bayesian ambiguity reduction within uncertain circumstances.

> ‘According to Bayes' theorem, two causally related events are therefore also more likely to follow each other closely in space and time than two unrelated events are. Given that human time perception is inherently uncertain and noisy, it makes sense for the perceptual system to attempt to resolve ambiguities by drawing on prior experience of temporally contiguous cause-effect pairings and shifting estimates of cause and effect time toward one another. Critically, the nature of the cause is irrelevant, as long as the organism has prior knowledge or experience of the causal relation and its time course.’ (Buehner, 2012, pp. 1490/91)

The first study to show causality as a sufficient condition was Buehner and Humphreys, (2009). In a task where participants anticipated the time at which the outcome stimuli appeared, they completed baseline and causal control conditions with three intervals each (500, 900, and 1300ms). Participants anticipated two target tones' onsets (T1 and T2) preceded by two go-signal preparatory tones separated by 200ms, lasted 100ms (P1 and P2) in baseline exposure trials. In baseline experimental trials, they synchronised their first keypress response(R1) to T1 and the second(R2) to T2. In causal control exposure, they freely press the key, and then after the intervals as mentioned above, T2 was presented. They learned the contingency between keypress and tone in these causal-control exposure and training phases. In causal-control experimental trials, they performed the same task as in the baseline experimental block. However, predictability and the actions were the same in both conditions, researchers suggested that the contribution of causal connection in the causal-control condition is not apparent. They added a new condition in experiment 2 to achieve a causal link between the two events. The addition was that if participants did not press R1 within the 300ms window of T1, T2 would not be presented; therefore, T2 would undoubtedly be the cause of the first keypress (R1). The intent to show a contingency between events was now achieved, and predictability was kept the same across experiments. In both experiments, they found temporal binding only in causal-control conditions compared to the events happening in isolation and concluded that intentional action without contingency and temporal predictability alone could not induce temporal binding. If intentional actions are performed without causally linked event perception, binding vanishes. To recapitulate, in two experiments, Buehner et al. (2009) argue that firstly, causality inference is sufficient; secondly, intentional actions without causality are not sufficient; and thirdly, intentional action is not necessary.

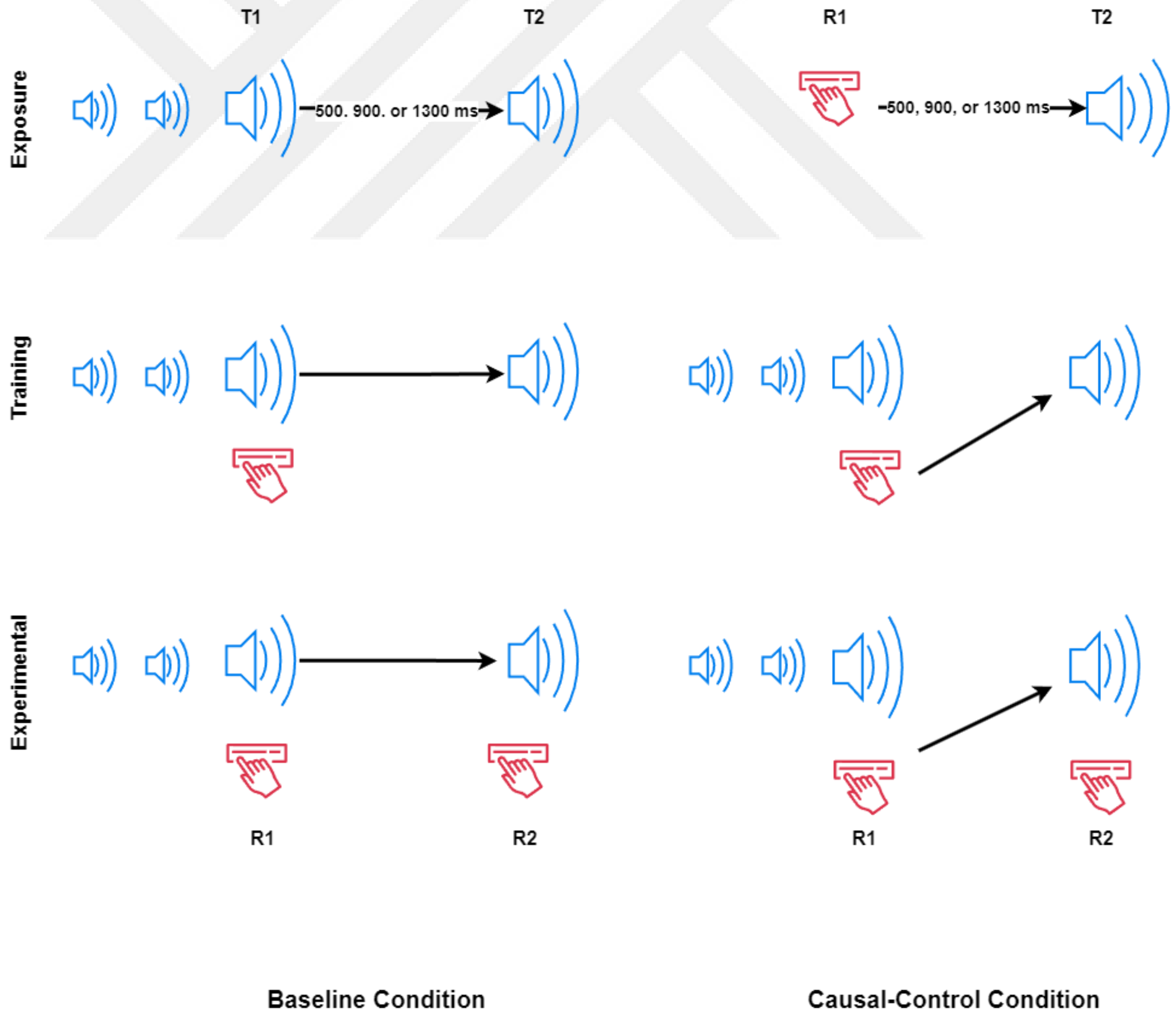


Figure 1. Experiment 1 of Buehner & Humphreys (2009)
In Experiment 1, the task was to synchronize two responses, R1 and R2, to two targets, T1 and T2, respectively. In the baseline condition, T1 and T2 were separated by an interval (t) of 500, 900, or 1,300 ms. The participants were first exposed to this interval during the exposure phase. Then, during the training phase, they synchronized R1 to T1. Finally, during the experimental phase, they synchronized both R1 and R2 to T1 and T2. In the causal-control condition, R1 generated T2 after an interval (t) of 500, 900, or 1,300 ms during the exposure phase. Participants then synchronized R1 to T1 during the training phase, and finally, during the experimental phase, they synchronized both R1 and R2 to T1 and T2. Figure and caption adapted from Buehner & Humphreys (2009).

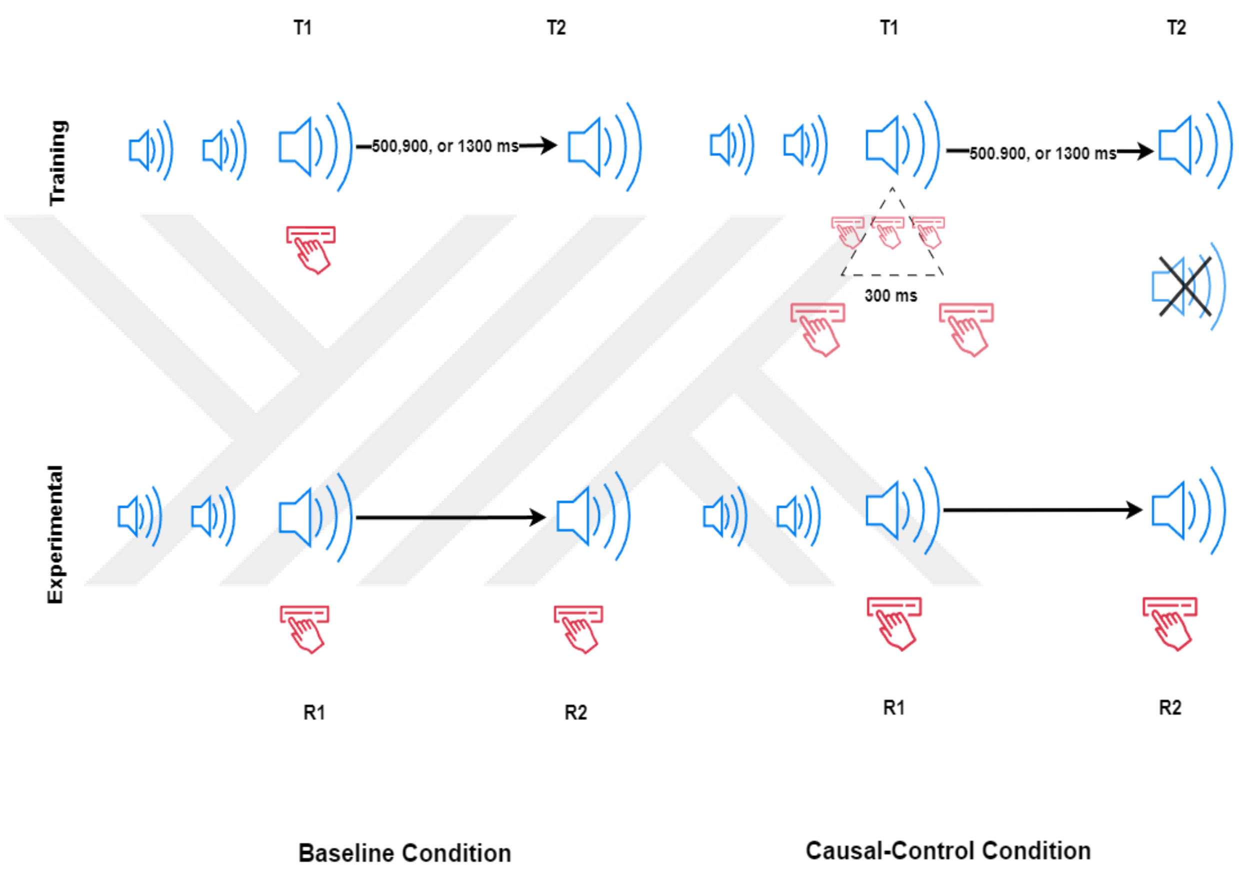


Figure 2. Experiment 2 of Buehner & Humphreys (2009)
Experiment 2 involved synchronizing two responses, R1 and R2, to two targets, T1 and T2. The baseline condition had T1 and T2 separated by an interval (t) of 500, 900, or 1,300 ms. Participants first synchronized R1 to T1 during the training phase and then synchronized both R1 and R2 to T1 and T2 during the experimental phase. In the causal-control condition, participants learned that if R1 was synchronized within a 100-ms window around T1, T2 would occur at an interval (t) of 500, 900, or 1,300 ms after T1. If R1 was not executed within this window, nothing would happen. Participants then synchronized both R1 and R2 to T1 and T2 during the experimental phase. Figure and caption adapted from Buehner & Humphreys (2009).

The binding effect cannot be elicited solely through intentional action, causality inference is a must in the equation. This finding was supported further by Buehner

(2012), who also provided evidence that intentionality is also not necessary for the binding effect. In three conditions - self-causal, machine-causal, and baseline - no differences in binding were found between the conditions where participants' actions caused the outcome and machine press caused it, compared to the baseline. Participants synchronised their responses to the flash stimulus where either their keypress caused the flash, or the machine caused it, or a preceding flash was the indicator of the target flash. They used three intervals: 500, 900, and 1300ms. They also reported an intentional boost effect only in the short interval conditions (500ms), but the effect did not replicate in experiment 2. In conclusion, the binding effect being insensitive to self vs other causal can imply that the absence of intentionality impacts causal binding marginally.

In other words, learning that there is a causal relationship/link between two events can sufficiently generate temporal attraction between them. In another study by Suzuki et al. (2019), the magnitude of the temporal binding effect was found to be similar in both intentional action and fake hand conditions where participants watched a virtual hand press a button.

Participants heard two tones in succession in an interval estimation task, separated by three selected intervals - 200, 400, and 800ms- in the baseline condition. They conducted the experiment in a virtual reality environment and recorded participant hand movements. In the active hand condition, participants made the keypress; in the no-hand condition, they observed the button being depressed; in the fake hand condition, they were explicitly told not to move their hand, and they watched the virtual hand press the button. The results indicate that the perception of causality in the fake hand condition is sufficient for temporal binding to occur, similar to the active condition.

Another piece of evidence for the causality perspective comes from the study of Dogge et al. (2012), in which they found temporal attraction between an action and an effect even though the participant's fingers were moved passively; however, they believed themselves to be the cause of the second event. They subjected the participants to a Libet clock task using a fixed interval (250ms). Participants either executed a voluntary or involuntary keypress, which was induced via lever pulling down their finger momentarily. Voluntary movement condition is used as a baseline control, whereas involuntary movement conditions are manipulated by explicit causal instruction. In the implied self-causation condition, participants were told to regard themselves as the cause of the tone; in the no implied self-causation condition, they were kept in the dark. The binding effect was more prominent in the implied causation condition relative to the involuntary condition without any instruction. A typical binding effect was detected in both action and tone shifts in the voluntary movement condition. When the causality link between the events is broken but still implied, a significant binding effect arose only in the shift of the tone and smaller magnitude to the voluntary action condition. Lastly, without an actual or implied causal link coupled with an involuntary action, both shifts in the effect evaporated.

These results suggest that our beliefs about causality can affect how we perceive the timing of events, indicating that causality may be more important than voluntary or involuntary movements in shaping our experiences. Further, temporal binding can occur through implied causality despite the fact that participants actively know that the causal structure in the voluntary condition is inherently more pronounced than the involuntary implied causation condition.

Evaluating intentionality account with regard to causality has left out the temporal prediction discussion in the studies above. One of the other particular components in the intentional binding account of Haggard et al. (2002) was temporal prediction and contiguity. In the study by Kirsch et al. (2019), the essentials of temporal predictability with intentional actions portrayal were contested and modified to a temporal prediction under the highlight of causal inference view instead of intention being necessary for the effect. When controlling for the temporal predictability of event perception, they found temporal binding in both voluntary and involuntary movement conditions. In a study with two experimental sessions and seven experimental blocks, participants were asked to judge either the occurrence of an action or a tone by looking at a clockface. In operant blocks (A through D), participants pressed the key, or their finger was depressed involuntarily, and either judged the occurrence of the keypress or the tone. The constant time interval between events was 250ms. Baseline blocks(E-F-G) consisted of time judgments of either the keypress or the tone while witnessing them occurring not together. The tone was not presented after voluntary/involuntary keypresses, and there were no actions preceding the tone. They also controlled the predictability of critical events. After a random interval between 2000, 3000, and 4000ms, the clock hand changed colours, indicating what was to come. Participants either pressed the key or their finger was pulled down; in the involuntary operant conditions, they adjusted the mechanics to start after 350ms from the colour change according to the approximate RTs of the voluntary conditions.

The study found that the binding effect was present in both action conditions, regardless of intention, as compared to when only the tone was presented. This suggests that the same level of binding in both conditions may be due to the participants' belief in causality. If they assume that the first event caused the second event, then motor planning is not required as a cue. The study proposes that intentionality is not essential for triggering temporal attraction between events. Instead, it is the x-caused y principle that guides the temporal prediction process. It seems that the presence of causality alone is often considered enough to create a sense of time being compressed, and the function of causality as an adaptive process can breach into and shorten our perception of time. These discoveries ascertain that the compression of time is not necessarily dependent upon intentionality itself, as the externally induced movement does not cancel out this sense of connection in situations where there is a clear cause-and-effect relationship between an action and its outcome. To recapitulate, causal binding is in, and intentional binding is out.

Is it really the causality that drives temporal binding without any assistance? Some researchers argue that causality could be just necessary and not sufficient, as well as intentionality adding something to the experience.

2.1.3 Causal Binding with an intentional boost

Contrary to causality or intentionality account being a necessity alone, some studies state neither is sufficient to produce the effect alone. In line with this proposition, Cravo et al. (2009) put both intentional action and causal relation down as prerequisites for eliciting the temporal binding effect. The study employed Michottean launching stimuli. In each trial, the screen had two discs apart from each other in the border of two vertical white lines inside the frame. The causal condition was dubbed as a collision in the experimental design, implicating that the first disk was the cause of the second disk moving. In collision blocks, the first disk moved from left to right and stopped upon hitting the second disk- at the centre-launching it to the right border. At the start of each non-collision trial, two discs were positioned next to each other in the centre of the screen. The disc on the left side moved first towards the left border, and once it stopped, the disc on the right side moved towards the right border. The time between these events was either 200 or 300 milliseconds. Each block had two conditions. In the active condition, participants managed the movement of the first disc, whereas, in the passive observation condition, the computer governed it. Participants were asked to rate the causal effect between two events using a scale of 0-10. The researchers used the interval estimation method to measure the duration or delay after the first event's movement ended. Participants were given a scale between 0 and 1000ms to estimate this delay. The results showed that the causal ratings were significantly more increased in collision blocks compared to non-collision blocks. Moreover, they found higher causality ratings in the short duration (200ms) compared to the long duration. Still, they only found temporal binding in collision conditions and only when the participant initiated the action sequence. This study provides evidence that intentionality and causality collaborate to underlie temporal binding, making causal inference necessary, however insufficient by itself.

The results of necessity and sufficiency of intentionality and causality are still debated, and the experimental designs contrasting the two are in scarcity. However, by implementing a novel design, Shiloh et al. (2017) proposed that causal binding could be subjected to an intentional boost while being the root cause of temporal binding. In the search for appropriate control conditions, they eliminated tactile or auditory feedback. In a general keypress-outcome design, participants obtained proprioceptive feedback as well as causal connection. In contrast, in the control conditions, only seeing or listening to two events happening sequentially, this type of feedback was missing. They replaced the traditional sequence of pressing keys to achieve an outcome with a light sensor that responds to a laser beam aimed in its direction. When the laser beam hits the sensor, it turns on an LED bulb. There was a wooden paddle to be moved to pass the beam through the light sensor. The experiment contained three conditions:

1) self-causal: The participants adjusted the wooden paddle until the laser beam passed through the gap.

2) machine-causal: The paddle's wheel rotated automatically, enabling the beam to go through the gap in the mechanism once with every rotation.

3) Non-causal: A small red light was put in place of the laser, and it would turn off once during each rotation.

During the experimental blocks, the laser sensor switched to a red LED upon detecting the laser pointed at it (causal conditions), or the red LED is switched off after a randomized, uniformly distributed delay between 200 and 400ms. The task was to accurately measure the interval between two consecutive events by holding down the left mouse button for as long as the user wished.

According to their hypothesis, there were three possible outcomes. The causality account suggested that temporal estimates would be lower in causal conditions than in non-causal ones (self-causal = mechanical-causal < non-causal). On the other hand, the intentionality account proposed that the machine and non-causal conditions would have similar results, and only self-causal conditions would result in underestimation (self-causal < mechanical-causal = non-causal). Finally, the expected intentional boost account predicted that only the causal condition would show a binding effect compared to the non-causal condition, with the self-causal condition showing a more significant effect than the machine-causal condition (self-causal < mechanical-causal < non-causal) (Shiloh et al., 2017).

The results demonstrated support for intentional binding account when they conducted frequentist analyses which were less conclusive. However, the Bayesian factor was the highest for intentional boost account. They clarified that this discrepancy may be stemming from the effect size being too small to detect under frequentist analyses. They alluded to the perceived differences between self-made and observed action being an additional influence on causal binding, making a combined influence of cues to consider in the shift of event perceptions. All in all, with regard to causality itself being sufficient for the binding to occur in this study, the boost effect coming from the presence of intentional action may be that because it increases our confidence level in the causal link, we can explain the magnitude difference, albeit slightly.

2.2. General experimental designs

2.2.1. Methodologies

To this date, in the matter of shifts of event perception, temporal binding has been replicated in Libet clock methods (Desantis et al, 2012; Haering & Kiesel, 2014; Dogge et al, 2012; Kirsch et al, 2019; Ruess et al, 2017). Along with this, the outcome shift toward action has been shown in other methodologies like anticipation/synchronisation tasks (Buehner & Humphreys., 2009; Buehner, 2012) in which participants were asked to synchronise their keypress with the outcome event. The outcome shift has also been demonstrated via simultaneity judgment tasks (Cravo et al, 2011).

