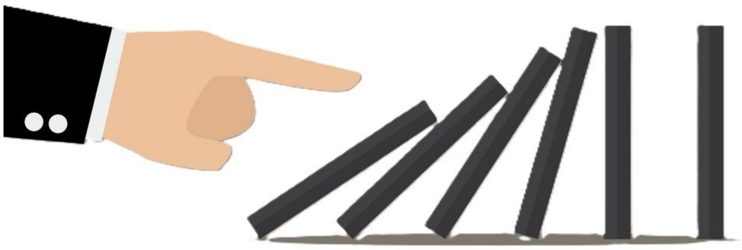
A Novel Paradigm for Assessing the Sense of Agency

Combining Intentional Binding with the Kappa Effect



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Abstract

The Sense of Agency (SoA) is the experience that one's intentions have an effect on the external world, which is vital for successfully experiencing contingency between one's intentions and actions. When SoA is aberrant it can cause a lack of coherence in the self, inducing symptoms such as will-, thought- and motor interference as observed in schizophrenia. A perceived contraction of time between intentional action and a subsequent sensory consequence, known as intentional binding, has been suggested as a measure of SoA. Unfortunately, previous measures of intentional binding contain a range of methodological issues including being susceptible to demand characteristics, being complex to perform, demanding divided attention, and being prone to several biases and confounding variables. To circumvent these issues a novel paradigm is suggested, which combines a paradigm of intentional binding with the Kappa effect, a perceptual phenomenon, where the spatial distance between two events affects the temporal perception between them. This novel paradigm was tested on 35 participants. The results showed that intentional binding was found for the group of participants that was administered the Intentional condition first, but not for the group that was administered the Non-intentional condition first, while the Kappa effect was found for neither. Additionally, it was found that participants in most conditions reported experienced agency of the expected sensory events, though this did not apply in the Intentional condition for the group that was administered the Intentional condition first. It was also investigated whether the reported amount of agency and the actual ability to detect control correlated with intentional binding, but the results showed that this was not the case. In conclusion, this novel paradigm did not prove to be a reliable measure of SoA, as it failed to reliably elicit an effect of intentional binding. Additionally, this novel paradigm does not control for one important confounding variable: perceived causality of sensory events, which plausibly affects the phenomenon of intentional binding to some extent. Furthermore, the lack of a correlation suggests that one single measure of SoA cannot capture the entirety of SoA. Future studies should be concerned with resolving the lack of intentional binding in one group and the lack of the Kappa effect in both groups, with investigating the extent to which perceived causality affects intentional binding, and with developing a more comprehensive protocol to assess SoA that does not rely solely on one measure.

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Introduction

Imagine you are driving a car. You are driving at a rather fast pace along a curved mountain road. You feel in control of the vehicle as the car responds to the movements of your hands, which automatically follow your intentions as usual. Suddenly, you realize that you are not in control of your hands. Your hands do not seem to follow your intentions, rather they seem to act by a will of their own. Though your hands seemingly keep turning the steering wheel along the curves of the road, as you want them to, they seem to act prior to your intention to do so. Perhaps someone else is externally controlling your hands? You start to panic, realizing that this is potentially a very dangerous situation, as you are not consciously in control of the vehicle. The experience of oneself being the source of a willed action is called the Sense of Agency (SoA) (Gallagher, 2000). It is an experience that we normally take for granted, but it is a crucial feature of our consciousness, as it allows us to feel in control of our actions.

Usually, when we perform an action, we automatically attribute the intention of acting to ourselves thus experiencing SoA, but for some this is not the case. One condition that is associated with an aberrant SoA is alien hand syndrome (Frith, 2005). Alien hand syndrome is caused by lesions to the supplementary motor area or anterior corpus callosum causing the experience that one’s hand acts without one’s will to do so. Alien hand syndrome is thus characterized by a lack of SoA (Frith, 2005).

Another condition linked to SoA is schizophrenia. A characteristic feature of schizophrenia is what Parnas (2009) calls ‘influence phenomena’, also called passivity symptoms. Influence phenomena are experiences of external control over one’s will, impulses, thoughts, feelings, body-experiences and motor control. This can be experienced as another person controlling the movement of one’s body or as thoughts being inserted into one’s mind. Frith (2005) suggests that influence phenomena are, like alien hand syndrome, linked to an altered SoA, but in contradiction to alien hand syndrome, a lack of SoA is not sufficient to explain influence phenomena, as schizophrenic people sometimes attribute the will of their actions to someone else (Frith, 2005), suggesting an aberrant, rather than lacking, SoA (Haggard et al., 2003).

To help people struggling with a lacking or aberrant SoA, it is vital to have accurate methods for assessing the SoA. This article will present the models that have been suggested to explain SoA along with the methods used to measure SoA. Thereafter the issues involved with the various methods will be presented, and lastly, a novel paradigm to assess SoA, that circumvents some of the most prevalent challenges, will be presented. Hopefully this paradigm can be used to further investigate the mechanisms behind SoA to aid in the development of treatment to people with an aberrant SoA.