On the other hand, considering the temporal binding effect as compression in time perception rather than shifts of events, researchers have primarily been using interval estimation tasks (Hearing & Kiesel, 2014; Ebert & Wegner, 2010; Fereday &

Buehner, 2017), in which participants made direct inter-event interval judgments verbally or using keypads or scales.

By this time, the Libet clock and temporal estimation measures have been utilised in most of the temporal binding studies, the Libet clock being the forerunner of the research. However, despite its widespread usage, the Libet clock method has not suffered without criticism. To begin with, changing the temporal binding perspective from shift perception to illusion in the perceived interval, the clock method has become an indirect measure, seeing as it focuses on the individual events' starting and ending points in time compared to the numerical interval between them (Humphreys & Buehner, 2009). Another limitation is that the Libet clock measures always go hand in hand with auditory outcomes. Not using visual outcome stimuli allows participants to focus only on the clock moving when the target event happens. Thus, the possible attentional shift away from the clock hand to the visual stimulus may affect the timing of events due to the speed of the clock hand or the task being cognitively more demanding. In line with this, using tactile stimuli also has its challenges, paying attention to the clock while performing a movement requires a distraction-free visual attention zone from the action execution and planning (Engbert et al., 2007).

Within the interest of this research, only a few other methods have seldom been utilised to reproduce the binding effect. Additional evidence has emerged through the study by Nolden et al. 2012, in which participants were asked to determine whether varying comparison intervals were longer or shorter than the actual interval between events (method of constant stimuli). Plus, other studies have implemented the interval reproduction method (Dewey et al., 2014; Humphreys &

Buehner, 2010; Poonian et al, 2013; Shiloh, White & Buehner, 2017) where participants press the selected key or nob for the period of perceived interval.
This research aims to use the interval reproduction method to show, first, that it is a reliable method and alternative to the Libet clock or interval estimation, and second, our interest lies within the event perception as a whole and the compression of interval length itself. In accordance with Poonian et al. (2013), we speculate that keypress measurements of interval rather than asking participants for an estimate after every trial, the participants will respond more accurately and without a hitch. Moreover, the participants will perceive the event as a whole rather than relying on different processes like memory or other attentional resources to make verbal estimates after the outcome event. Action fluency will be maintained, and there will not be any time to think after the fact. Given that different methodologies used here could be tapping into different mechanisms under the temporal binding effect, the temporal reproduction method will be fruitful for the purposes of this research.

2.2.2 Inter-event intervals: Fixed vs random intervals

One of the critical elements reporting the temporal binding effect in the 2002 paper was temporal contiguity. Consequently, papers utilising the Libet clock method almost always paired this method with fixed inter-event intervals. In their experiment (2002), Haggard et al. uncovered that the binding effect diminished as the time intervals got longer. At 250ms, the effect was the most evident, and it lost its density at 400ms, going down still at 650ms. When they presented these delay intervals in random order in a trial block rather than separate blocks, the binding effect vanished altogether for the outcome shifts. They inferred that the binding effect lessens when temporal contiguity is less obvious and that longer intervals kill the effect inevitably.

However, two recent studies found a more complex relationship of inter-event intervals using a Libet clock between both action and outcome event shifts and the range of semi-random delays. Ruess et al. (2017) revealed that the effect might be warped not only by temporal contiguity but also by their range and the context of action-effect. When employing a small range (200, 250, 300ms) in Experiment 1, they found a continual increase of outcome binding effect. The outcome binding increase turned into a decrease, however, at 400ms, with an extended range (100, 250, 400ms) in Experiment 2. They also manipulated the predictability of delay intervals. In an unpredictable block, the intervals were presented randomly, whilst, in predictable sessions, the blocks contained the same interval across trials. Similar to the results of Haggard et al. (2002), they discovered the effect to be decreased at longer intervals only in predictable blocks, and the decline did not happen in unpredictable sessions. According to the findings of Ruess et al. (2017), action binding was found to be unaffected, akin to outcome binding in unpredictable blocks. However, in Experiment 2, an increase in the binding of an action was observed at longer delays, with the interval range being 300ms. This specific increase was not observed in Experiment 1, which had a smaller interval range of 100ms.

In another study by Ruess et al. (2018), the results showed additional complexity in the relationship between temporal contiguity, predictability, and event shifts when measured using the Libet clock method. Experiment 1 used visual effects for the outcome event with five different delay durations (150, 250, 350, 450, and 650ms). Experiment 2 was carried out using the same five delay intervals with the auditory effect as outcomes. With the visual effects, in line with their previous research, it was found that the strength of the binding effect decreased as the time interval increased; however, the difference in magnitude only actualised in single contrast comparisons that have at least a 300ms range between them (150 vs 650ms, 250 vs 650ms, 350 vs 650ms, 150 vs 450ms).

Similar to the visual effects, the magnitude of binding was weaker at longer intervals in experiment 2 with auditory effects. These results are consistent with Haggard et al.'s (2002) results displaying a lesser magnitude of intentional binding when the lag is longer in one respect, but in opposition to their own study (Ruess et al, 2017), showing an initial increase of binding effect for short intervals as in from 100 to 250ms. They merely detected a decrease in the longer delays, yet, with auditory outcome events, the magnitude of the effect was not significantly different between the shorter delay durations (150, 250, 350, and 450ms), as well as being significantly different when the range is at or greater than 300ms just as in their Experiment 1. Consequently, these discrepancies between the two studies do not provide further evidence or insight into the binding effect vanishing at longer intervals unequivocally in the Libet clock measure.

The premise of temporal contiguity being an unchallenged concept for intentional binding has provided mixed results under scrutiny, potentially opening a new path of theorising an adaptive and context-dependent version of intentional binding. Another explanatory difference could be that the divergent results of the Libet clock measurements are not necessarily pervasive over the other methods used in temporal binding research. Humphreys & Buehner (2009) discovered the temporal binding effect by measuring time intervals directly, rather than focusing on the specific timepoints of individual events. Using an interval estimation task, they found that the effect was present for intervals up to 4 seconds, without any decrease reported at longer intervals. Moreover, employing semi-random intervals such as 500, 900, and 1300ms with a synchronisation task Buehner and Humphreys (2009)

reported the temporal binding effect with these intervals as discussed above. In addition to this, Humphreys & Buehner (2010) studied the effect using random intervals varying between 1200-1600ms and asked the participants to reproduce the interval by pressing a key. Again, the temporal binding was equally in effect.
Going from the Libet clock method to other equitable psychophysical methods and also fixed intervals to fully random intervals, the researchers above proposed that the divergent results between shifts of event perception via the Libet clock and the perceived interval via estimation tasks could stem from the rudimentary distinction of the underlying mechanism that leads to the temporal binding effect. A proposed explanation for the compression of delay intervals is that it may be due to a slowing down of an internal pacemaker as a pre-emptive measure. However, a recent study by Fereday and Buehner (2017) questioned whether this slower rate in the pacemaker is a general process or if it's specific to certain circumstances. Moreover, the newly found branch of divergent mechanism could also contain an intersection. Fereday & Buehner (2017) suggested that event- vs clock-based stances of binding do not have to be mutually exclusive, instead, a specific clock slowing might explain both perceived contraction of time and event shifts.

Along with using shorter or longer intervals, the dominance of temporal prediction by using fixed intervals vs unpredictable or varied intervals has also been proven divergent and seems to be only affecting studies investigating event perception. All previously mentioned studies here used fixed intervals with the Libet clock measure (Haggard et al. 2002 -in part- Desantis et al. 2012; Hearing & Kiesel 2014; Dogge et al. 2012; Kirsch et al. 2019), except Ruess et al. (2017) which we consider it to be semi-random using three or more fixed intervals randomly. With respect to the impact of temporal predictability on outcome binding, while Ruess et al. (2017) did not uncover any diminishing effect of binding for varied intervals, when Haggard et al. (2002) tested the effect using varied intervals in a random order, they reported that the outcome binding reduced. Cravo et al. (2011) corroborated Haggard et al.'s (2002) results showing that the effect was only present when there is an action and temporal predictability. In experiment 1, they used fixed (250ms) vs random(250-750ms), and either 300 or 600ms or both in experiment 2 in a simultaneity judgment task. When the random intervals were presented, the effect did not show even where the action occurred, similarly, when they presented 300 or 600ms in randomized order, the binding effect disappeared compared to when there is an action coupled with the short interval (300ms) between the two events.

Having said that, there are no mixed results within the realm of other methods like temporal estimation and reproduction in terms of temporal predictability reliance. The studies reported temporal binding with semi-random/categorical delay intervals (Ebert & Wegner, 2010; Humphreys & Buehner, 2009) and random intervals (Humphreys & Buehner, 2010). While Humphreys & Buehner (2009) found the effect using intervals ranging from 150 to up to 4000ms, Ebert & Wegner (2010) reported that when the action is congruent with the naturalistic effect, the attraction between the two events took place. They asked participants to give their interval estimates on a 10-point scale ranging from 0 to 900ms in 100-ms increments. The inter-event intervals used in the study were 100, 400 or 700ms. Humphreys & Buehner (2010) found evidence for the binding effect using random intervals within a range in a reproduction task design. Employing operant(active) vs observational(passive) conditions with a varying between 1200 and 1600ms interval, they reported the effect in operant trials. Another admission of random interval usage came from Poonian et al. (2013). In that study, they observed the binding effect in both self-made and observed action conditions compared to the baseline control condition with an inter-event interval between 500 and 1500ms.

With such few inquiries into the temporal prediction process modulating the binding effect and the differing results coming from experimental designs investigating the event or time perception, we aim to sever the relationship between temporal prediction and temporal control by applying fully random intervals and fixed intervals as well in a learning environment where relations of both events and delay interval are manipulated between abstract events. Additionally, taking into account that the temporal predictability effect might result from experimental designs and whether the perceived interval or shift in events is measured, we will intend to use the temporal reproduction task as it is rarely used in the research and as our interest lies within the compression of time perception framework. We have no inclination to expect a reduced binding with longer or randomized delays as suggested in the above studies, given that only a reduction of the effect was reported when they investigated the outcome shift in binding, and these results look to be exclusive to the event shift perception research.

2.2.3. Acquisition phases

Whether an experimental design needs an acquisition, learning or top-up phase might lie within which stimuli might be called into play. Outside the lab environment, we can directly and even subconsciously produce a causal link between two contiguous and contingent events. However, these naturalistic relations of the environment are seldom used in temporal binding research. Ebert & Wegner (2010) combed the relationship between a joystick and the picture of everyday objects, and recently Thanapoulos et al, (2018) matched the hand or foot presses to the nob to audio and visual of the same presses without the need for adaptation phases. On the other hand, research - as we will be - commonly employs an abstract relationship between two subsequent events, such as button presses and audio or visual outcome stimuli. As we are interested in whether controlling identity prediction will have an effect on temporal binding, we see the necessity to adapt a pre-learning phase to acquire and maintain action-outcome associations and fortify the relationship between the action and its consequence. A few other studies made use of acquisition phases in their design, Buehner & Humphreys (2009) used a training phase in their synchronisation task, Hearing & Kiesel (2014) employed a learning phase in Experiment 2, and Desantis et al, (2012) preceded every block with an acquisition phase.

The need for an acquisition phase is further advocated in Thanapoulos et al, (2018) study. They aimed to replicate Cravo et al.'s (2011) experiment 1 with an exact design except for the nob press and without the adaptation phase. They found no intentional binding effect in blocks with both an action and temporal predictability(250ms). They attributed these results to not using a top-up phase to reinforce the causal link between the two events and the number of practice trials being minimal for familiarisation of the task. As we want the participants to learn action-outcome associations of the task and the interval, we want our participants to exercise 10 practice trials to learn to produce the inter-event intervals beforehand as many runs as they need. In the case of the number of trials needed for an acquisition phase, there are no strict rules that have been established in the research, as some use 50 or even up to 100 trials, seeing as it is claimed that these action-outcome links could be acknowledged with 12 trials or even 8 (Wolfenstellar & Ruge, 2011), we are confident in using 30 acquisition trials to establish the link between an action and outcome with different validities.

2.3 On predictive processes that affect temporal binding

Hughes and colleagues (2013) reevaluated previous studies and did not find a clear connection between motor predictive processes and temporal binding. They highlighted the critical control conditions for contrasting predictive processes, stating that some studies might inadvertently contrast more than one prediction process simultaneously. For instance, Haggard et al. (2002)'s voluntary and involuntary action conditions differed not only in action-outcome prediction, i.e. motor-identity prediction but in the ability to control the onset of events, in other words, temporal control. They emphasized that in order to find what process drives temporal binding, researchers should not compare voluntary and involuntary action conditions or fixed and random inter-event intervals. The comparisons made in previous research were unable to identify the specific predictive processes involved in the binding effect. Therefore, it is necessary to design experiments that manipulate one predictive process while keeping other elements fixed to evaluate the temporal binding effect more accurately. Researchers have noted the lack of valid comparison conditions in previous studies designed to investigate motor-identity prediction. Based on the research conducted by Desantis et al. in 2012, it was concluded that the driving force behind temporal binding may lean on the capacity to control the beginning of the trial and the onset of the outcome stimulus rather than solely on identity prediction in motor control.

According to Hughes et al. (2013), identity prediction may not be involved in temporal binding. Their aim was to assess if outcome shifts can be explained by motor predictive mechanisms; therefore, they only reviewed studies that employ the Libet clock method. Behind this assessment, the reasoning was that the outcome shifts are the result of predictive processes, and the action shifts are postdictive (Moore et al., 2010). As per the findings of Waszak et al. (2012), the temporal binding effect happens because our brain predicts the outcome of an action and matches it with the actual outcome. This matching is easier when the expected outcome is congruent with the action, and the threshold is reached more quickly due to an increased baseline when the expected outcome occurs. The research at the time explained the temporal binding effect as a result of action-outcome prediction matching on the basis of the prediction of congruent stimuli after the action, which increases the baseline when the expected results transpire, making it easier to reach and surpass the threshold. They tested this hypothesis and concluded that motor-identity prediction mechanisms do not modulate temporal binding; however, temporal control now might take up space for explaining the effect (Desantis et al., 2012).

According to Desantis and colleagues (2012), if temporal binding is connected to a predictive mechanism that links an action to its outcome, then it should be influenced by the participant's ability to predict both what will happen and when it will happen after an action is performed. In the first experiment, participants were asked to execute two different actions - pressing either the right or left key - and then, after a fixed delay of 450ms, they received either a high or a low tone in two different action conditions. Action conditions differed in terms of action-outcome mappings. In one condition, the outcome corresponded to the action performed 100%, whereas in the other, the outcome probability was chosen at random, irrespective of the action. In the third (control) condition, the action was replaced with a tone, and after the fixed interval, they received another tone randomly. Each block was preceded by an acquisition phase in which they learned the contingencies over the course of 50 trials. Everything was the same as the above conditions. The study discovered that the inter-event interval is compressed in the action conditions but not in the control condition. Both action conditions produced the effect in similar magnitudes, which implies that the binding effect was not dependent on the prediction mechanisms of motor identity.

They carried out a second experiment to rule out a possible confound. The criticism was that identity prediction might also be involved in the action condition where the outcome probability was 50%, just as much as the other action condition in which actions corresponded with outcomes from beginning to end. The argument is that if the outcomes have the same probability of occurrence, then this also could easily be predictable by the forward action mechanisms. In experiment 2, the alternative actions produced the tone either congruently or incongruently with respect to the acquired action-effect mappings. Participants learned the association between the two events with 100% accuracy in the acquisition phases, and the overall probability of being presented with an incongruent outcome was set to 20% in experimental conditions. In the action-to-tone condition, left or right keys corresponded with a high or low tone, and in the tone-to-tone condition, two random sounds and two tones matched, or the association as previously learned was violated. In both conditions, the events were separated by a 400ms interval. They replicated the results of Experiment 1 and again did not find any effect of identity prediction on the binding effect. They found no evidence that accurate predictions of action outcomes or congruency between previous and actual outcome identities affected temporal binding, even at 80% validity.

It has been claimed that identity predictions do not affect temporal binding. This claim has been supported by two studies: one conducted by Haering and Kiesel in 2014 and the other by Bednark et al. in 2015. Both studies replicated the findings of a previous study by Desantis et al. (2012) using different methods, such as interval reproduction and the method of constant stimuli. From these studies, we can infer that the role of identity prediction in temporal binding may not be necessarily straightforward. Without implementing a learning phase, Haering and Kiesel (2014) tested the temporal binding effect through the method of constant stimuli in their experiment 1. In their study, left and right keypresses resulted in congruent outcomes (red or blue squares) in 80% of the trials, in the remaining trials, the same action yielded incongruent outcomes. Two conditions of this structure were introduced to the participants in which the two events were separated by 250 or 400ms intervals. Experiment 2 included a learning session in which participants learned the action and effect pairings with 100% validity. Similar to their first experiment, participants' actions produced congruent outcomes in 80% of the trials in the experimental phases, and they changed the outcome stimulus from visual to audio. In experiment 3, learning phases were excluded, and experimental phases were divided into two parts. They rendered the probability of congruent outcomes as 100% in the first part and as 50% in the second part. The order of these parts was counterbalanced. They also informed the participants whether they were about to see the part in which the validity was 100% or the outcomes were random. Finally, in experiment 4, they carried out experiment 3 with two additional methods: the Libet clock and interval estimation. Overall, the results indicated that the predictability of outcomes or the congruency between actions and their effects, thus stable action-effect associations, could not influence temporal binding, therefore strengthening the results of Desantis et al. (2012).

Bednark et al. (2015) conducted an electrophysiological study on temporal binding. The behavioural results were in line with the claim that action-outcome-based identity predictions have an indistinguishable influence on the binding effect, as suggested above. They examined temporal binding through interval reproduction task in three conditions: Control-Predictable, Action-Predictable, and Action-Unpredictable. Control-Predictable condition consisted of external tones as the two events separated by a variable interval (800, 1000, or 1200ms). In the Action-Predictable condition, participants pressed the spacebar, and then after a variable interval, a high or a low tone was presented. The predictability of the outcome tones was set to 75% congruent and 25% incongruent. However, the predictability of outcome was non-existent in the Action-Unpredictable condition. The chance of receiving either tone after the specific action was 50%. The first four trials of predictable conditions were used for participants to foster valid action-outcome pairing, i.e., interchangeable prediction-congruent tone (Tone-1 or 2). The results showed that there was no significant difference between Action-Predictable and Action-Unpredictable conditions nor between the prediction-congruent (Tone-1) and prediction-incongruent (Tone-2) in the Control-Predictable condition or Action-Predictable condition. Consistent with Desantis et al. (2012) and Haering and Kiesel (2014), the underestimation in action conditions and the overestimation in the control condition ascertained that, irrespective of whether congruent or incongruent effect ensues based upon identity-specific predictions, a mere presence of action is the chief force for influencing the binding effect, not the motor-identity predictive mechanisms.

While Desantis et al. (2012) and Haering and Kiesel (2014) included acquisition/learning phases in their design as separate blocks, Bednark et al. (2015) did not employ an adaptation phase. Participants were given the opportunity to acquire outcome predictions based only on the first four trials of each predictable condition. Contrary to Desantis et al. (2012) and Hearing & Kiesel (2014), we used a novel design where there are both acquisition/adaptation or top-up phases and, afterwards, a test phase within the same block. Further, we utilised seldom used tasks in the literature, such as interval reproduction, for our preferred method. Moreover, contrary to Bednark et al. (2015), we had a choice of actions or two distinct external events to map to the outcome events instead of a single choice-two outcomes design.

The aim of this thesis is to investigate how predictive mechanisms, especially temporal control imbued with temporal prediction, influence temporal binding effect when contrasted with each other, manipulated within the same block, and also whether -dissociated from temporal prediction- temporal control alone could be the root cause of the binding effect. To this aim, we adapted the concepts that Hughes et al. (2013) introduced to our design and engineered their meanings within the same block to witness whether a learning-based paradigm- both timewise and mapping-wise - could individually affect temporal binding. Furthermore, a secondary objective of this thesis was to supply additional input to the results that the binding effect is corollary of mechanisms specific to motor identity but instead is driven by independent mechanisms from forward action models.

CHAPTER 3

EXPERIMENTS

3.1 Experiments 1a and 1b

3.1.1 Method

3.1.1.1 Participants

Ten graduate and undergraduate students (one is the author, and one is the supervisor) were recruited from the Vision Lab of Bogazici University for experiment 1. All participants had normal or corrected-to-normal vision; also, they did not have colour blindness or any other colour vision-related deficiencies.

3.1.1.2 Apparatus and stimuli

The experiment's stimuli and code were implemented in PsychoPy (Pierce et al., 2019) and ran on an LED monitor with a resolution of 1920 x 1080 and a 120 Hz frame rate (Eizo Foris FG2421). The display was calibrated with a colourimeter (Spyder4Elite). White and black luminance were set to 145.49 and 0.09 cd/m^2, respectively. Participants were seated approximately 55 cm away from the monitor, and their heads were rested on a chinrest tool to keep their movements to a minimum. The experiment was conducted in a dark and sound-attenuated room. The visual stimulus was either a red or green circle (300 pixels^2) presented 200 ms at the centre of the screen and served as the outcome of the first event, i.e., action or tone separated by a variable interval. Two sinusoidal frequency waves of 500 Hz and 100 Hz were used as a first event in some blocks delivered via headphones. Lastly, a white fixation cross (20 pixels²) was presented at the centre of the screen on a grey background at the beginning of each trial.

3.1.1.3 Design and procedure

The study utilised three factors: Condition type, which contained three levels: Identity Control (Action with validness), Temporal Control (Action without validness), and Identity Prediction (No-action with validness); interval type of two levels (fixed, random) for both acquisition and test phases and congruency measure (congruent, incongruent). Every block consisted of two phases: the acquisition phase, in which the participants learn the interval and congruency between two events simultaneously and the test phase, where we tested the participants' interval and congruency judgments and whether the learned association just before the test phase affected their interval judgments. The dependent variable, measured after every trial, was estimates of inter-event interval durations.

Experiment 1a contained four block conditions: two types of identity control and two types of identity prediction. We contrasted the action with validness conditions with no-action with validness conditions. We manipulated time and congruency in all four conditions with the same block structure to surface the effect of the action component in temporal binding. In addition to cross-examination between two condition types, the design also included a time manipulation in the acquisition phases of both condition blocks, which was the object of how learning the interval beforehand affects the data within these conditions. We will dub these blocks 1 through 4. Block 1 (Fixed- Identity Control) involved a fixed interval for both acquisition and test time, and further, participants learned that their actions produced the same effect 100% of the time in the acquisition phase and the action-effect associations were fully randomized in the test phase. In Block 2 (Random-Identity control), the congruency factor was kept the same, except the time factor was changed to random interval only in the acquisition phase. The trial of Block 3 matched with Block 1, except there was a missing component of action to start the trials in Block 3(Fixed-Identity Prediction). Lastly, Block 4(Random- Identity Prediction)'s design was the same as Block 2, again, except there was no action.

In Experiment 1b, the blocks were only of temporal control conditions (Action without validness). The interest was only in changing time manipulations, where in which they learned the interval and were asked to report the interval to configure how temporal control may affect the binding and whether it could be the driving force for the effect to occur. These blocks will be dubbed as 5 through 8. The participants neither learned that their action was congruent with the outcome in the acquisition phase nor were they subjected to valid-invalid outcomes in the test phase. The congruency measures were kept at random throughout the whole blocks. In Block 5, the interval was random for both acquisition and test phases. In Block 6, the interval was fixed in the acquisition phase and random in the test phase. In Block 7, the acquisition phase's interval was random, and the test phase's was fixed. In Block 8, both intervals were fixed in two phases.

Identity-Control and Temporal-Control blocks began with the grey screen and fixation cross on the centre. The participants were given two choices: press the left or right key to start the trial. The fixation cross disappeared immediately after the keypress, and the stimuli appeared at the centre after a designated interval. They were also told to press either key as random or unplanned as possible. After the keypress, depending on the block design, the stimuli appeared after a fixed time (550ms) or random time between 0 and 1100ms. Both phases required participants to direct their attention towards the inter-event interval between the keypress and the onset of the circle, as well as the relationship between the two events. They just observed the interval and relations of events in this phase. There were two key-outcome associations 100% of the time, and these associations varied for different participants or just fully randomised key-outcome relations in these blocks according to the above design. The randomisation in this experiment was not controlled, the learned action-outcome mapping of 100% congruency could be within the range between 80/20% or 50/50% in the test phase. Identity Prediction blocks also began with the grey screen and fixation cross on the centre. Instead of the first event being the action, the participants received random tones via headphones and the beginning and the end of the tone marked the first event for the trial structure in these blocks. The inter-event interval began at the end of the tone and finished at the onset of the outcome stimulus. In every trial, the tone started after 2000ms. In the acquisition phases, they, again, acquired whether there is a relation between the two tones and the stimuli, as well as whether the inter-event interval was fixed or random. In the test phases, participants were instructed to press the space key for the duration of the interval they received after each trial.

Every block contained 100 trials, 50 acquisition and 50 test trials. After every block, they additionally, of their own accord, gave verbal reports of what they thought happened timewise and their congruency judgments, some even tried to give a percentage of relations. These verbal reports were not included in the data analyses, they were just indicative of their performance and also solidified that they understood the objectives of the experiment and carried out the task correctly.

Before the experimental sessions began, all participants completed a practice session with ten trials, as many runs as they needed. These practice sessions were put in place to prepare the participants for the reproduction task and adjust their time of keypress to their optimal performance. Their task was just to reproduce the interval between two events in 10 trials. Inter-event intervals used here were between 0 and 1000ms, we utilised a different random interval range and also different numbers to ensure that this is different from what to expect in the experimental blocks, this was not part of the experiment. For good measure, the participants were told that the intervals would not exceed 1500ms. After the practice session, they were given feedback on all ten trials, both the physical duration and their reproduced duration. If the participant was content with the difference between their response and the actual duration, and if they had said that they were meant to press the amount they thought they perceived, the experimental session would take part next. If they thought that they needed more time to be ready and content with their performance, and all of their data was too far away from the physical durations, they would retake the practice session until they were suitably prepared for the objectives.

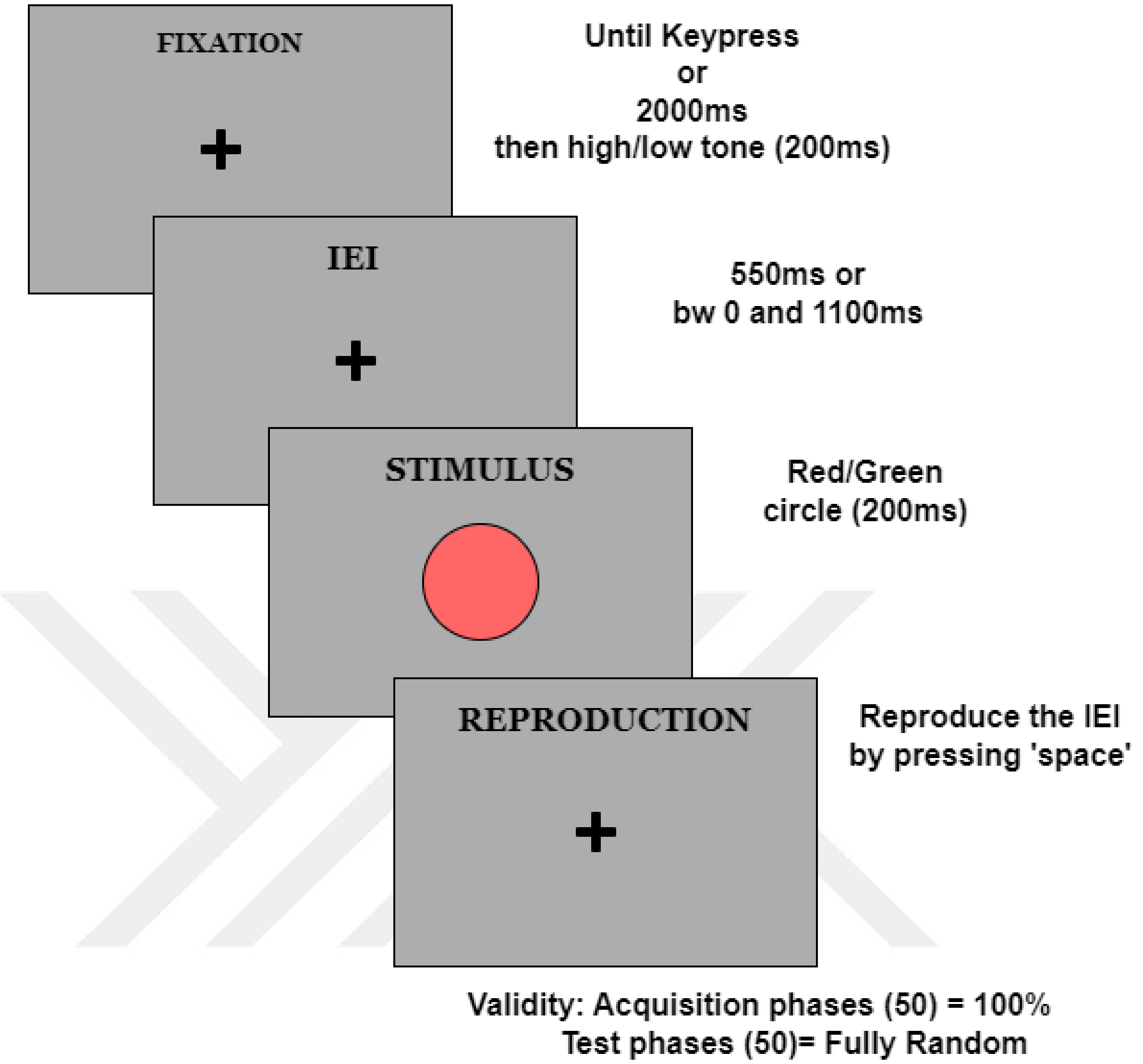


Figure 3. Design of experiments 1a and 1b.
In action blocks (IC and TC), the fixation cross disappeared when they pressed left or right. In no action blocks (IP), the fixation cross disappeared after 2 seconds. After a varied or fixed interval, participants were presented with a red or green circle for 200 milliseconds. After the disappearance of the circle, they were prompted to reproduce the inter-event interval by pressing the space key.

3.1.1.4 Results

3.1.1.4.1 Experiment 1a (IC vs IP)

A linear mixed model was fit with varying intercepts and slopes model with three factors coded as 1 and -1. The first model introduced the predictors *Condition Type* (active [+], passive [+]), *Acquisition Time* (fixed, random), and *Validity* (true, false). The random effect structure consisted of a random intercept for participants and random slopes for condition type and acquisition time by participants. The models were produced in an iterative backward selection fitting procedure using likelihood ratio testing (LRT) with chi-square. Ratio, which is space-pressed duration divided by physical duration, was used as the dependent variable. The best-fitting model comparing three main effects included a significance of condition type (χ^2 = 1225.1, $p < 0.001$). Participants underestimated the duration more in the action with validness (active [+]) blocks than in the no action with validness blocks (passive [+]). The main effect of validity was also significant (χ^2 = 8.82, p = 0.002; see Fig). Participants mostly made underestimations when the outcome was congruent compared to incongruent.

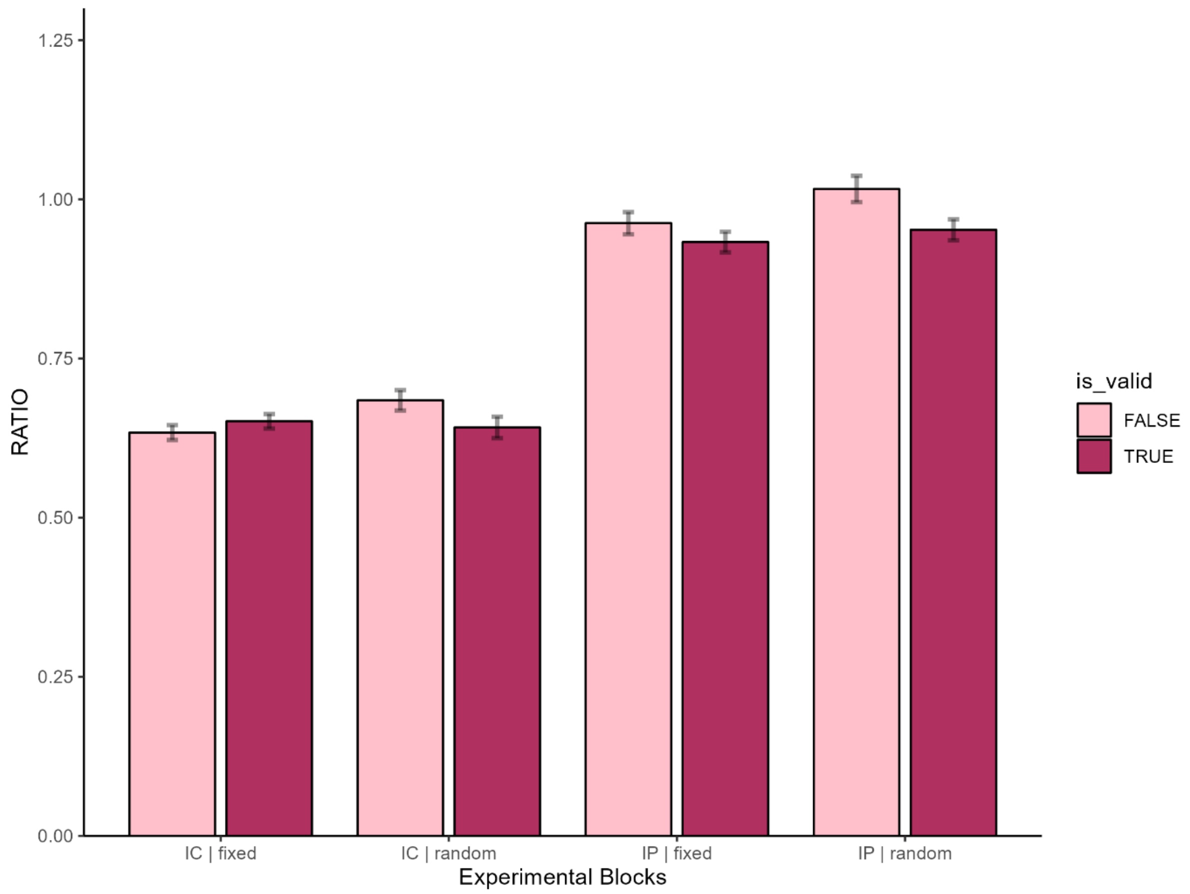


Figure 4. Results of experiment 1a.

The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as IC | Fixed, IC | Random, IP | Fixed, and IP | Random. On the y-axis, the ratio of space-pressed duration to physical duration is shown. The legends are categorised as true and false, indicating congruent outcomes (in maroon) and incongruent outcomes (in pink). The error bars describe the standard errors of the mean.

3.1.1.4.2 Experiment 1b (Temporal Control blocks)

A linear mixed model was fit with varying intercepts and slopes model with two factors coded with sum contrast. The first model introduced the predictors *Acquisition Time* (fixed, random), and *Test Time* (fixed, random). Both acquisition and test phase time levels are coded as 1 and -1 (fixed time coded as 1 and random coded as -1). The random effect structure consisted of a random intercept for participants and random slopes for acquisition time and test time by participants. To meet the model assumptions, the dependent variable ratio was first log-transformed. The best-fitting model contained a two-way interaction between acquisition and test time (χ^2 = 20.83, p < 0.001). The participants made underestimations in the blocks where the acquisition time was fixed and the test time was fixed, in addition to when the acquisition time was random, and the test time was fixed. The main effect of test time was also significant (β_{Fixed} = -0.10, SE = 0.04, t-value = -2.29, p = 0.047). Underestimations were more present when the test phase time was fixed than when it was random (See Fig).

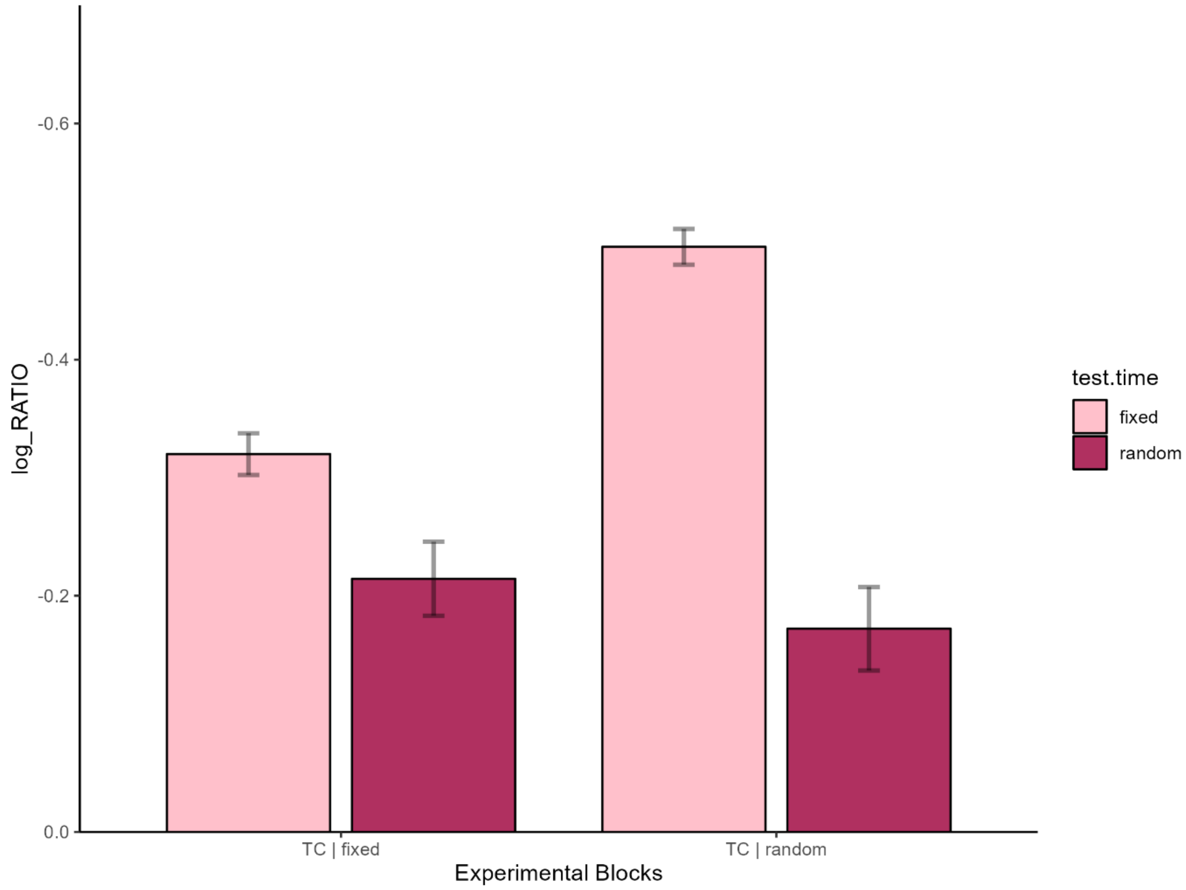


Figure 5. Results of experiment 1b.
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as TC | Fixed, TC | Random. On the y-axis, the log ratio of space-pressed duration to physical duration is shown. The legends are categorised as fixed and random, indicating random test phase intervals (in maroon) and fixed test phase intervals (in pink).

3.1.1.4.2 Experiments 1a vs 1b

Two analyses were carried out between the blocks of Experiments 1a and 1b: Identity control vs. temporal control and identity prediction vs. temporal control.

A linear mixed model was fit with varying intercepts and slopes model with factors coded with sum contrast in both analyses. The first model introduced the predictors *Condition Type* (active [-], active [+]), and *Acquisition Time* (fixed, random) for the comparison of identity control and temporal control conditions. For the comparison of temporal control and identity prediction blocks, the first model included the predictors *Condition Type* (active [-], passive [+]), and *Acquisition Time* (fixed, random) Condition type and acquisition time factor levels are coded as 1 and -1. The random effect structure consisted of a random intercept for participants and random slopes for condition type and acquisition time by participants. The models were produced in an iterative backward selection fitting procedure using likelihood ratio testing (LRT) with chi-square. Ratio, which is space-pressed duration divided by physical duration, was used as the dependent variable.