Review

Models of Sense of Agency

Before presenting the various methods that have been used to assess SoA, the models suggested to explain how the SoA arises will be presented.

Comparator Model

The comparator model of SoA, also called the forward model, relies on a model of sensorimotor processing, in which an actual state of the motor system is compared to a desired state in order to guide action (Frith et al., 2000; Frith, 2005; Haggard, 2005). According to Frith et al. (2000) the motor system is a control system in which the input is the motor command that produces a movement, while the output is the sensory consequences of that movement. To produce a goal-directed movement the system must estimate its current state and also represent its goal (the desired state). An inverse model, conducting processing of perception to movement (affordances), elicits motor commands, and at the same time an efference copy of the motor commands are send to a forward model (Haggard, 2005), whereby discrepancies between current and predicted states can be detected (See Figure 1).

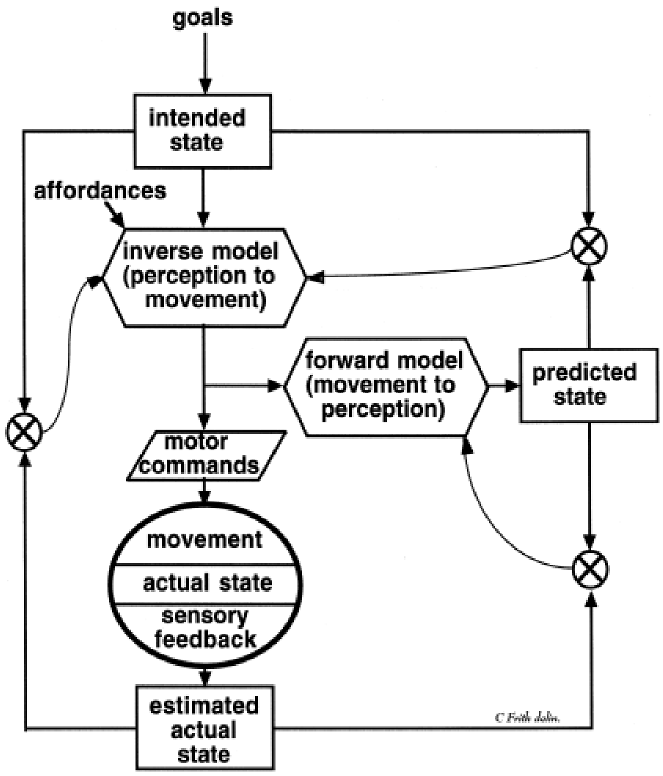

Figure 1: The comparator model as suggested by Frith et al. (2000). The crosses represent points at which the motor system can compare the intended, predicted and estimated actual state of voluntary action. Forward processing works alongside inverse processing, which is imprecise on its own. By detecting discrepancies between these two processing systems, the system is able to update the motor sequences needed to elicit a desired motor state and to compare it to the outcome. In people with delusions of control, dysfunction of the forward model leads to a disruption of the predicted state, which causes actions to feel as if they are being committed prior to the intention to commit them.

According to Frith et al. (2000) people with delusions of control, i.e. influence phenomena, have a dysfunction in the forward model and thereby the predicted state of the system. As the rest of the system works, these people can carry out motor actions successfully, but lack awareness of their intention to perform the action, which causes an aberrant SoA (Frith et al., 2000).

The comparator model is one of prediction, as predictive processes elicit SoA, and of internal cue processing, as processing is based on the efference cue, which is purely internal.

Model of Apparent Mental Causation

The Model of Apparent Mental Causation was developed by Wegner and Wheatley (1999) and explains SoA by downplaying the contribution of the motor control system. According to the model of Apparent Mental Causation there is an unconsciously derived causal pathway responsible for voluntary action, which corresponds to the processing of the motor control system. Likewise, there is an unconsciously derived causal pathway responsible for the associated thoughts about actions. But at the same time there are processes that we are conscious of, including the intention to act and the act itself, which are connected by an apparent causal path. So, though we experience that our intentions to act have a causal relationship with our actions, this is not the case, as unconscious processes drive actions. The conscious intention to act is just a correlational phenomenon allowing us to experience agency (See Figure 2).