IC vs. TC (Identity control vs. Temporal Control): The best-fitting model included a two-way interaction between condition type and acquisition time (χ^2 = 136.39, $p < 0.001$). The results show that participants underestimated the interval in the fixed-identity control [active (+): fixed] and random-temporal control [active (-): random] blocks more than the other two blocks. We also found significance in the main effect of condition type. Participants underestimated the inter-event interval more in the identity control conditions than in temporal control conditions (β_{Active} (-) = 0.03, SE = 0.01, t-value = 8.99, $p = 0.037$; see Fig).

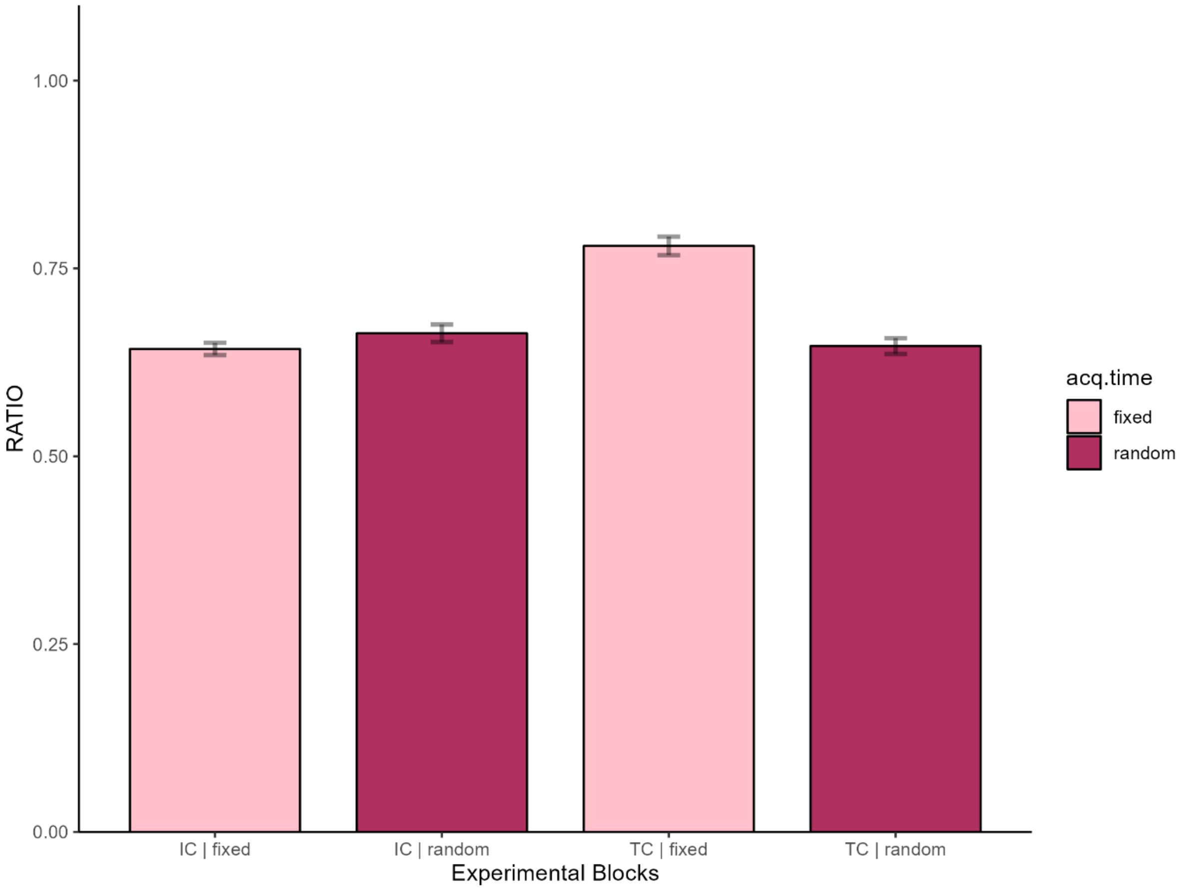


Figure 6. Results of experiments 1a vs 1b (IC vs TC)
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as IC | Fixed, IC| Random, TC | Fixed, and TC | Random. On the y-axis, the ratio of space-pressed duration to physical duration is shown. The legends are categorised as fixed and random, indicating random acquisition phase intervals (in maroon) and fixed acquisition phase intervals (in pink).

TC vs. IP (Temporal control vs. Identity prediction): The best-fitting model included a two-way interaction between condition type and acquisition time (χ^2 = 101.71, $p < 0.001$). Participants underestimated the duration more in the fixed: temporal prediction [passive (+): fixed] and random: temporal control [active (-): random] blocks. We also found significance in the main effect of condition type.

Participants overestimated the duration in the identity prediction blocks. (β_{Active} (-) = -0.12, SE = 0.02, t-value = 9.00, p < 0.001; see Fig).

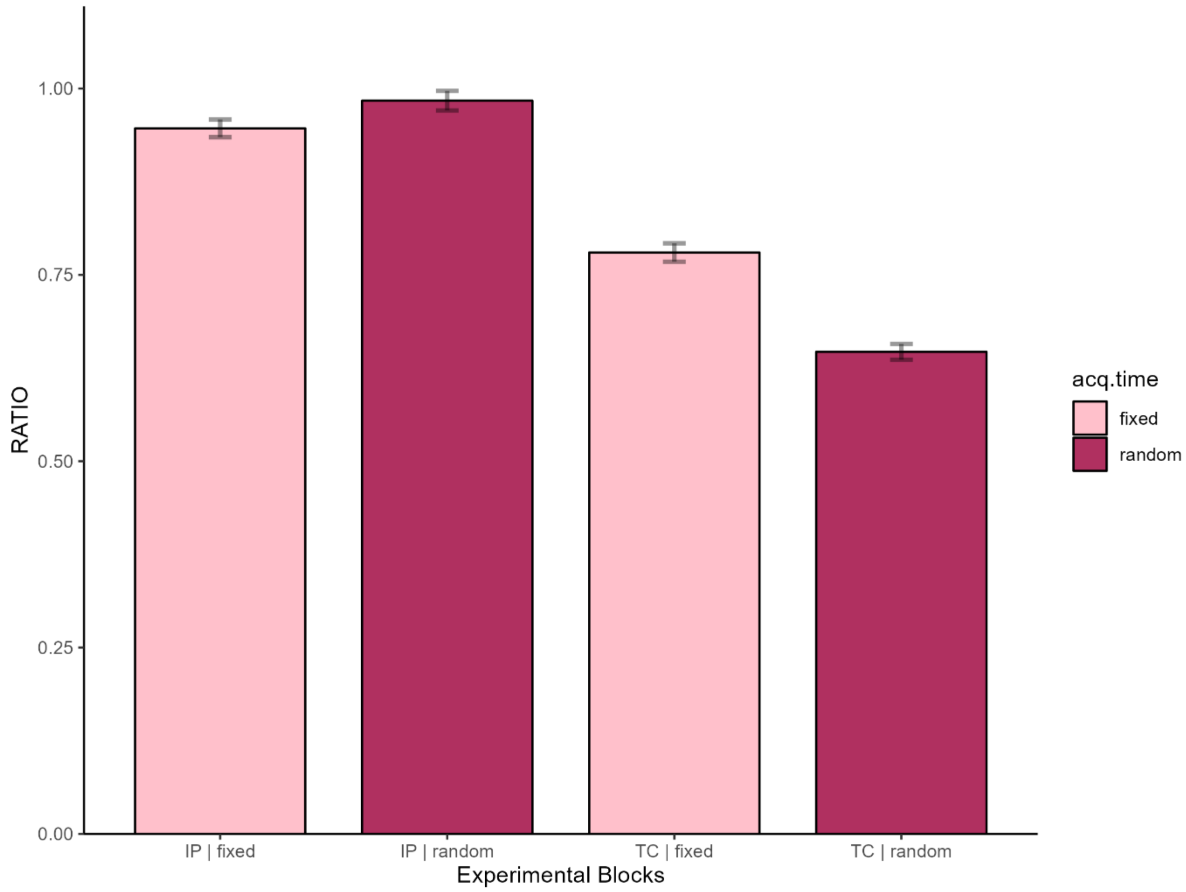


Figure 7. Results of experiments 1a vs 1b (IP vs TC)
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as IP | Fixed, IP | Random, TC | Fixed, and TC | Random. On the y-axis, the ratio of space-pressed duration to physical duration is shown. The legends are categorised as fixed and random, indicating random acquisition phase intervals (in maroon) and fixed acquisition phase intervals (in pink).

3.1.1.5 Discussion

In experiment 1, temporal predictability and validity factors influenced the temporal binding effect. Our findings failed to partially replicate the results of Desantis et al. (2012). Firstly, we discovered that the congruency of the outcomes played a significant role; when the outcomes were expected, as previously learned, participants tended to underestimate the interval. Furthermore, we observed a more pronounced compression effect when the inter-event interval was fixed, which contradicted our hypothesis that temporal prediction would not be intricately linked with temporal control.

We expected there to be no difference in the magnitude of underestimation between identity control and temporal control, as the only dissimilarity between them was the conceptual dissimilarity in learning action-outcome mappings. However, despite both conditions involving an action and causality inference component, we found that the underestimations were more prevalent in identity control blocks than in temporal control blocks.

However, as for the novelty in our design, we found that acquisition time interval learning affected the binding effect in unexpected ways. One potential issue in experiment 1 might be the uncontrolled parameters, and we believe that implementing fully controlled variables with additions such as catch trials and reaction time data as manipulation checks could affect the results in different ways than above.

3.2 Experiments 2a and 2b

3.2.1 Method

3.2.1.1 Participants

Forty-two undergraduate students were recruited using the subject pool of the Psychology department of Bogazici University for experiment 2. All participants had normal or corrected-to-normal vision; also, they did not have colour blindness or any other colour vision-related deficiencies. Participants were provided with 1.5 course credits after the completion of experimental blocks.

3.2.1.2 Apparatus and stimuli

The apparatus and stimuli were the same as in Experiment 1.

3.2.1.3 Design and procedure

The procedure and block structures remained the same as in Experiments 1a and 1b. We added new elements and made some adjustments to the design. The validness conditions in the test phases of Experiment 2a and the acquisition and test phases of Experiment 2b are set to 50%. Now, the congruency factor is semi-random, and the number of times that one stimulus occurs is equal to the other possible outcome. Next, we added reaction times as manipulation checks to see if we could capture the forward action model hypotheses in RTs but not in interval reproduction measures. Further, the design was updated in the acquisition phases of Experiment 1a with 20% of catch trials. This was done to make sure that the participants learned action-effect associations without a doubt. Together with this adjustment, we reduced the acquisition phase trial numbers from 50 to 30 to both lessen the cognitive and attentional load of participants and the level of difficulty of the experiment. Moreover, 8 or 12 trials should be more than enough to form the associations of specific action-effect mappings (Wolfenstellar&Ruge, 2011). The test phases were kept at 50 trials. Finally, the fixed inter-event interval for all blocks was changed to 650ms and the random interval to between 150 and 1150ms.

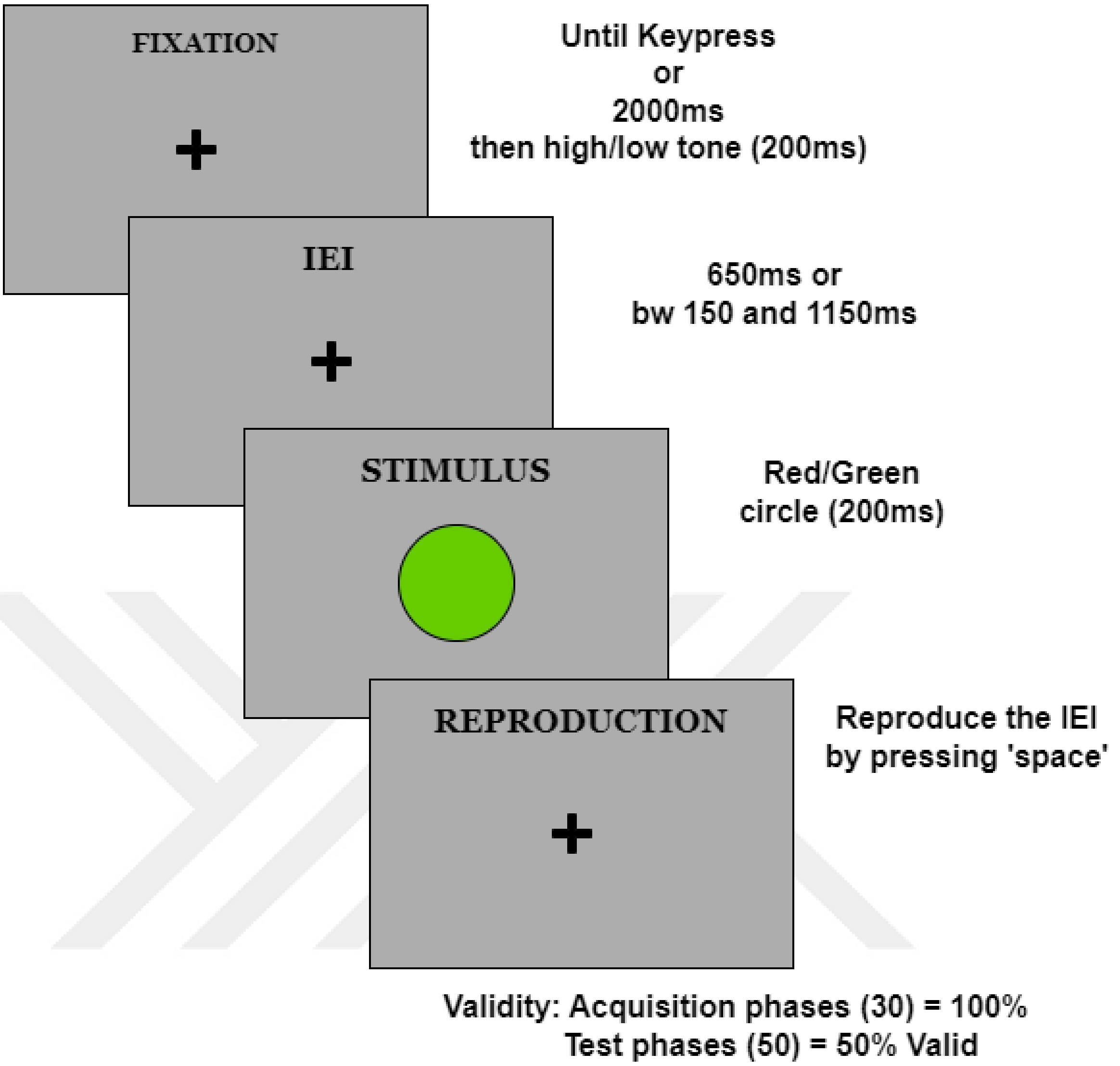


Figure 8. Design of experiments 2a and 2b
In action blocks (IC and TC), the fixation cross disappeared when they pressed left or right. In no action blocks (IP), the fixation cross disappeared after 2 seconds. After a varied or fixed interval, participants were presented with a red or green circle for 200 milliseconds. After the disappearance of the circle, they were prompted to reproduce the inter-event interval by pressing the space key.

3.2.1.4 Results

The participant's responses were evaluated based on the catch trials. Participants who accurately identified less than 80% of the catch trials were eliminated from further analysis. One participant was excluded as they only correctly identified 77.08% of the catch trials. Catch trial performance landed as 97.76% after the exclusion of one participant.

Prior to conducting linear mixed model analyses, participants' trials were cleaned from the data if the reaction times were under 100 ms or over 2000 ms. One participant's trial was deemed invalid as a result of a technical issue and, therefore, excluded from the analyses.

3.2.1.4.1 Experiment 2a (IC vs IP)

A linear mixed model was fit with varying intercepts and slopes model using sum contrast on the predictors. The first model introduced the predictors *Condition Type* (active [+], passive [+]), *Acquisition Time* (fixed, random), and *Validity* (true, false). The random effect structure consisted of a random intercept for participants and random slopes for condition type and acquisition time by participants. The models were produced in an iterative backward selection fitting procedure using likelihood ratio testing (LRT) with chi-square measure. Ratio, which is space-pressed duration divided by physical duration, was used as the dependent variable. The best-fitting model showed a two-way interaction between condition type and acquisition time (χ^2 = 61.67, p < 0.001). Participants underestimated the durations more in the fixed identity prediction and fixed identity control blocks**.** The main effects of condition type (β_{Active} (+) = -0.19, SE = 0.01, t-value = -12.23, p < 0.001) and acquisition time (β_{Fixed} = -0.03, SE = 0.01, t-value = -2.63, p = 0.012) were also significant (see Fig). In addition to intervals being overestimated in the identity prediction block, overestimations were more present when the inter-event intervals were random.

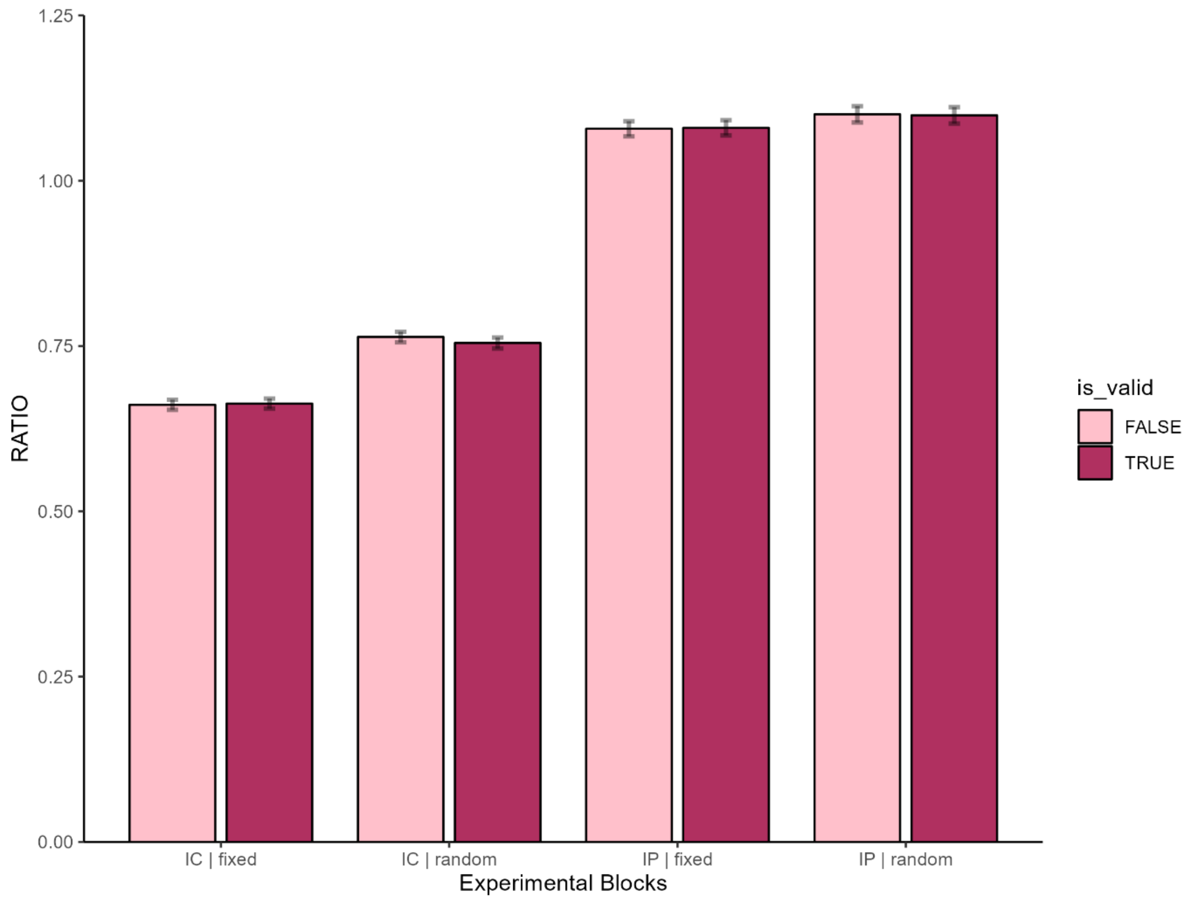


Figure 9. Results of experiment 2a
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as Identity-Control | Fixed, Identity-Control | Random, Identity-Prediction | Fixed, and Identity-Prediction | Random. On the y-axis, the ratio of space-pressed duration to physical duration is shown. The legends are categorised as true and false, indicating congruent outcomes (in maroon) and incongruent outcomes (in pink). The error bars describe the standard errors of the mean.

3.2.1.4.1.1 Experiment 2a- Reaction time analysis

A linear mixed model was fit with varying intercepts and slopes model using sum contrast on the predictors. The first model introduced the predictors *Condition Type* (active [+], passive [+]), *Acquisition Time* (fixed, random), and *Validity* (true, false). The random effect structure consisted of a random intercept for participants and random slopes for condition type and acquisition time by participants. The dependent variable reaction time (RT) was log-transformed to meet the models' assumptions. The best fitting model comparing main effects showed that only the condition type factor significantly improved the models fit (χ^2 = 11.60, p < 0.001). Participants reacted faster in the identity control blocks and temporal prediction blocks to the interval reproduction task.

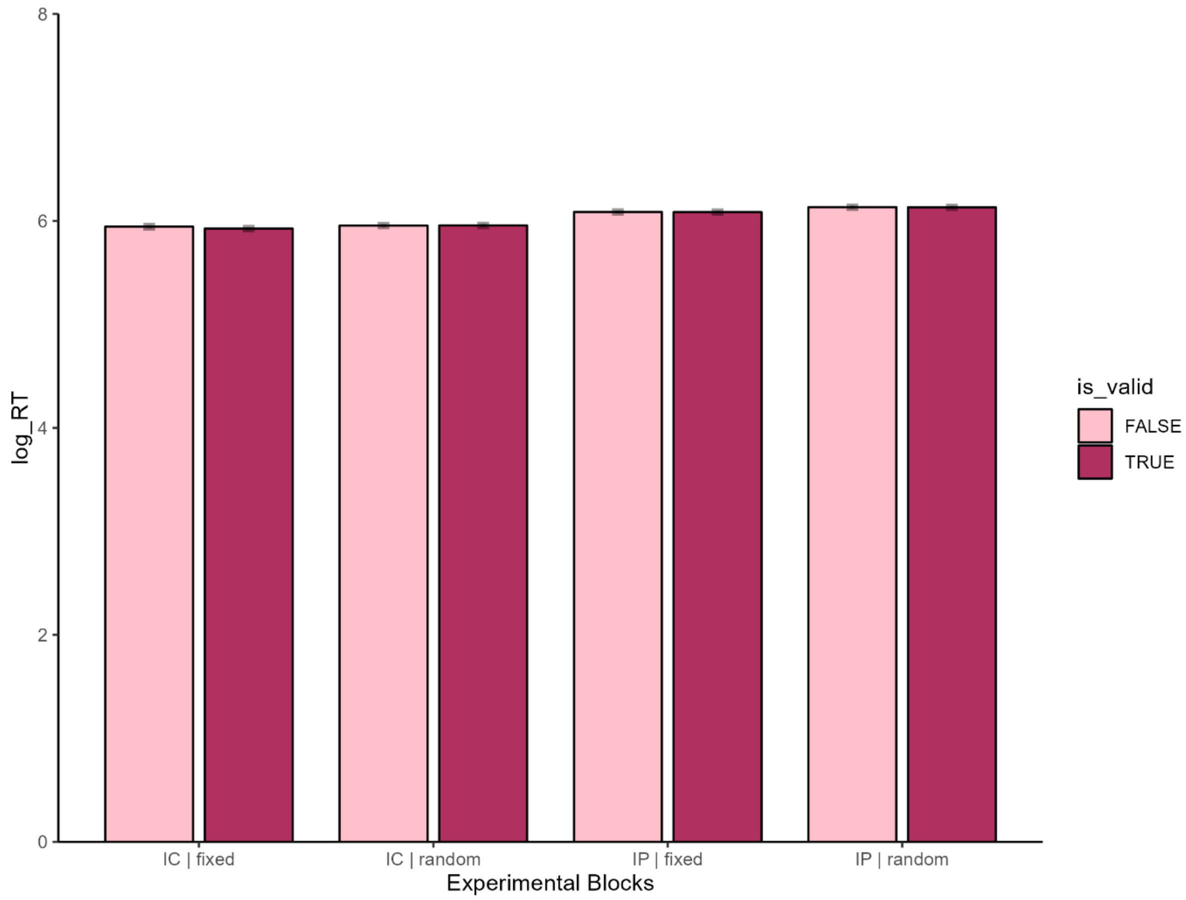


Figure 10. Reaction time results of experiment 2a
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as IC | Fixed, IC | Random, IP | Fixed, and IP | Random. The y-axis displays the log reaction time measurements in milliseconds. The legends are categorised as true and false, indicating congruent outcomes (in maroon) and incongruent outcomes (in pink).

3.2.1.4.2 Experiment 2b (Temporal Control Blocks)

A linear mixed model was fit on the log-transformed ratio variable with varying intercepts and slopes model. Predictors acquisition and test time were sum coded, fixed interval as 1 and random interval as -1. The random effect structure consisted of a random intercept for participants and random slopes for acquisition time and test time by participants. Both main effects and interaction term were not significant. The main effect test time was marginally significant (χ^2 = 3.570, p = 0.058; see Fig).

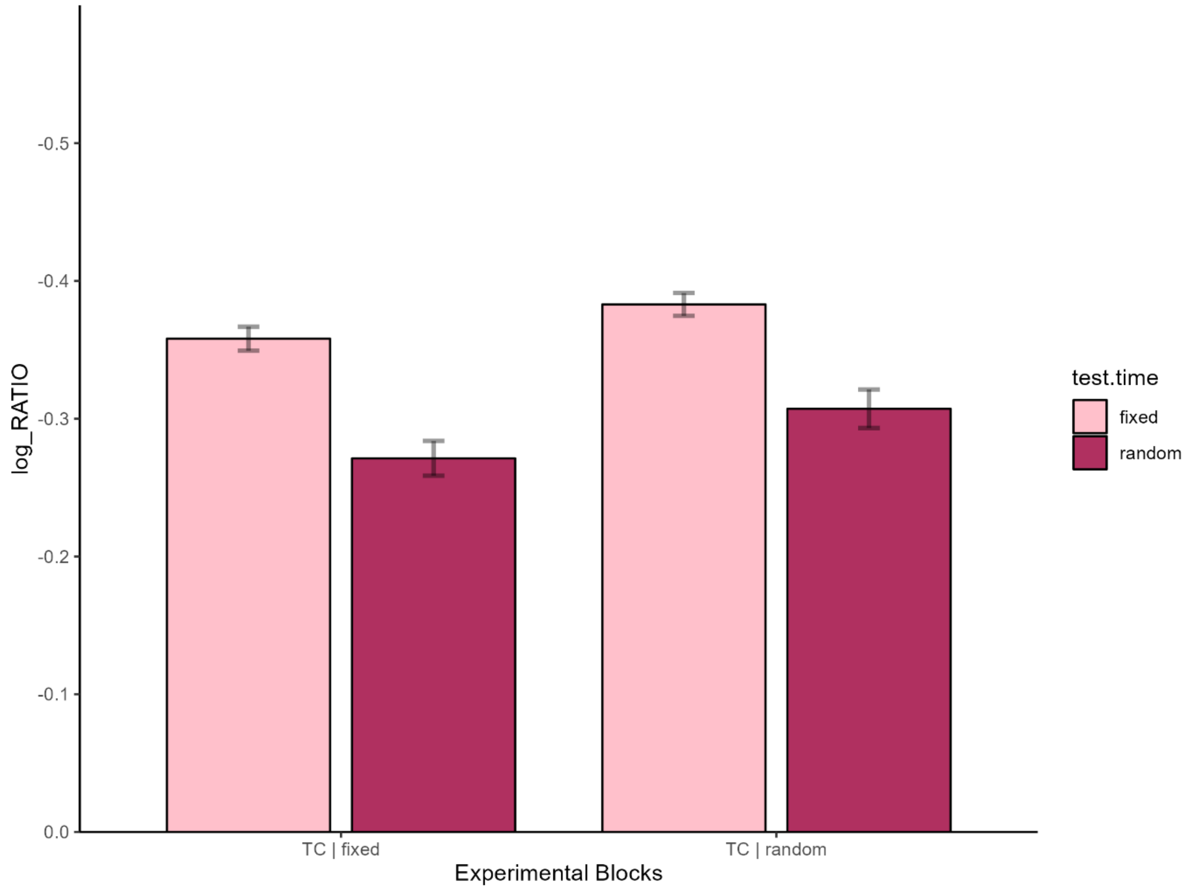


Figure 11. Results of experiment 2b
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as TC | Fixed, and TC | Random. On the y-axis, the log ratio of space-pressed duration to physical duration is shown. The legends are categorised as fixed and random, indicating random test phase intervals (in maroon) and fixed test phase intervals (in pink).

3.2.1.4.3 Experiments 2a vs. 2b

Two analyses were carried out between the blocks of Experiments 2a and 2b: Identity control vs. temporal control and identity prediction vs. temporal control.

A linear mixed model was fit with varying intercepts and slopes model with factors coded with sum contrast in both analyses. Condition type and acquisition time factor levels are coded as 1 and -1. The random effect structure consisted of a random intercept for participants and random slopes for condition type and acquisition time by participants. Ratio, which is space-pressed duration divided by physical duration, was used as the dependent variable.

IC vs TC (Identity control vs temporal control): The best-fitting model showed a two-way interaction between condition type and acquisition time (χ^2 = 338.29, $p < 0.001$). Participants underestimated the interval less in the fixed identity control (fixed: active [+]) and random temporal control (random: active [-]) blocks.

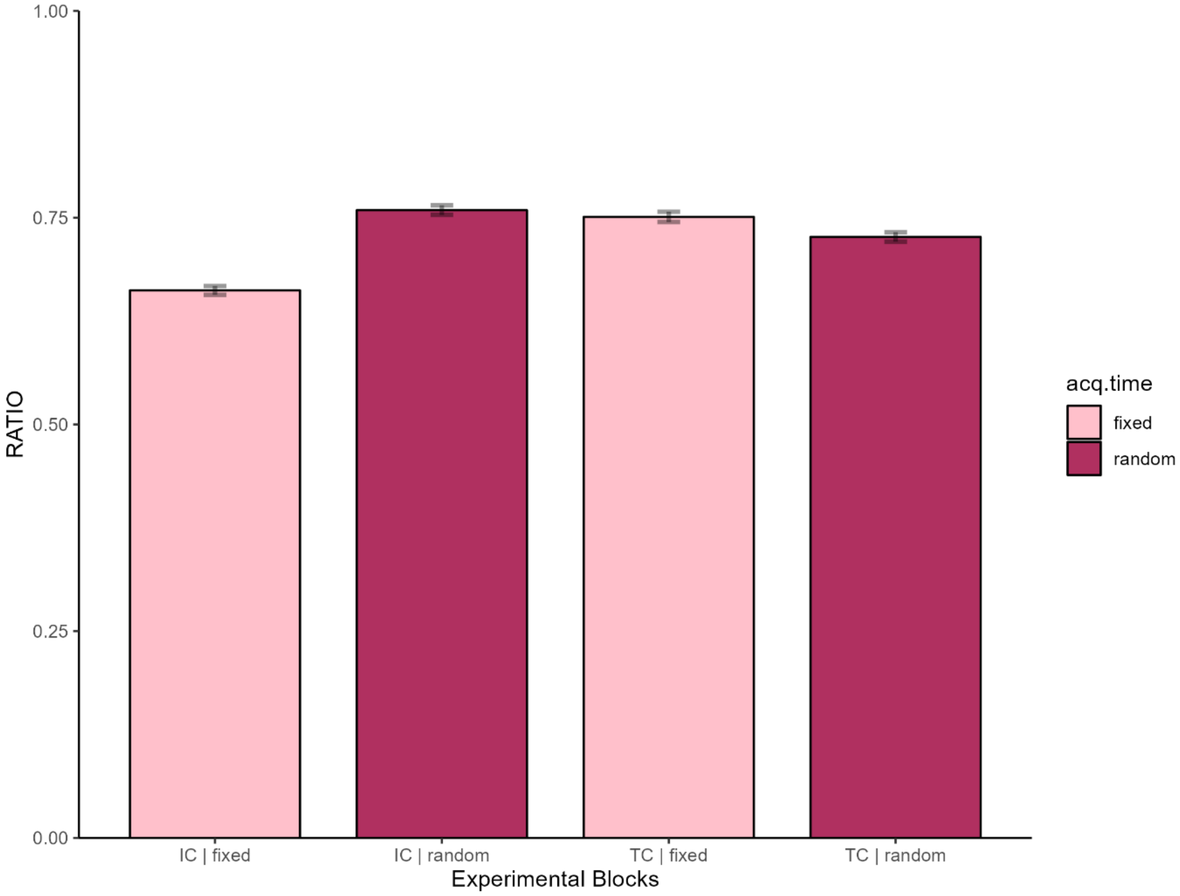


Figure 12. Results of experiment 2a vs 2b (IC vs TC)
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as IC | Fixed, IC | Random, TC | Fixed, and TC | Random. On the y-axis, the ratio of space-pressed duration to physical duration is shown. The legends are categorised as fixed and random, indicating random acquisition phase intervals (in maroon) and fixed acquisition phase intervals (in pink).

TC vs. IP (Temporal control vs identity prediction): The best-fitting model showed a two-way interaction between condition type and acquisition time (χ^2 = 27.90, p < 0.001). Underestimations were more present in the fixed identity prediction (fixed: passive [+]) and random temporal control (random: active [-]) blocks. Condition type as a main effect was also found to be significant ($\beta_{Active\ (-)}$ = -0.17, SE = 0.01, t-value = -2.63, p < 0.001). Participants overestimated the interval in the identity prediction blocks.

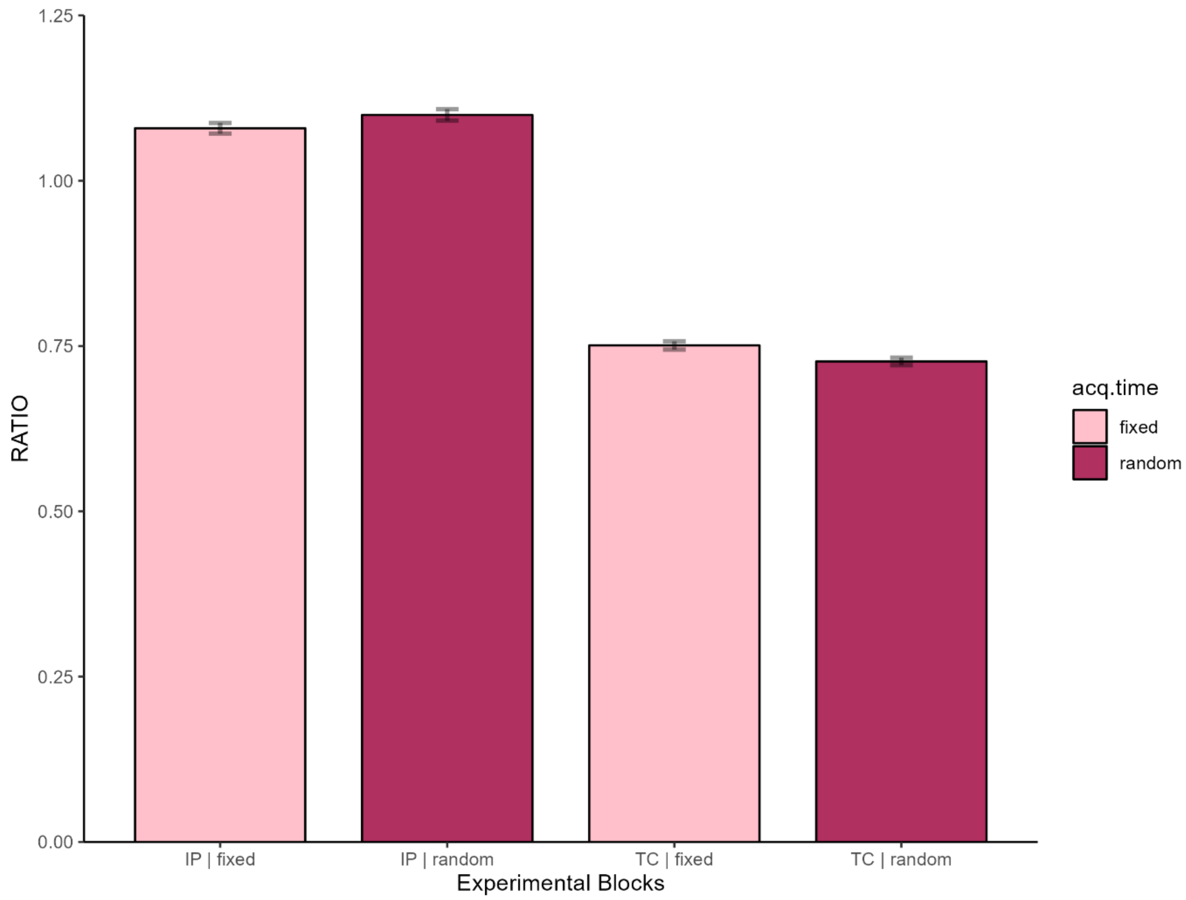


Figure 13. Results of experiment 2a vs 2b (IP vs TC)
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as IP | Fixed, IP | Random, TC | Fixed, and TC | Random. On the y-axis, the ratio of space-pressed duration to physical duration is shown. The legends are categorised as fixed and random, indicating random acquisition phase intervals (in maroon) and fixed acquisition phase intervals (in pink).

3.2.1.5 Discussion

In Experiment 2, we confirmed all our hypotheses, and we were able to replicate the results of three previous studies conducted by Desantis et al. (2012), Haering & Kiesel (2014), and Bednark et al. (2015). We discovered that the validity effect has no bearing on binding. In terms of reaction times, the congruency component did not affect the participants' responses to the outcomes. This was expected because half of the trials were congruent, and the other half were incongruent. However, the participants responded faster in the identity control blocks compared to the identity prediction blocks.

Our research findings indicate that dissociating temporal control from temporal prediction does not lead to a lack of binding. There were no significant differences between temporal control blocks, which supports our hypothesis. On the contrary, the presence of action with the apparent causal link could be the only driving force for temporal binding. However, there is still room for debate regarding the slightly larger underestimations in the fixed blocks.

We have corroborated the results of Humphreys and Buehner's study from 2010 by using random intervals between events. The temporal binding effect was observed when action was used as an initiator at varying intervals. In our experiment, we found that learning the interval during the acquisition period had an effect on other factors, which produced new results, similar to our first experiment. Our findings indicate that the apparent causal inference is pertinent to the binding effect between two events (Hoerl et al., 2020), which was not present in blocks without actions, even though temporal predictability and validity learning were present.

3.3 Experiments 3a and 3b

3.3.1 Method

3.3.1.1 Participants

Forty-four undergraduate students were recruited using the subject pool of the Psychology department of Bogazici University for experiment 3.
Three participants were excluded due to not finishing the whole experiment. All participants had normal or corrected-to-normal vision; also, they did not have colour

blindness or any other colour vision-related deficiencies. Participants were provided with 1.5 course credits after the completion of experimental blocks.

3.3.1.2 Apparatus and stimuli

The apparatus and stimuli were the same as in Experiment 1 and 2.

3.3.1.3 Design and procedure

The design and procedure were the same as in Experiment 2a except for one: Congruency proportions in the test phases of the blocks in Experiment 3a were set to 80/20%.

Experiment 3b remained the same as Experiment 2b.