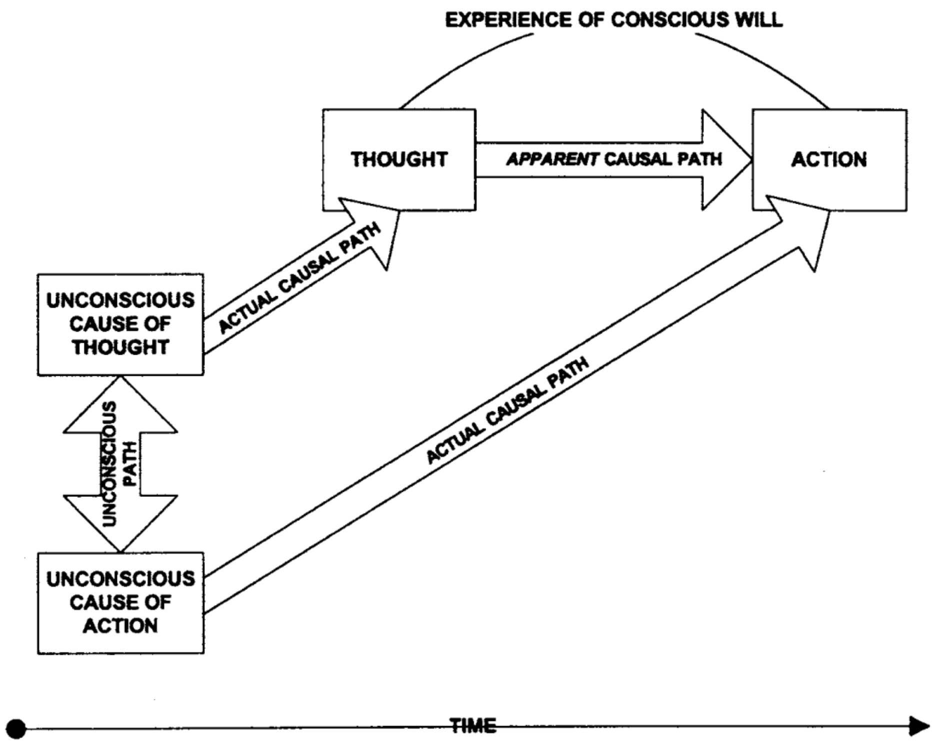

Figure 2: The Model of Apparent Mental Causation as suggested by Wegner & Wheatley (1999). The actual causal path between cause of action and action works irrespective of the apparent causal path, causing intentions/thoughts to have a non-causal relationship to actions. In people with delusions, a discrepancy between intention and action causes the experience of aberrant SoA.

Wegner & Wheatley (1999) argue that some factors must be present for us to experience willful action, i.e. SoA. If our intention to act happens before the action (within a few seconds before), is consistent with the action, and is the only good explanation for the action, then SoA is elicited.

On the notion of delusions of control, Wegner & Wheatley (1999) argues that this might be due to a lack of consistency between thought/intention and action. If these are adequately inconsistent, the person might infer that they are not related, causing the intention to act to be inferred to stem from someone else. The Comparator Model and the Model of Apparent Mental Causation agrees that delusions of control are due to a disruption of the consistency between intention and action. But in opposition to the Comparator Model, the Model of Apparent Mental Causation is one of retrospection, as the SoA is inferred irrespective of the causal action (possibly after the conduction of an action). Furthermore, the Model of Apparent Causation emphasizes external cue processing, as processing of cues in the external world preludes SoA, which is also in disagreement with the Comparator Model.

Two-Step Account of Agency

The Comparator Model and the Model of Apparent Mental Causation have been perceived as mutually exclusive, as the Comparator Model relies on internal sensorimotor processes, whereas the Model of Apparent Mental Causation relies on external cues (Moore, 2016).

This view has been challenged by studies finding that both internal sensorimotor prediction and external action outcomes contribute to SoA (Haggard et al., 2008; Voss et al., 2010; Moore et al., 2009). This has caused Syfonzik et al. (2008) to argue for a more nuanced model of SoA, that takes both predictive intrinsic processing and retrospective extrinsic processing into consideration. This model is called the Two-Step Account of Agency. Synofzik et al. (2008) consider the SoA as consisting of the Judgment of Agency (JoA) and the Feeling of Agency (FoA). Whereas JoA represents the conceptual, interpretative judgment of being the agent of an action, FoA represents the non-conceptual, low-level feeling of being the agent of an action (Synofzik et al., 2008). The JoA is related to retrospective extrinsic processing, as it receives input in terms of intentions, thoughts, contextual cues and social cues. The FoA is related to predictive intrinsic processing as it receives input in terms of feed-forward cues, proprioception and sensory feedback. These interact with respectively top-down and bottom-up processing (See Figure 3).

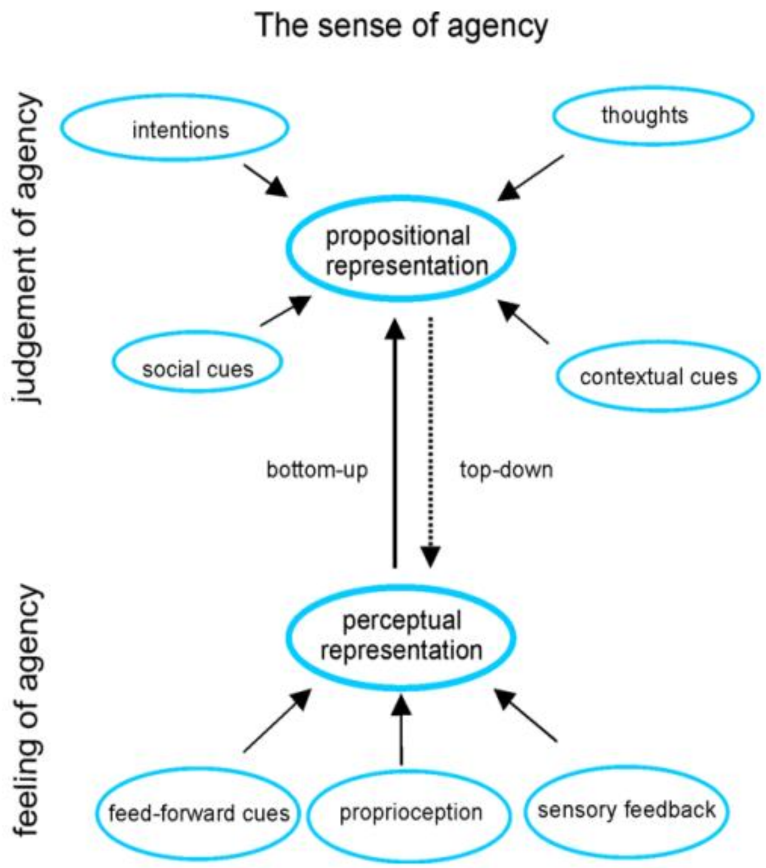

Figure 3: The Two-Step Account of Agency model suggested by Syfonzik et al., 2008. Bottom-up processing interacts dialectically with top-down processing to integrate various cues in the assessment of agency.

According to Syfonzik et al. (2008), SoA is elicited by a continuous weighing process of basic bottom-up processing and more elaborate top-down processing. The most basic levels consist of sensorimotor processes, i.e. comparator mechanisms, while more elaborated levels consist of conceptual and meta-representational processes. The basic and more elaborate levels interact dialectically. For example, when intention and effect match sufficiently FoA is taken at face-value, but when some degree of mismatch occurs, top-down processing aids in determining the agency.

Past Methods of SoA

The most prominent methods that have been used to give evidence to the above models are presented in the following chapter. First, a brief overview of the most commonly used methods will be presented, and then methods of the most used measure, intentional binding, will be investigated more thoroughly.

Explicit Measures

One way of investigating SoA is to simply ask people to rate to what degree they felt responsible for an action. These kinds of measures are called explicit measures (Moore, 2016). In relation to the Two-Step Account of Agency, explicit measures primarily assess the JoA, as they assess the conceptual, interpretative judgment of being the agent of an action. Explicit measures include action recognition judgements, where participants are asked to conduct an action and afterwards receive feedback, which were either elicited by the action of themselves or by the action of someone else. Participants are then asked to judge whether their action was responsible for the feedback (Farrer et al., 2008). Another explicit measure requires that participants report their judgment of agency for action outcomes. This can be done by asking participants to conduct an action, e.g. a button press, which does or does not elicit some kind of sensory feedback, e.g. a tone, and then having participants report the degree of experienced agency of having produced the feedback (Sato & Yasuda, 2005).

Implicit Measures

Another way of investigating SoA is with implicit measures, which assess a correlate of voluntary action and infer something about the SoA from this (Moore, 2016). Since implicit measures do not directly assess the interpreted agency experience, and since they are related to motor action and thus internal cues, they primarily assess the FoA with regard to the Two-Step Account of Agency.

Sensory Attenuation

One class of implicit measures is sensory attenuation, which is a phenomenon where sensory consequences elicited by voluntary action are perceived as less intense than sensory consequences elicited by passive movements (Blakemore et al., 1998; 1999). An example of sensory attenuation is that our own touch on our body feels less intense, than when someone else touches us (Weiskrantz et al., 1971; Shergill et al., 2003), causing us to be unable to tickle ourselves (Blakemore et al., 1998). This is presumably because we can predict our own touch, but not the touch of someone else, and therefore the system downplays the sensory experience of self-touches (Frith, 2005). Because this phenomenon is caused by voluntary action, and because voluntary action necessitates SoA, sensory attenuation has been suggested as a measure of SoA (Blakemore et al., 1998; 1999). If a sensory experience caused by oneself is as intense as a sensory experience caused by someone else, a lack of SoA is inferred. This pattern is observed in patients with delusions of control, supporting the notion that lowered sensory attenuation is an indication of altered SoA (Blakemore et al., 2000). Unfortunately, sensory attenuation has been argued to represent a much broader physiological phenomenon than solely SoA, thus rather reflecting the ability of predicting coming sensory consequences than reflecting the agency involved in producing such consequences, causing it unusable to measure SoA (Grünbaum & Christensen, 2020).

Intentional Binding

The most commonly used implicit measure is intentional binding, also called temporal binding (Moore, 2016). Intentional binding is a perceived contraction of time between a voluntary action and its sensory consequence (Haggard et al., 2002). Intentional binding is inferred to be a measure of SoA, as it only occurs when the person in question is the agent causing an effect (Haggard et al., 2002; Engbert et al., 2007). The first study discovering intentional binding found that voluntary actions contracted (binded) the perceived time between a keypress and a tone, whereas TMS-induced keypresses caused repulsion, and sham-TMS had no effect on perceived time, leaving the intention to act as the only viable explanation to this binding effect (Haggard et al., 2002). These findings were conducted with the Libet Clock method (Libet et al., 1982; 1983; Haggard et al., 2002), where participants were asked to look at a rotating clock and to note the position of the clock hand when they conducted a keypress or at the onset of a tone. Single event registration of clock hand positions established a baseline to compare to the agency condition, where the tone followed the keypress with a 250 ms delay (See Figure 4).