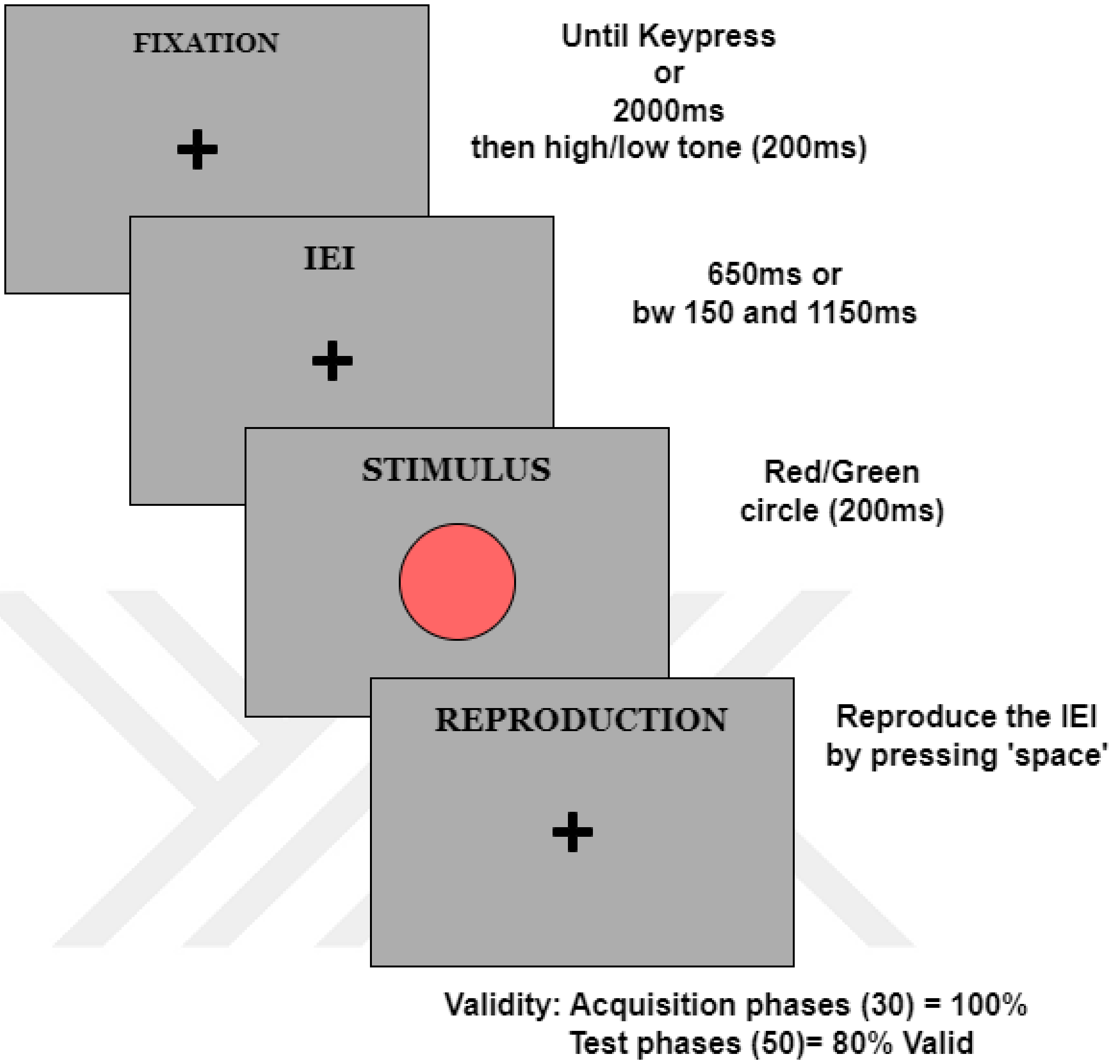


Figure 14. Design of experiments 3a and 3b
In action blocks (IC and TC), the fixation cross disappeared when they pressed left or right. In no action blocks (IP), the fixation cross disappeared after 2 seconds. After a varied or fixed interval, participants were presented with a red or green circle for 200 milliseconds. After the disappearance of the circle, they were prompted to reproduce the inter-event interval by pressing the space key.

3.3.1.4 Results

The participant's responses were evaluated based on the catch trials. Participants who accurately identified less than 80% of the catch trials were eliminated from further analysis. No one was under the exclusion criteria in experiment 3. Overall catch trial performance landed as 98.02%. One participant's trial was deemed invalid as a result of a technical issue and, therefore, excluded from the analyses.

Prior to conducting linear mixed model analyses, participants' trials were cleaned from the data if the reaction times were under 100 ms or over 2000 ms.

3.3.1.4.1 Experiment 3a (IC vs IP)

A linear mixed model was fit with varying intercepts and slopes model with three factors coded as 1 and -1. The first model introduced the predictors *Condition Type* (active [+], passive [+]), *Acquisition Time* (fixed, random), and *Validity* (true, false). The random effect structure consisted of a random intercept for participants and random slopes for condition type and acquisition time by participants. The best-fitting model showed a two-way interaction between condition type and acquisition time (χ^2 = 5.59, p = 0.017). Participants underestimated the interval more identity control and prediction more in random than fixed blocks. Condition type as a main effect was also found to be significant ($\beta_{Active\ (+)}$ = -0.18, SE = 0.01, t-value = -9.95, $p < 0.001$). Participants underestimated the interval in the identity control blocks and overestimated the interval in the identity prediction blocks.

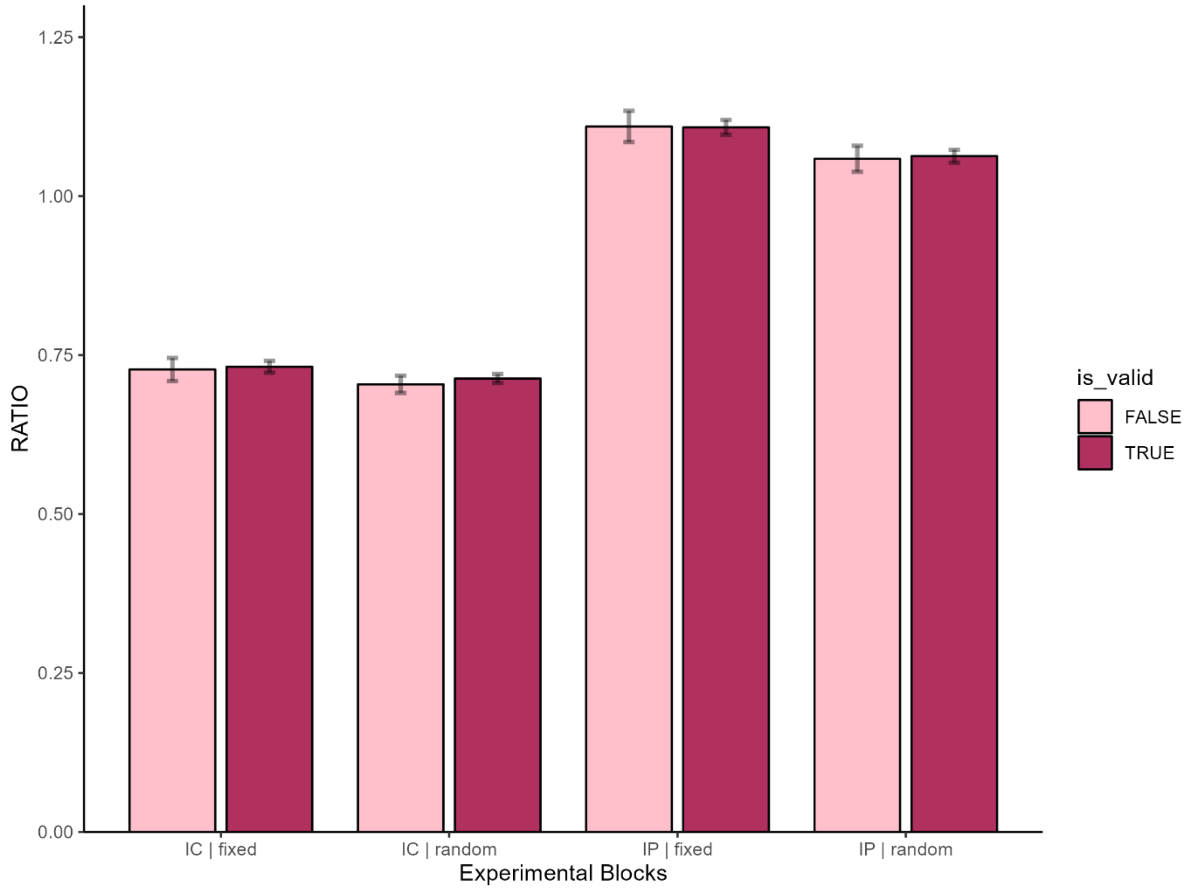


Figure 15. Results of experiment 3a
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as IC | Fixed, IC | Random, IP | Fixed, and IdP | Random. On the y-axis, the ratio of space-pressed duration to physical duration is shown. The legends are categorised as true and false, indicating congruent outcomes (in maroon) and incongruent outcomes (in pink).

3.3.1.4.1.1 Experiment 3a- Reaction time analysis

A linear mixed model was fit with varying intercepts and slopes model using sum contrast on the predictors. The first model introduced the predictors *Condition Type* (active [+], passive [+]), *Acquisition Time* (fixed, random), and *Validity* (true, false). The random effect structure consisted of a random intercept for participants and random slopes for condition type and acquisition time by participants. The dependent variable reaction time (RT) was log-transformed to meet the normality assumptions. The best fitting model produced a significant three-way interaction between condition type, acquisition time, and validity (χ^2 = 7.20, p = 0.007). The main effects of condition type ($\beta_{Active\ (+)}$ = -0.09, SE = 0.02, t-value = -4.04, p < 0.001) and validity (β_{False} = 0.02, SE = 0.005, t-value = 4.98, p = 0.012) were also significant (see Fig). Participants were faster in the Identity control conditions and faster reaction times were recorded when the action-outcome mappings were true to what they had learned in the acquisition phase.

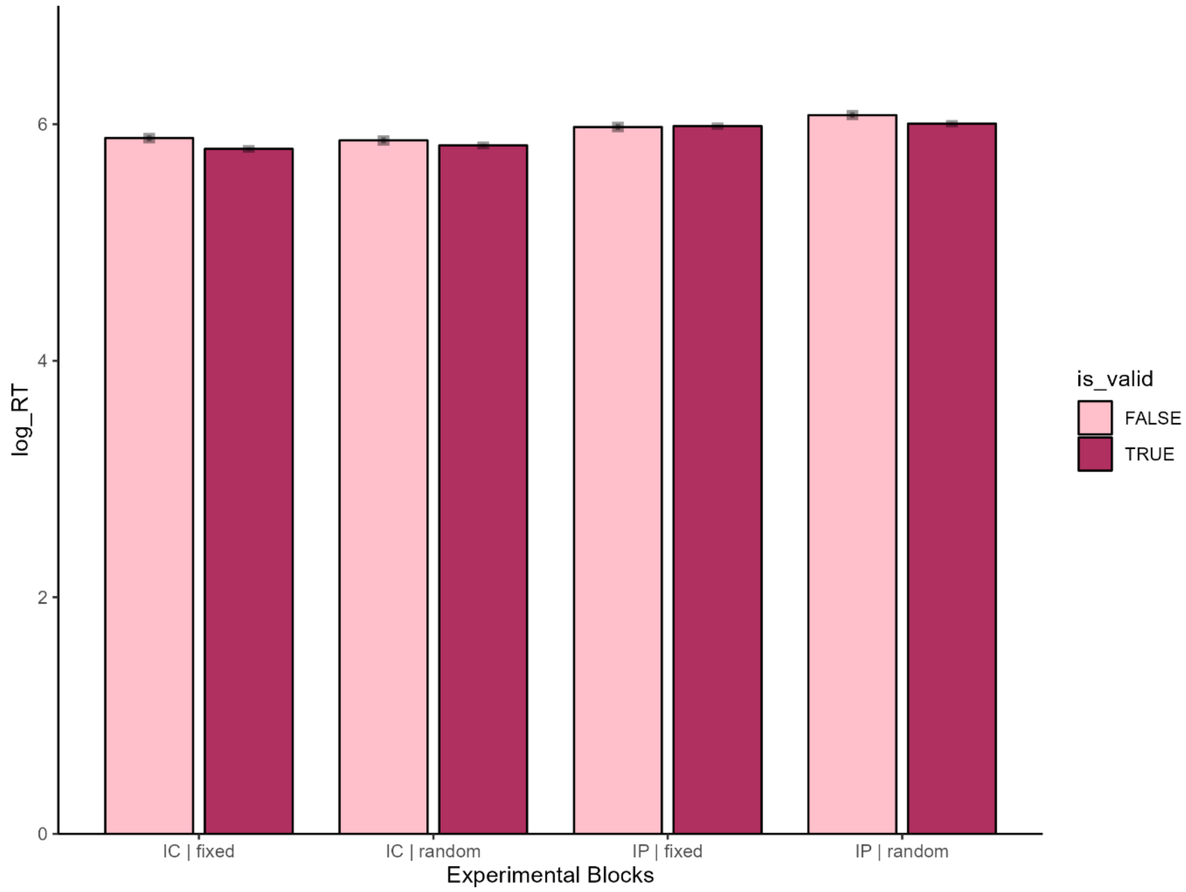


Figure 16. Reaction time results of experiment 3a
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as IC | Fixed, IC | Random, IP | Fixed, and IP | Random. The y-axis displays the log reaction time measurements in milliseconds. The legends are categorised as true and false, indicating congruent outcomes (in maroon) and incongruent outcomes (in pink).

3.3.1.4.2 Experiment 3b (Temporal control blocks)

A linear mixed model was fit with varying intercept and slopes model, and the predictors acquisition time and test time were sum coded as 1 and -1. The random effect structure consisted of a random intercept for participants and random slopes for acquisition time and test time by participants. The dependent variable was ratio log-transformed. We found the significance in the model only for the main effect of test time (χ^2 = 6.80, p = 0.009). Participants underestimated the interval more when the test phase times were fixed than random.

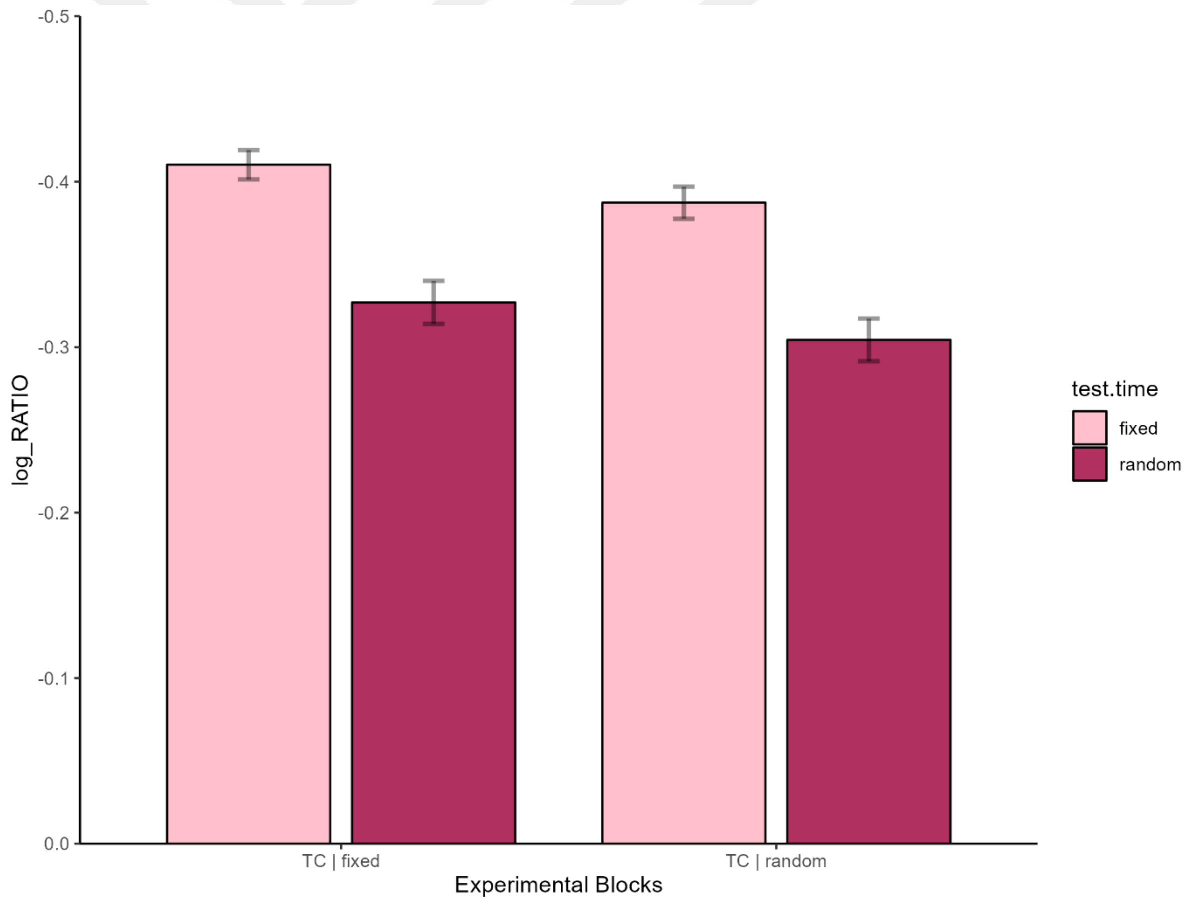


Figure 17. Results of experiment 3b
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as TC | Fixed, and TC | Random. On the y-axis, the log ratio of space-pressed duration to physical duration is shown. The legends are categorised as fixed and

random, indicating random test phase intervals (in maroon) and test acquisition phase intervals (in pink).

3.3.1.4.3 Experiments 3a vs. 3b

Two analyses were carried out between the blocks of Experiments 3a and 3b: Identity control vs. temporal control and identity prediction vs. temporal control.

A linear mixed model was fit with varying intercepts and slopes model with factors coded with sum contrast in both analyses. Condition type and acquisition time factor levels are coded as 1 and -1. The random effect structure consisted of a random intercept for participants and random slopes for condition type and acquisition time by participants. The dependent variable ratio was log-transformed to meet the model's normality assumptions.

IC vs TC (Identity control vs temporal control): The best-fitting model showed a two-way interaction between condition type and acquisition time (χ^2 = 6.70, p = 0.009). The underestimations occurred when the blocks were fixed, temporal control (active [-]: fixed), and random, identity control (active [+]: random).

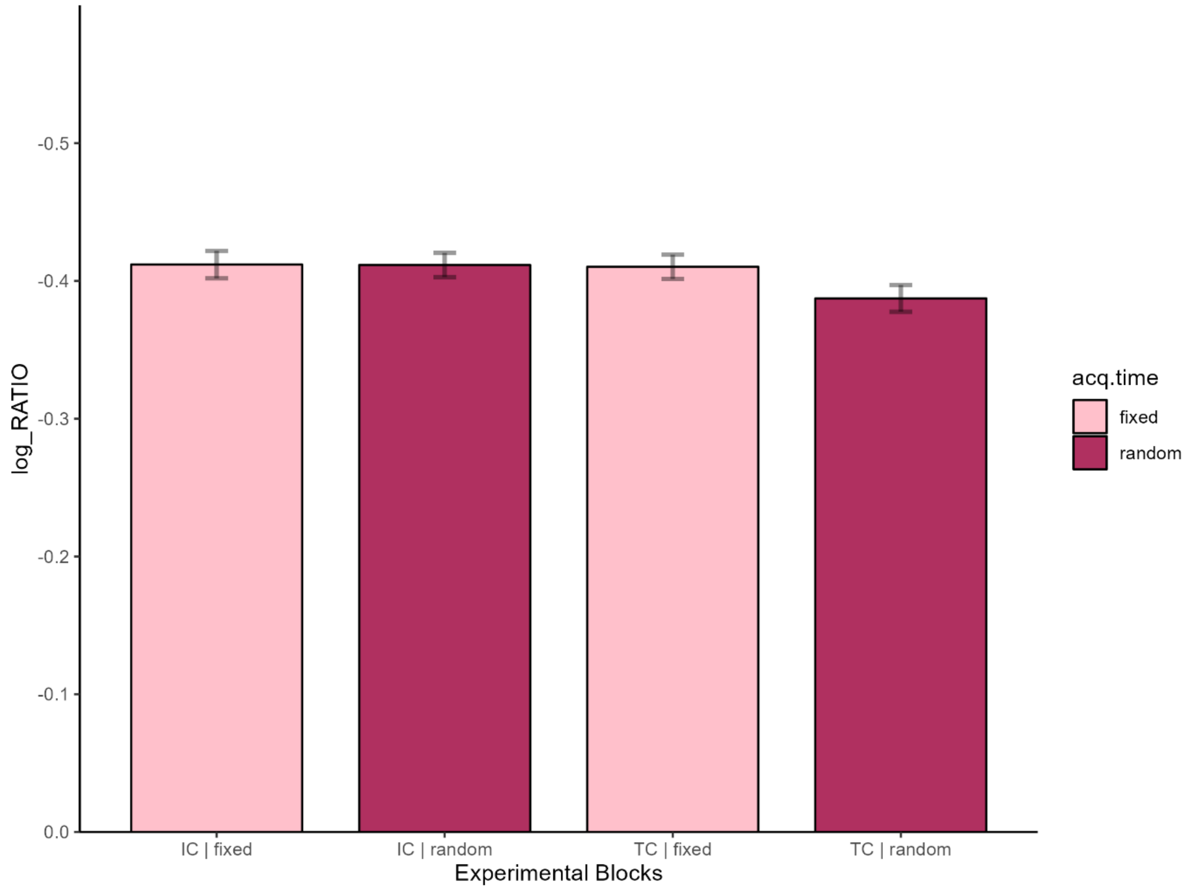


Figure 18. Results of experiment 3a and 3b (IC vs TC)
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as IC | Fixed, IC | Random, TC | Fixed, and TC | Random. On the y-axis, the log ratio of space-pressed duration to physical duration is shown. The legends are categorised as fixed and random, indicating random acquisition phase intervals (in maroon) and fixed acquisition phase intervals (in pink).