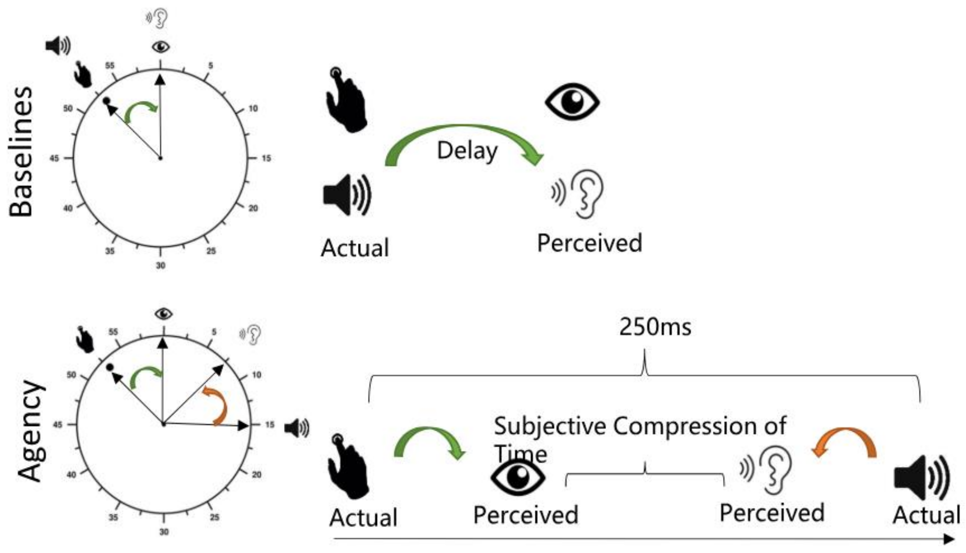

Figure 4: In the Libet Clock method participants are asked to note clock hand positions of a moving clock, while conducting an action and perceiving a subsequent sensory consequence. In the baseline conditions the action and sensory consequence occurs in isolation, whereas in the agency condition, the sensory consequence occurs subsequent to the action. The illustration is borrowed from Render & Jansen (2021).

In a subsequent experiment, delays of 450 ms and 650 ms were added, which produced the same effect of intentional binding, but to a lesser degree, suggesting that intentional binding is most pronounced at short delays. These findings have been replicated in a number of studies (e.g. Moore & Haggard, 2008; Haggard & Clark, 2003, Voss et al., 2010).

Another way of investigating intentional binding is with Time Interval Estimation, which was first used by Engbert et al. (2007). Instead of having participants judging the onset of single events, Engbert et al. (2007) asked participants to report the entire interval between an action (a keypress conducted with the right index finger) and a subsequent event (a lever moving under the left index finger). The results showed a contraction of time, when the participant was the agent, but not when the experimenter was the agent, which is inferred as an effect of intentional binding, as the participant only conducted an intentional action in the condition, where he/she was the agent. The binding effect occurred irrespectively of whether the effect happened to the participant's or the experimenter's left index finger, suggesting that intentional binding represents a connection between voluntary actions and their effect on the external world (Engbert et al., 2007).

Time Interval Estimation has also been modified to include a reproduction of the perceived interval instead of verbal reporting, a method denoted Time Interval Reproduction. In this method participants are asked to reproduce the duration of the perceived interval by pressing a key for the same duration. The reproduced durations are typically shorter when the action causing a sensory consequence is conducted by the participant, which is inferred as an effect of binding (Humphrey & Buehner 2010). Interestingly, Humphrey & Buehner (2010) used temporal delays between action and sensory consequence of 1200-1600 ms, which suggests that intentional binding can occur at delays above 650 ms (as found in Haggard et al., 2002).

To sum up, the past methods consist of two categories: explicit measures, which directly assess SoA, and implicit measures, which indirectly assess SoA. The most commonly used implicit measure is intentional binding, which will be investigated thoroughly in the following chapter.

Intentional Binding and Models of SoA

As intentional binding is the most used method to assess SoA, this chapter will investigate which model of SoA the evidence on intentional binding weighs in favor of. To investigate this, the current chapter will present evidence of predictive- and retrospective processing in various studies, as the models of SoA are built on different predictions regarding these processes. Evidence of predictive processing weighs in favor of the Comparator model, whereas evidence of retrospective processing weighs in favor of the Model of Apparent Mental Causation. Evidence of both predictive and retrospective processing weighs in favor of the Two-Step Account of Agency.

Predictive Processing

Evidence for the predictive account of intentional binding can be found in the study of Haggard & Clark (2003), who found that intentional binding, investigated with the Libet clock method, could be diminished by introducing TMS induced movements in between action preparation and action conduction, which thereby disrupted the intentional conduction of the action. As TMS induced movements are expected to disrupt predictive processing, but not retrospective inferential processing, the authors concluded that intentional binding is primarily driven by predictive processing.

This conclusion is supported by Haggard et al. (2009), who had participants either conducting an intentional action or endogenously inhibiting an intentional action, whereafter either a tone linked to the originally intended action or a tone not linked to the originally intended action occurred. They found intentional binding for intentional actions followed by a tone, but no effect for inhibited intentional actions followed by a tone. In fact, a trend towards repulsion of the perceived shift of the tone was found, causing the authors to suggest that endogenous inhibition of an intended action causes an updated prediction that the sensory consequence should not occur (Haggard et al., 2009). Since the participants were aware of their intention to act before inhibiting the action, a causal belief account would predict that participants are able to retrospectively infer that the outcome is related to the inhibited action, but as this was not the case, predictive processing seems to be more vital for intentional binding than causal beliefs, thus supporting the Comparator Model.

Wenke & Haggard (2009) sought to investigate exactly how the perceptual system conducts intentional binding and found that it is due to changes of an internal clock rate. To explain the phenomenon of intentional binding, Wenke & Haggard (2009) suggested that two broad classes of explanation exist: the effect can be due to changes in the rate of an internal clock, such that intentional binding is the result of a slowing of internal clock rate, or the effect can be due to a recalibration of the perceived onset of sensory events, so that sensory events are pre-dated to elicit agency.

The first explanation is related to predictive intrinsic processing, as changes of an internal clock rate begin before a possible sensory consequence is detected, thus relying on internal prediction. The latter explanation is related to extrinsic retrospective processing, as recalibration would happen post the detection of a sensory consequence thus relying on inferential properties. These two explanations both predict an intentional binding effect for voluntary actions compared to passive actions, but they have different predictions regarding the temporal discrimination of two sensory events occurring within the given interval. The recalibration mechanism suggests that there should be no difference in the temporal discrimination between active and passive movements, whereas the clock rate mechanism suggests that there should be impaired temporal discrimination in active movements due to fewer ‘time-units’ within the action-sensory consequence interval.

This was investigated by including a task of temporal discrimination of shocks occurring either early or late in the action-sensory consequence interval. It was demonstrated that recalibration of the time of sensory events does not explain intentional binding, and neither does a constant slowing of clock rate during the interval. Instead, the results suggest that the clock rate slows transiently after a voluntary action and then speeds up to compensate, though not reaching complete remediation, as this would eliminate intentional binding (Wenke & Haggard, 2009). This was found as decreased temporal discrimination thresholds for active movements compared to passive movements was found only when discrimination stimuli were delivered early after voluntary action and was not found when the stimuli were delivered late in the interval. This supports the notion of predictive processing eliciting intentional binding, as intentional binding is suggested to be due to a modulation of an internal clock caused by the motor system anticipating a coming sensory consequence.

The conclusion of Wenke & Haggard (2009) is supported by Graham et al. (2015), who used the Time Interval Estimation method to investigate binding across a wide age span while including measures of Psychotic Like Experiences (PLE).
As older people have been found to underproduce intervals of more than 1 second in an Interval Production Task (Espinosa-Fernandez et al., 2003), Graham et al. (2015) hypothesized that older people experience a speeding up of an internal pacemaker, which results in decreased intentional binding. The results of Graham et al. (2015) showed that, for short temporal delays, intentional binding was found for younger, but not for older participants, which was also expressed in a negative correlation of age and binding. Graham et al. (2015) suggest that the explanation is that dopamine levels decrease in the aging brain (Carlsson & Winblad, 1976; Ponzio et al., 1978; Ponzio et al., 1982), and that it has been found that dopamine widens the window of associability in which two events can be bound (Albrecht et al., 2011; Seitz & Dinse, 2007), causing elderly people less able to bind action and sensory consequence. Thus, Graham et al. (2015) suggest that in younger people the increased level of dopamine creates a wider temporal window, in which intentional binding can occur. Decreased dopamine levels reduce this window in older people, so that events must be closer together than 200 ms for intentional binding to occur. Surprisingly, across temporal delays, Graham et al. (2015) found that increasing age was associated with a reduction in the reported length of the interval regardless of movement condition, which, in contrast to what was expected, implies a slowing down of an internal pacemaker with increasing age.

At short temporal delays intentional binding was found to positively correlate with PLE-scores, predicting increased binding in people with schizophrenia (Graham, 2015).
Increased dopamine transmission is suggested to be an explanation (Graham et al., 2015), as this has been found in people with higher PLE-scores (Chen et al., 2012; Howes et al., 2013; Taurisano et al., 2014). The higher dopamine levels may cause a widening of the window in which two events can be bound, which could explain the aberrant agency experiences characterizing schizophrenia. If the temporal window for binding is broadened, there is an increased possibility for external stimuli to be bound, why external cues might be perceived as a possible cause of body input, causing symptoms such as will- and thought interference (Graham et al., 2015).
Surprisingly, across temporal delays, increasing PLE-scores were related to increases in the perceived time interval between action and sensory consequence across conditions.