TC vs. IP (Temporal control vs. Identity prediction): The best-fitting model showed a two-way interaction between condition type and acquisition time (χ^2 = 26.16, p < 0.001). Participants made relative overestimations in the random temporal control and fixed identity prediction blocks compared to their counterparts. Condition type as a main effect was also found to be significant (β_{Active} (-) = -0.20, SE = 0.02, t-value = -8.94, p < 0.001). The interval was underestimated in the temporal control blocks and overestimated in the identity prediction blocks.

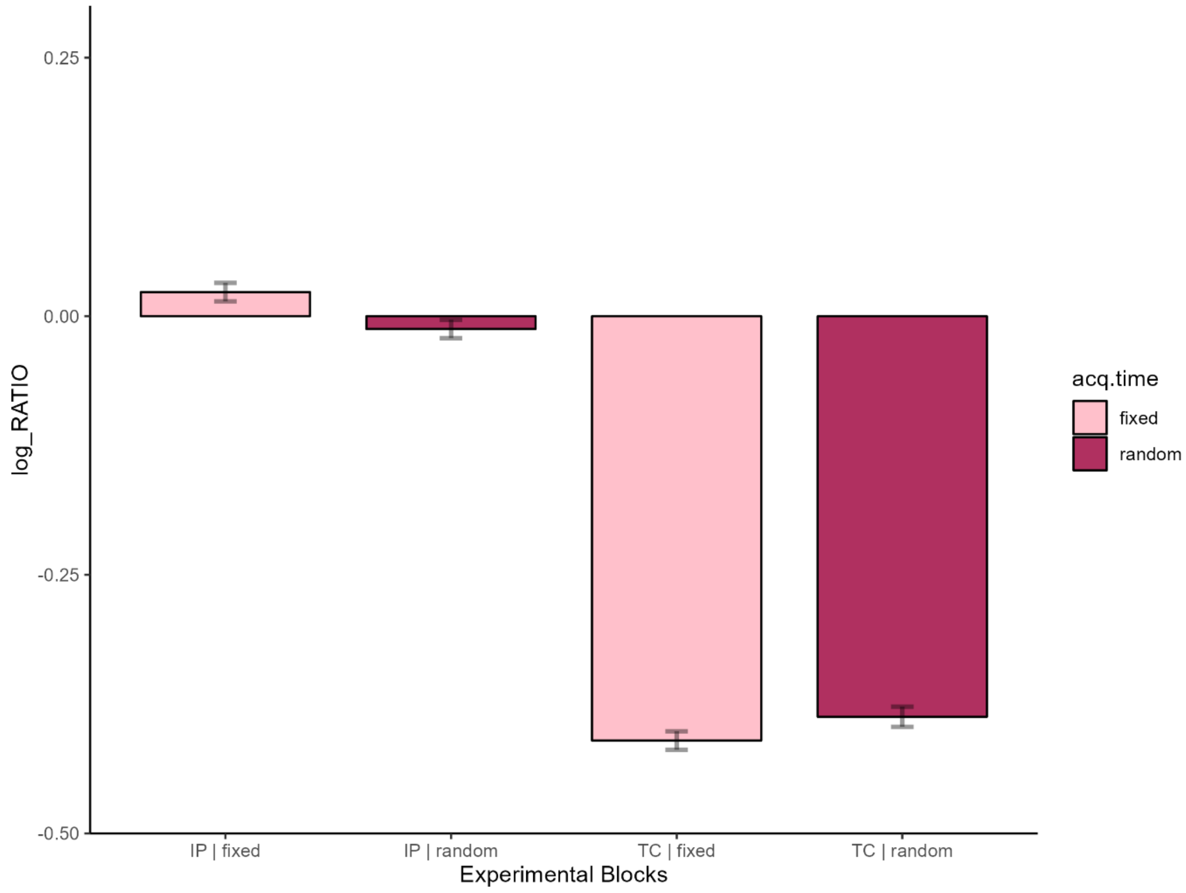


Figure 19. Results of experiment 3a and 3b (IP vs TC)
The graph displays data on the x-axis for experimental blocks represented by condition type and acquisition time interval. These are grouped as IP | Fixed, IP | Random, TC | Fixed, and TC | Random. On the y-axis, the log ratio of space-pressed duration to physical duration is shown. The legends are categorised as fixed and random, indicating random acquisition phase intervals (in maroon) and fixed acquisition phase intervals (in pink).

3.3.1.5 Discussion

In experiment 3, we were able to confirm the findings from experiment 2. We found that temporal binding was not influenced by validity, and it was enough for the action to be present with the causal link for binding to occur. However, in addition to the faster reaction times observed in the identity control blocks, we also noted that participants reacted faster in 80% of the trials when the outcome was congruent, which was consistent with the results obtained by Haering & Kiesel in 2014.

Additionally, the manipulation of the intervals between acquisition times was found to be significant once again, although in different ways. We believe that the results of learning the intervals between events during the acquisition phase may vary depending on the context. This suggests that the temporal binding phenomenon is adaptable and context-dependent, as suggested by Humphreys and Buehner (2010). Moreover, the underestimation of intervals was more noticeable when the interval was fixed in the temporal control blocks. However, it is recommended that further research be conducted to investigate this phenomenon in terms of how temporal control would still be adequate for the effect, dissociated from temporal prediction, when using random intervals within a range. Seeing as the binding effect was actualised when the random inter-event intervals were used, as well as fixed intervals, we still believe that temporal control alone could be the root cause of binding under the guise of causal inference assumption.

CHAPTER 4

GENERAL DISCUSSION

The temporal binding effect refers to the perceived compression of time between an action and its outcome or two events that are causally related. Extensive research has been conducted on this effect ever since its introduction by Haggard et al. (2002). Initially, it was observed as an effect separating an intentional action and a secondary event, and since then, the factors that cause and modify the effect have been discussed in detail. The two primary explanations of the effect to this date have been intentionality and causality and continue to be the focus of research. However, the topic of which mechanisms drive the binding effect and how it occurs remains under-observed. This thesis aimed to explore which predictive mechanisms could be the underlying process of temporal binding and whether learning the relationships between events, as well as the intervals before the test phase, affects the magnitude of binding or manipulates it. We were interested in particularly the mechanisms of identity prediction, which is the ability to anticipate which outcome would be displayed in relation to prior action or to an external event, whether one controls the start of an event, namely temporal control, and predicts at the time which secondary event occurs without initiating the first event, namely temporal prediction.

We aimed to dissociate some of these concepts, which were introduced at the beginning of this thesis, classified by Hughes et al. (2013). The emphasis was on the process of temporal control. Through the use of both fixed and random intervals during test phases, we calibrated the concept of temporal control, which refers to the action component that influences the occurrence of the second event within a time window rather than at a specific time.

We investigated how predictive processes affect binding by examining the differences in conditions where temporal control varied from identity control and identity prediction. We also compared the validity factor of identity prediction and identity control in all three experiments. Participants were tasked to judge the inter-event interval after every trial between the two events via reproduction in all experiments. Experimental blocks differed based on whether they were inclined to learn or not learn any relationships between two events. Additionally, the interval was either varied or kept constant during the acquisition phases to see how this would impact the participants' ability to learn and remember the event mappings and intervals. The prior circumstances were then manipulated in the subsequent test phases to see how well the participants retained the information. We expected to find no identity prediction effect on temporal binding, however, the effect of the identity prediction process would be ascertained in reaction times regardless of the temporal binding process. We also hypothesized that the magnitude of binding would not be discernible between the action blocks, identity, and temporal control. In accordance with the hypothesis mentioned above, we also anticipated that the absence of action components in the initial stage would lead to an absence of temporal binding effect in identity prediction blocks.

The results of preliminary experiment 1 showed two unexpected outcomes. Firstly, we observed a validity effect on temporal binding, indicating that participants perceived durations as shorter when the outcome was congruent. However, these results were not replicated in experiments 2 and 3, in which the probability of congruent outcomes was controlled and set according to experimental design, as mentioned. Secondly, contrary to our expectation of action blocks not resulting in a magnitude difference in their binding effect, participants underestimated the interval more in identity control blocks than in temporal control blocks. This result was also absent in experiments 2 and 3, and the disparity between these experiments might be the product of design variables that were altered. Overall, the results were in line with the hypotheses that we set:

I.) Inter-event intervals were judged shorter in action blocks compared to no-action blocks. When participants did not perform any action, the effect of temporal binding was not observed.

II.) The identity prediction process had no effect on the binding effect, yet it was present in reaction times data, indicating participants were faster in pressing the button when the outcomes were congruent.

4.1 Interpretation of the results

We investigated, in three experiments, how temporal binding is modulated and influenced by predictive processes and hoped to find which process drives the binding effect in a novel design. We also aimed to differentiate one of these predictive processes, namely temporal control, as Hughes et al. (2013) introduced the concept that intertwined with temporal prediction. In Experiment 1, we replicated the results of Desantis et al. (2012) and Haering and Kiesel (2014) by demonstrating that the mere presence of action is sufficient to create temporal binding. However, we failed to replicate that identity prediction does not influence binding. It is imperative to mention that in our preliminary experiment 1, we did not control the percentage of valid/invalid trials, so one might argue that this could be behind the significance of validity findings in experiment 1. Furthermore, we did not gather reaction time data, so we can only speculate that the significance of validity could also be demonstrated in faster reaction times in every trial of congruent outcomes.

Ultimately, in experiments 2 and 3, we replicated the results of the studies as mentioned earlier, and Hughes et al.'s (2013) claim that temporal control is the deciding factor on the binding effect and identity prediction, therefore, the forward action mechanisms do not modulate the effect. In experiment 2, we changed the experimental design to fully controlled in terms of the percentages, added catch trials and collected reaction time data as manipulation checks. When examining the effects of validity on 50% congruent and incongruent outcomes in experiment 2, we found that our hypothesis regarding the influence of identity prediction on binding effect was supported. The identity prediction process was found to be uninfluential to temporal binding, and these findings extended the results of Desantis et al. (2012) using an interval reproduction task. The validity effect was absent in reaction times data as well. The probability of seeing an outcome equally does not seem to affect participants' congruency judgements. Dissociating temporal control from temporal prediction as part of novelty in our design, the temporal binding effect was present when both fixed and random intervals were presented, supporting Humphreys & Buehner's (2010) results that utilising fixed inter-event intervals is not the main factor for temporal binding to occur. Thus, we believe that exact temporal predictions need not be taken into account where there is apparent causality between an action and its effect for binding to occur. Furthermore, we argue that rather than relying on temporal prediction, temporal control alone should suffice, as the effect may be attributed to the causal associations brought about by an action. As per the other novelty in our design, we found that manipulations of acquisition time alone did not affect temporal binding, however, it interacted with the other factors, revealing that learning whether the interval is fixed or random before the test phase could lead to new interpretations and investigations for future research.

We further replicated the findings of Haering and Kiesel (2014) as well as Bednark et al. (2015) in experiment 3. The only difference between experiments 2 and 3 was changing the congruency percentage to 80% to explore the validity effect in a more pronounced way. Once more, we found that temporal control is the driving force of temporal binding effect rather than temporal or identity prediction processes. However, using 80% congruent trials, we discovered that the reaction times were now faster in valid compared to invalid trials. This indicates that first, participants learned the event mappings prior without any confusion. Second, forward action models have a reach that extends to pre-reflective measures, such as reaction times. Still, contrary to Haggard et al.'s (2002) claim, it does not go over to the binding effect as a modulating factor (Haering & Kiesel., 2014).

This thesis aimed to explore the mechanisms of binding, specifically to identify which predictive processes contribute to the resulting effect. We argue that temporal control, especially the apparent and unambiguous link between two dynamic events without regard to identity predictions of outcomes and without the need for a strict, fixed time window, is the underlying mechanism for temporal binding effect. On the other side of the discussion - as to why binding occurs- as discussed in the previous sections, we believe that temporal binding can be explained under the realm of causal binding, making it the most plausible explanation. As productive as the intentional vs causal binding discourse, we consider that the effect of action would be more pronounced in magnitude, as Shiloh et al. (2017) suggest that it gives a boost to the effect compared to mechanical-causal conditions. Temporal binding effect can only be achieved through induced causality, as opposed to relying on fixed identity or temporal prediction predictive processes. Consequently, causal binding accounts should be immersed in explaining the enhanced effect of one's own action, as it makes the causal link between events more conspicuous. Hoerl et al. (2020) have proposed an explanation for the boost effect of action, which we believe is a plausible approach towards the discoveries made in temporal binding research.

4.2 Putting a new philosophical framework into perspective

Hoerl et al. (2020) have put forward a novel framework that explains temporal binding as a top-down effect which is attributed to the belief in causality. Their proposal includes the historical ways of defining and determining the binding effect in two different conceptualisations, and after explaining the context of both, they conclude that there is a way in which we could unify those two accounts without the need for a conflict.

The first way of conceptualising temporal binding was the 'intentional' binding accounts, represented after Haggard et al. (2002) study. In this framework, the effect is a result of pre-reflective mechanisms such as the forward model of motor control (Blakemore, Wolpert and Frith, 2002) between voluntary actions and their consequences. In this model, there are agents initiating intentional movements and relegating their actions to an outcome that is certain by means of expectations. The model contains a desired state(goal-directed), a motor command (kinematic information for the movement), and a predicted vs. actual state of the outcome. If the desired or predicted outcome matches with the actual outcome of intentional action, this entire process could be the underlying process of the binding effect. Hoerl et al. (2020) state that the processes involved in motor control are inaccessible to conscious awareness and are sub-personal.

The second way of conceptualising temporal binding involves the contexts of involuntary or mechanical actions. The framework posits that the temporal binding effect originates from instances of perception that are top-down in nature and reflect a belief in causality. Simply observing a sequence of events that are causally related and attributing causality to them based on their apparent relationship (Buehner & Humphreys 2009; Buehner 2012; Poonian et al. 2015) could be the emergent reason behind the temporal binding effect as well as intentionality in this context. Another example they stated was Borhani et al. (2017), in which the temporal binding effect occurs even when a participant's finger is pressed down by an experimenter.

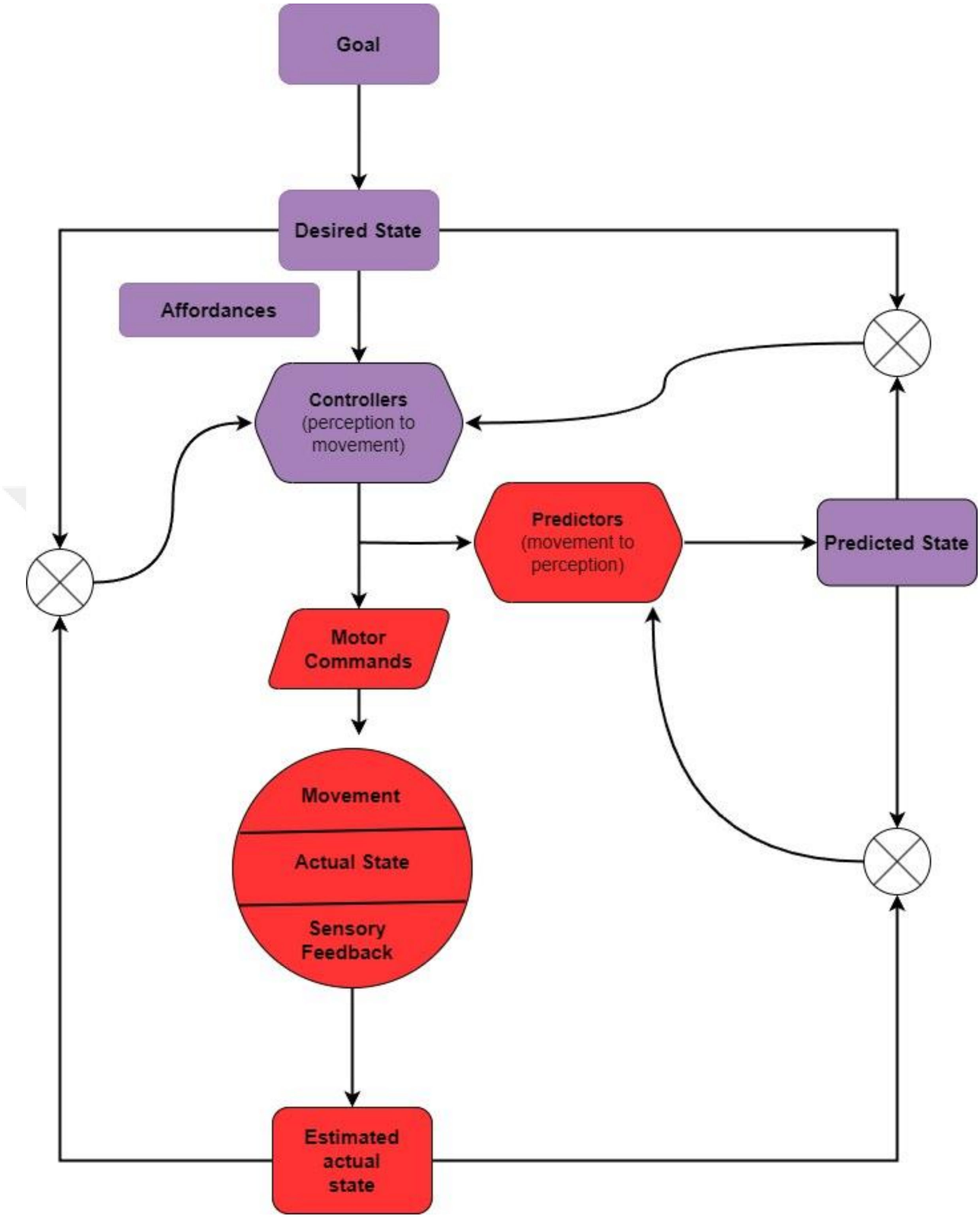


Figure 20. Framework of motor control system in Blakemore et al. (2002).
The motor control system is comprised of multiple types of motor representation. Some of these representations are available to our conscious awareness (colored in purple), while others are not (colored in red). 1) The current state of the system cannot be directly perceived by the central nervous system. Instead, an estimated actual state of the system is inferred based on the motor commands, predictions based on motor commands, and sensory feedback. 2) The representation of the desired state of the system reflects the immediate goal of the system and is available to our conscious awareness. 3) The next predicted state of the system provides an estimate of the future state of the system, which is derived from the predictors. The predicted state appears to be available to our

conscious awareness. 4) Motor commands are generated by the controllers and are refined by sensory information (affordances) about the current state of the world, such as visual information about the position and shape of the object to be grasped. We are not conscious of the motor commands or the fine adjustments made to them. 5) Sensory feedback is the result of the action performed, along with any environmental events. Experiments suggest that we have only limited awareness of the consequences of our actions. Figure and caption re-created from Blakemore et al. (2002).

Hoerl and his colleagues (2020) consider these two conceptualisations as coming from two different mechanisms on the grounds that the contexts in which binding occurs when involuntary action takes place cannot be explained by the forward motor control model, which takes voluntary and goal-directed actions to be the essential part of its process. However, the conceptual issue in this differentiation, as they emphasise, is whether or not voluntary action contexts resulting in binding effect are just about voluntary action or might include the beliefs of cause-effect relations. The need to draw a clear distinction between these two possibilities is essential for the 'intentional' binding account that argues that the pre-reflective voluntary actions are the root cause of the temporal compression illusion.