There is a contradiction between the findings of decreased binding for older people at short temporal durations, but not at long temporal durations, and for increased binding for people with high PLE-scores at short temporal duration, but not at long temporal durations.
A possible explanation for the contradictory findings is that decreasing dopamine levels cause different effects at different temporal intervals. It has been found that manipulation of dexamphetamine and selective dopamine blockers show changes in the speed of the internal clock particularly for intervals that are shorter than 500 ms (Buhusi & Meck, 2002; Meck, 1996; Rammsayer, 2009). This would result in a decrease of the speed of the internal clock as dopamine activity decreases with age. Previous studies that investigate time perception in aging have only investigated temporal intervals larger than 1 second, and it might therefore be that timing mechanisms for processes operating on temporal intervals less than 500 ms are separate than those mechanisms involved with temporal intervals above 500 ms (Graham et al., 2015).
Graham et al. (2015) therefore suggest that their findings indicate that there are two separate but functionally related mechanisms (one below 500 ms delays and one above 500 ms delays) underlying intentional binding. Additionally, intentional binding is found to be related to internal clock rate changes through its relation to dopamine transmission, thus supporting the importance of predictive processing.

Haggard et al. (2003) likewise reached the conclusion that dopamine is involved in intentional binding, as they found intentional binding in participants with schizophrenia. They employed the Libet Clock method and found that participants with schizophrenia exhibited a much stronger binding effect than controls, judging the interval between action and outcome of 250 ms to be just 51 ms, compared to controls' judgment of 229 ms. The authors suggested that participants with schizophrenia exhibit this hyperbinding effect as they over-attribute their own causation of events, which could be due to excessive levels of dopamine, as dopaminergic circuits of the basal ganglia and the medial forebrain have been found to play a role in associative learning of actions and their effects in animal studies (Robins & Everett, 1986; Carlson, 2001; Schultz, 2002), and as excessive dopamine transmission has been found in people with schizophrenia (Meyer-Lindenberg et al., 2002). Since dopamine transmission is related to the explanation of changing rates of an internal clock (Graham et al., 2015), intentional binding seems to be driven by predictive processing, thus yielding support to the notion that SoA is driven by predictive processing.

Retrospective Processing

Other studies have found that retrospective processes affect intentional binding and SoA.
Though not addressing intentional binding, Wegner & Wheatly (1999) sought to investigate their Model of Apparent Mental Causation and found that participants could be deluded to experience will of a sensory consequence, though they did in fact not control the object in question. Participants and a confederate were asked to move a plate in collaboration and to stop at certain points. While the participant believed that both controlled the plate stops due to certain auditory cues, only the confederate controlled the stopping as he/she was secretly instructed when to stop. But the participant nonetheless reported experiencing control of the stops on certain trials, which indicate that retrospective processing can aid in experiencing agency.

The influence on agency of retrospective processing is likewise indicated by the study of Stetson et al. (2006), who found that recalibration of motor-sensory mechanisms can happen in the system in an action-sensory consequence task, where the appearance of action and sensory consequence can illusionary be perceived to switch place, when the participant has been adapted to a fixed action-sensory consequence delay and the temporal delay is shortened. This task neither investigated intentional binding, but the fact that retrospective processing affects agency in a task very similar to intentional binding paradigms suggests that this is also possible in intentional binding tasks.

Investigating intentional binding, Ebert & Wegner (2010) found that retrospective processing affects binding, as congruence between bodily movement and the movement of an external object was found to enhance the amount of intentional binding. Participants moved a joystick, which made an object move either congruent or incongruent with the joystick direction, where intentional binding was found to be strongest in the congruent condition. As congruence can first be determined after perceiving the external object move, this finding suggests that retrospective processing can affect intentional binding, which yields support to the Model of Apparent Mental Causation.

Both Predictive and Retrospective Processing

Encompassing both the predictive and retrospective account, Moore & Haggard (2008) found that both types of processing influence intentional binding, as they used the Libet Clock method, but included varying degrees of uncertainty in the sensory feedback. This was done by having participants perform blocks of trials, where key presses elicited tones with 50% and 75% probability. In the 75% probability condition keypresses more often elicited tones, making participants more prone to predict that a sensory consequence would happen, causing them to rely on predictive processing. For the 50% probability condition there was an equal chance that the keypress would cause a tone or not, causing participants to rely more on retrospective processing compared to the 75% probability condition. Moore & Haggard found a difference in the magnitude of forward shift of the perceived timing of the action between the different probabilities. There was a larger shift in the 75% probability condition when the action did not elicit a tone compared to the 50% probability condition, yielding support to the predictive processing account. But at the same time, there was a larger forward shift of the perceived timing of the action in the 50% probability condition, when the tone occurred, compared to when the tone did not occur, yielding support to the retrospective processing account. Thus, both predictive and retrospective processes are involved in intentional binding, yielding support to the notion that both contribute to SoA, which is in line with the Two-Step Account of Agency.