> Our argument is thus that we need to draw a clear distinction, even in cases in which temporal binding occurs in the context of a voluntary action, between the claim that it is a measure of a pre-reflective sense of agency and the claim that it is a consequence of a belief that the two events that are being bound together stand in a cause–effect relationship. The latter is simply a belief about a causal connection between two events, conceived of as two events, irrespective of the further question as to whether one of them constitutes a voluntary action. (Hoerl, et al. 2020, p.12)

Within this context, they turned to the prominent study of Haggard et al. (2002) to examine their conditions with respect to excluding other factors like causality from their design. The contrasted conditions -voluntary action, involuntary action, and a sham TMS (audible click)- not only differed in terms of intentionality, in which

Haggard et al. (2002) were interested in, but there were also clear cause-effect associations to be made or not made between those conditions making this an additional factor to weigh in (Buehner, 2015). The temporal contiguity and contingency were kept the same across conditions; however, the conditions were not exempt from the causality inference between the two events. In light of these considerations, Hoerl et al. (2020) supposed that only one of these conditions - voluntary action- led participants to believe that the two events are causally linked, and rather that belief would be a valid assumption as to pressing a button consequentially would be seen as the cause of the tone occurring. On the other hand, merely experiencing a twitch on the finger or hearing an external tone as the first event might be dissociative to the outcome event. Without an apparent cause-effect link between the two events, participants might have seen the events as two separate entities, and therefore, they are less likely to conclude that the concurrent second event was caused by the preceding event. Under these circumstances, they conclude that the effect may not be the result of intentional action, instead, the cause-effect inference may be put at the top of the list as a driving force for the observed binding effect in Haggard et al. (2002) study.

This alternative explanation of causal belief as the reason behind the temporal binding effect could be a valid possibility in relation to the previously explained study by Suzuki et al. (2019), as Hoerl and colleagues (2020) suggested. They found the temporal binding effect in intentional action and mere observation of cause-effect association conditions of equivalent magnitude using a virtual reality setup with tactile stimulation. Therefore, Suzuki et al. (2019) argued that if an experimental condition does not contain intentional action and still produces an effect of the same magnitude as the condition that possesses intentional action, one cannot make conclusive judgments about intentionality being the only influence on binding. Other elements of considerations, such as cause-effect sequence inference, need to be weighed in as additional cues for explaining the effect.

The question raised by Hoerl et al. (2020) is whether we can explain all the discrepancies between other studies contrasting intentional and non-intentional conditions by means of Suzuki et al.'s (2019) conclusions. They propose an alternative framework for explaining the temporal binding effect that is consistent with both conceptualizations despite the differences between the two approaches. The primary requirement for this new theoretical framework is that it should be able to account for why temporal binding effect is more pronounced in intentional action contexts. According to the authors, the tenets of causal selection and causal inference could be the key to satisfying this criterion. The reasoning behind this could be that apparent cause-effect inferences are necessary and sufficient for binding effect to surface, but also, those established causal beliefs can be permeated and strengthened by the fact that participants actively see themselves as the reason for bringing the second event on. Thus, as Hoerl et al. (2020) indicates:

> If temporal binding is a measure of causal belief, this could provide an explanation as to why binding is stronger in certain conditions involving voluntary action that turns only on factors about causal inference, rather than appealing to the idea of a pre-reflective sense of agency in the way the model sketched in Section 2 does. (Hoerl, et al. 2020, p.14)

4.2.1 Alternative conceptualisation of temporal binding

Alternative conceptualisation of the binding effect:

I.) "Temporal binding, even when it occurs in the context of voluntary action, is in fact the result of a belief in causality." (Hoerl et al. 2020)

This new model explains the binding effect in terms of a causal belief that links the two contiguous events without relying on pre-reflective forward motor control.

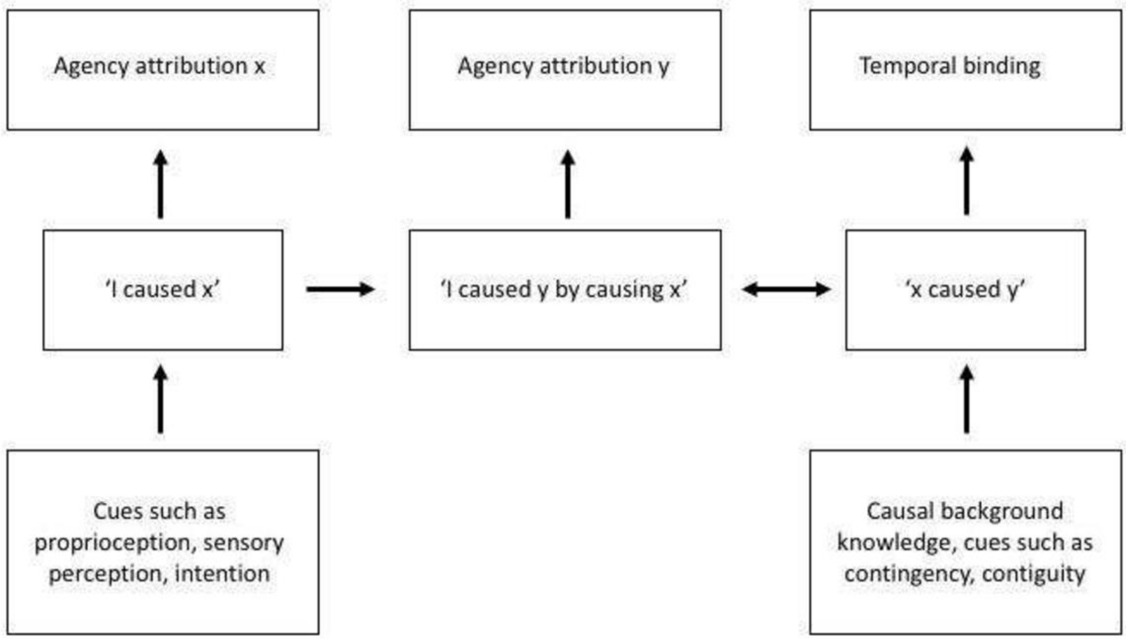


Figure 21. Alternative framework proposed by Hoerl et al. (2020).

As seen in the figure, we could attribute the temporal binding effect to the notion of 'x caused y' without the explicit regard for the notions of ' I caused x' and 'I caused y by causing x' because the former states the belief of a causal inference between two events, and one can hold this idea without crediting the first event to herself.

Therefore, the model includes the results of studies showing the binding effect in the context of involuntary and mechanical actions as a belief in causality and not agency, thus intentionality. However, using the word belief in this context opens a new discussion on this new notion being an implicit or explicit measure. We can simply ask participants after every trial whether they thought that the first event clearly brought about the second event. Hoerl et al.’s (2020) answer to this conundrum leaves the word 'belief' open to more liberal/unconventional interpretations. They state that even if it is defined as a causal belief, in the end, it might not be open to explicit questioning of participants rather, it might be more 'implicit' to pick it up in the first place. Moreover, they mention that explicit questioning might result in more binary answers as to the cause of effects, whereas the measure of cause-effect inference used in temporal binding judgments might act as ' a more sensitive continuous measure of the degree to which participants regard one event to be the cause of another' (Hoerl et al. 2020).

> On our proposed account, temporal binding, while being construed as a measure of causal belief, might constitute a measure sensitive to aspects of human causal inference that are not readily apparent from people’s explicit causal judgments. In other words, what we are calling causal belief, too, might come in a more pre-reflective variety that is not easily accessible to verbal report but still expresses itself through temporal binding. (Hoerl, et al., 2020, p.17)

Hoerl et al.'s (2020) account relies on causal belief as an explanatory principle, which poses some problems. Here, we think it is helpful to make a distinction between causal beliefs and causal representations. A causal belief is best thought of as a high-level propositional attitude which has a linguistic format of representation. However, causal representations need not be linguistically formatted this way. Consequently, using the word belief for causal inference alludes to beliefs as propositional attitudes, which might be off-putting in the temporal binding research. 'X caused y' principle might not be as explicit in resulting in temporal binding effect such as 'I believe that x caused y' as this represents a higher order causal belief. The causality principle, in this context, is readily available to the perceiver with cues like co-occurrence and low-level causal association. Therefore, using the term causal belief as the root cause of temporal binding effect might lead to an unrelated measure within the research, such as explicit causal judgements, which we find implausible and out of context. The perception of causing the outcomes through actions and rendering two events as causally linked relies on causal representations, which are formed via low-level cues such as proximity, contiguity, and contingency between two events, which uses causal inference as a glue to represent the outcome as one dynamic event with two occurrences. Taken together, we argue that rather than higher-order causal beliefs, inference of causality comes from contextual factors in experimental trials, forming the low-level, non-propositional causal representations needed for the binding effect to take place.

As affirmed by our results, two unrelated external events like tone and a visual stimulus occurring together do not unfold as temporal compression. When we perceive these two events, they are regarded as mere associations instead of causally linked. To be causally related, even if the circumstance demonstrates a target stimulus followed by a movement, the movement has to be the apparent cause of the target stimulus. Hence, the lack of causality inference in the condition where the button presses itself and then the stimulus appears after an interval is why we don't see the binding effect in Suzuki et al.'s study (2019).

How can this new framework account for the stronger binding effects observed in voluntary actions without relying on the concept of pre-reflective mechanisms? The answer lies in the existing research on making causal judgments, specifically in the areas of causal structure induction and causal selection as proposed by Hoerl and colleagues (2020). In the figure above, they noted that the notions of ' I caused y by causing x' and ' x caused y' have bidirectional interactions, which signifies those beliefs about the voluntary actions about distal events i.e., agency ('I caused y by causing x') could impact the causal inference beliefs ('x caused y'). Causal selection refers to the idea that only one or a small number of factors can be deemed as the cause or causes of an outcome. The other factors associated with the events would be rendered as background circumstances or put in the middle of the list rather than the top as possible factors. As for the causal structure induction (Lagnado et al., 2007; Meder, Mayrhofer, & Waldmann, 2014; see also Griffiths & Tenenbaum, 2005, 2009), the idea simply reflects if one can see an x being the cause of y. This binary question also contains one's confidence in reporting that there is, in fact, a cause-effect compound between x and y.

Hoerl et al. (2020) express that causal structure induction works in situations where x and y are correlated rather than causally related and have a common cause rather than x being the cause of y. In these cases, having confidence in bringing about the events themselves by means of a voluntary action instead of a probable common cause strengthens the binding effect in magnitude. They exemplified this principle by using 'bodily movement' as an x. If someone carries out the bodily movement themselves, this may indicate neglecting the possibility of a shared cause between x and y. On the other hand, if the bodily movement itself was a distal causal event, for example, the researcher activates the participant's bodily movement, bringing about the y, then this would be considered separate both via the route that one takes to causality and confidence level. By this reasoning, Hoerl and colleagues (2020) emphasise that there is an alternative route to take for explaining Borhani et al. 's (2017) results. Borhani et al. (2017) found temporal binding of different magnitude between conditions in which participants voluntarily pressed the button or the experimenter pressed down the participants' finger, achieving button press this way, and pin these findings on intentional action, thus pre-reflective forward motor control mechanisms being the influential factor compared to passive movement on binding. While this is a valid explanation for intentional binding accounts stated above as one of the earlier conceptualisations of temporal binding, Hoerl et al. (2020) go in a different direction, explaining these same results with respect to causal structure induction. In the voluntary action condition, participants' beliefs are stronger about their action('x') causing the y (the effect) compared to the passive action condition in which passive movement('x') and the y share a common cause. Being actively pressing a button makes it easier to pinpoint the causal structure between the two events as opposed to the experimenter causing the button press by pressing down the participant's finger and then by proxy causing the succeeding tone, making these two events seem separate instead of integrated and outside the flow of action-effect dynamics.

Pivoting to the causal selection principle, which is the process of singling out the apparent cause from the sea of particular various factors, Hoerl et al. (2020) argue that is the exit strategy out of causal chains and coercion conditions in certain studies (Caspar et al., 2016). Barlas et al. (2018) conducted a study using multiple choice questions and instructions to explore a causal chain where participants perceive themselves to be the cause to some extent. In an interval estimation task, they presented participants with four different conditions comprised of images of arrows pointing either left, right, up, or down. In the condition where participants were limited to one choice, they were instructed to press a specific button that had been previously chosen by the experimenter, following a semi-random interval, they were presented with an image of a button that was either congruent or incongruent with their prior selection. Whereas in the two-, three-, or four-choice conditions, they were free to choose which button to press at every trial. They found that as the choice level was increased from one to four alternatives, the temporal binding effect was significantly improved. These results can be explained within the causal selection principle, as choosing freely between alternatives gives participants a sense of picking themselves out from the causal chain as the apparent cause rather than the linking agent somewhere off the chain, Hoerl et al. (2020) claim.

Even though it is still regarded as speculative at this stage, this alternative framework has the capacity to offer an explanation as to why it has been discovered that the binding effect is stronger when voluntary action is involved. Even though it does not stand in as an alternative to explain underlying mechanisms of temporal binding -which we set out to examine- it is still to be reckoned with in terms of causality inference in general in temporal binding research and why we see the effect in action conditions vs no-action condition which can be regarded as correlated but non-associative event sequence, in our study.

4.3 Conclusion

The fundamental mechanisms underlying temporal binding—the contraction of time between two related events—have been demonstrated to be hard to pinpoint. Although theoretical explanations and empirical data, beginning with Haggard et al. (2002), point to a connection between the mechanisms involved in predicting the outcome of an action and binding effect, there are still pending questions about the underlying mechanisms and the essence of temporal binding. This thesis aimed to dissect such processes in a novel experimental design and found that, partially in agreement with Hughes et al. (2013), the predictive process of temporal control, albeit dissociated from temporal prediction, is the grounding factor of temporal binding effect given that there also must be low-level causal inference to tie the events. Additionally, we further supported the studies investigating congruency effect modulation on binding that discovered, in fact, that the binding effect was unfazed by the congruency factor (Desantis et al., 2012; Haering and Kiesel., 2014; Bednark et al., 2015). The congruency factor fails to modulate binding when half of the trials are valid or even when the validity is as high as 80%.

However, future research should delve into the methodological differences, such as the characteristics of the events used in experimental designs, to examine whether the congruency factor could modulate the binding effect in different circumstances. One might argue, in laboratory settings, that using audio or visual stimuli disconnected with keypresses or other tactile stimuli might not invoke the same effect as naturalistic stimuli. Barlas et al. (2018) presented participants with left, right, up, and down keypresses matching with the same directional visualisations and rendered these connections meaningful as opposed to abstract relations generally used within the research. On the other hand, learning and manipulating inter-event intervals before experimental or test phases but within the same block has never been explored to this date. We found that learning the acquisition time before interacts with other factors within our experimental design, such as condition type. Given that we can currently only speculate on this aspect, this newfound addition may be interpreted as the temporal binding effect being an adaptive and context-dependent phenomenon that requires further exploration. Even though the effect has been studied extensively thus far, more research on temporal binding could advance our knowledge of causality perception, predictive processes, and time compression, as well as how all three interact.

APPENDIX A

ETHICS COMMITTEE APPROVAL

Evrak Tarih ve Sayısı: 29.03.2021-9898

T.C.
BOĞAZİÇİ ÜNİVERSİTESİ
SOSYAL VE BEŞERİ BİLİMLER YÜKSEK LİSANS VE DOKTORA TEZLERİ ETİK İNCELEME KOMİSYONU
TOPLANTI TUTANAĞI

Toplantı Sayısı	:	14
Toplantı Tarihi	:	25.03.2021
Toplantı Saati	:	13:00
Toplantı Yeri	:	Zoom Sanal Toplantı
Bulunanlar	:	Dr. Öğr. Üyesi Yasemin Sohtorik İlkmen, Prof. Dr. Ebru Kaya, Prof. Dr. Fatma Nevra Seggie
Bulunmayanlar	:	

Özge Tepeli

Bilişsel Bilim

Sayın Araştırmacı,

"Duyu-Motorsal Etkileşimin Algısal Sonuçları" başlıklı projeniz ile ilgili olarak yaptığınız SBB-EAK 2021/12 sayılı başvuru komisyonumuz tarafından 25 Mart 2021 tarihli toplantıda incelenmiş ve uygun bulunmuştur.

Bu karar tüm üyelerin toplantıya çevrimiçi olarak katılımı ve oybirliği ile alınmıştır. COVID-19 önlemleri kapsamında kurul üyelerinden ıslak imza alınamadığı için bu onam mektubu üye ve raportör olarak Ebru Kaya tarafından bütün üyeler adına e-imzalanmıştır.

Saygılarımızla, bilgilerinizi rica ederiz.

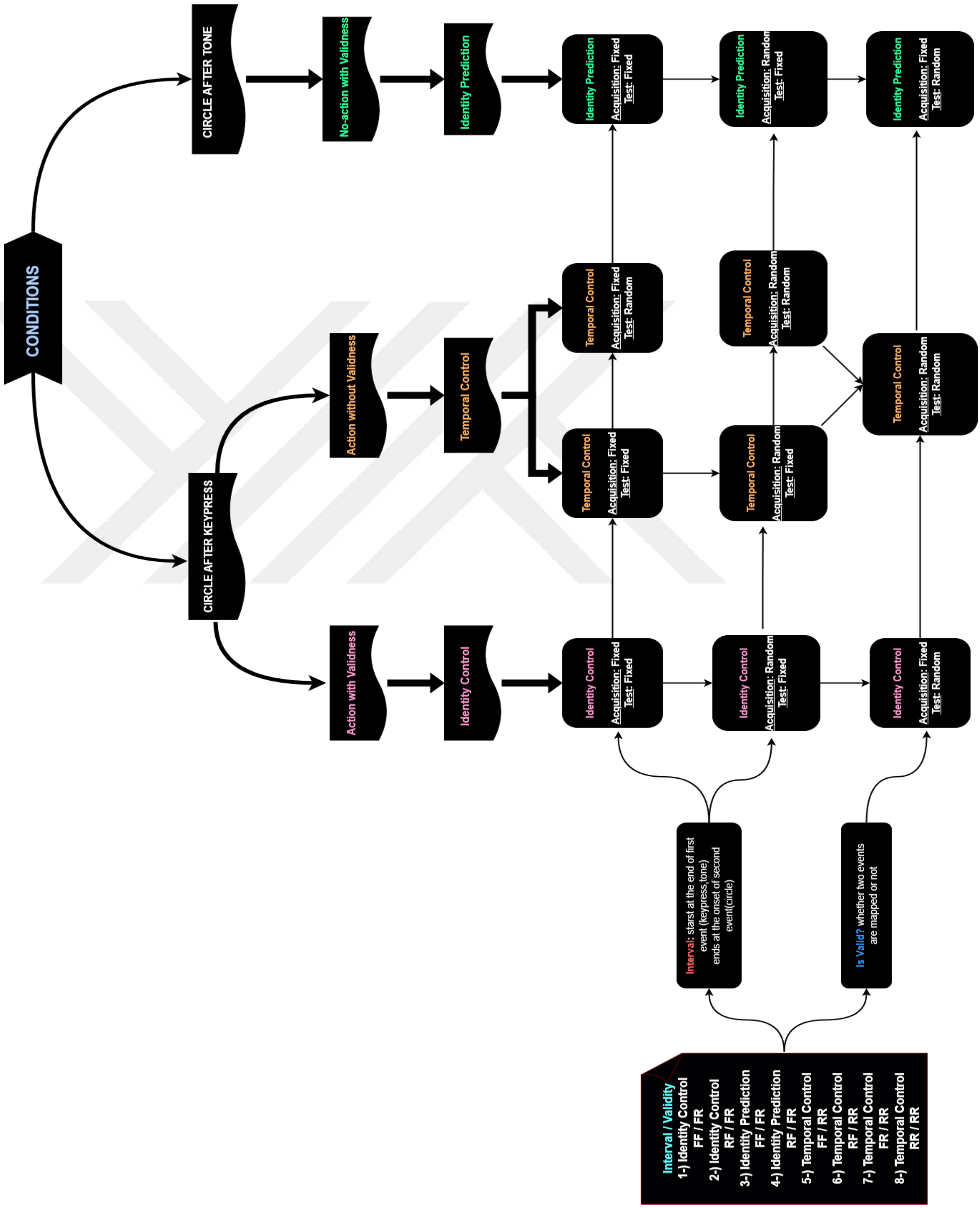
Prof. Dr. Ebru KAYA
ÜYE

e-imzalıdır
Prof. Dr.Ebru KAYA
Raportör

SOBETİK 14 25.03.2021

APPENDIX B

STRUCTURAL DESIGN OF EXPERIMENTS



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