Investigating people with schizophrenia, Voss et al. (2010) applied the method of Moore & Haggard (2008), to investigate whether altered intentional binding derives from alterations at the predictive or retrospective processing of intentional binding. In participants with schizophrenia, most intentional binding was found when the tone was present rather than absent across probability conditions, which suggests greater influence of retrospective processing. This was in opposition to controls, where most intentional binding was found in the higher sensory consequence probability condition, which suggests a greater influence of predictive processes. It was further found that in participants with schizophrenia, predictive processing was negatively correlated with positive symptoms, whereof influence phenomena are included. People with schizophrenia are thus argued to lack the ability to predict action-sensory consequences, causing them to rely solely on retrospective processing (Voss et al., 2010).

Maeda et al. (2012) likewise found increased reliance on retrospective processing regarding agency attribution in patients with schizophrenia, as they conducted an experiment, where participants conducted a keypress when hearing a beep, which either made an object move or was irrespective of the moving of the object, as the object moved shortly before the beep.

Participants with schizophrenia rated higher agency than controls, indicating that they show over-attribution of agency, though this was only significant at longer temporal delays. Importantly, patients with schizophrenia had a higher tendency to attribute agency in the sham condition, indicating that they felt a sense of causal effect, even when the external events preceded their actions, a phenomenon denoted ‘Backward Causation’ (Maeda et al., 2012). This supports the notion that retrospective processing may be the cause of over-attribution of agency observed in people with schizophrenia.

Moore et al. (2009) found that retrospective processing also affects intentional binding in healthy people, as they conducted an experiment where they elicited sensory stimuli both before and after an action. Participants were presented with a low- or high pitch tone before either voluntarily conducting a key press or involuntarily conducting a key press (the finger was attached to a cord controlled by the experimenter). After a variable amount of time a tone followed which was either congruent or incongruent with the first tone. Moore et al. (2009) found that congruence between the first and second tone increased the intentional binding both for voluntary- and involuntary movements, but especially for the latter. This finding suggests that SoA is modulated by both intrinsic and extrinsic cues, which Moore et

al. (2009) suggest are integrated in a Bayesian fashion, where weight is given to the cues based on inferred importance.
In a Bayesian model a hypothesis is tested by incorporating prior knowledge with continuously updated evidence. In terms of Moore et al.'s (2009) experiment, participants would be expected to rely their temporal judgments on continuously updated evidence from both predictive intrinsic processing and retrospective extrinsic processing, which can explain the finding that congruence between the first and second tone elicited stronger binding in the involuntary condition, as participants were not able to draw on intrinsic cues.

The findings of Desantis et al. (2011) are interesting in relation to Moore et al.'s (2009) suggestion of Bayesian weighting of cues, as they found that the binding effect was altered by manipulating participants' causal beliefs. Desantis et al. (2011) induced participants to believe that either they or another were responsible for producing a tone, or that the cause of the tone was ambiguous. A pre-movement cue prompted the participants to whom they should believe was responsible for producing the tone, but in fact the action of the participant always produced the tone. Desantis et al. (2011) found that intentional binding was present, when the participants believed that they produced the tone and non-present when they believed that their partner produced the tone. As the participants acted with intention in all trials, only causal belief was manipulated across conditions, indicating that retrospective processing contributes to the binding effect (Moore & Obhi, 2012). In terms of a Bayesian model, this would suggest that internal cues can be validated by external cues, which supports the Two-Step Account of Agency.

In sum, though retrospective processing seems to play a role in intentional binding (Stetson et al., 2006; Ebert & Wegner, 2010; Desantis et al., 2011; Moore & Haggard, 2008), and seems to be the driving factor of intentional binding in people with schizophrenia (Voss et al., 2010; Maeda et al., 2012), predictive processing seems to be of greater importance in healthy people (Haggard & Clark, 2003). Thus, both intentional binding and the SoA (Moore et al., 2009; Moore & Haggard, 2008, Synofzik et al., 2008) seem to be driven by both predictive and retrospective processes, but perhaps predictive processing is the primary factor in healthy people. This yields support to the Two-Step Account of Agency (Synofzik et al., 2008).

Critique of Past Methods

Unfortunately, the methods commonly used to assess SoA, i.e. explicit measures and intentional binding are problematic as the explicit measures and Time Interval Estimation/Reproduction are prone to demand characteristics, whereas the Libet Clock method contains a range of methodological issues such as demanding divided attention, is complex for participants to perform, and is prone to the flash lag bias and the prior entry effect. Additionally, the measures of these methods have been found not to correlate, causing concern as to what they actually assess. Furthermore, previous methods have struggled with an inability to control for confounding factors such as temporal predictability and perceived causality of events, and in addition some studies disagree as to whether intentionality is actually needed in order to elicit SoA. This chapter will investigate these issues further, before a novel method to measure SoA is proposed.

Demand Characteristics

An issue with explicit measures and Time Interval Estimation/Reproduction is that they are prone to demand characteristics, which represent the willingness of participants to act as 'good subjects' by which they might manipulate the effect that is investigated (Orne, 1962). As participants have voluntarily chosen to participate in an experiment, and as they participate in research tasks presumably perceived as of importance, they will, intentionally or unintentionally, try to act in a way aiding to the benefit of the experiment. If the participant has a grasp of the effect investigated, and how this effect will present itself in the effect- and control condition, the participant might behave in a way contributing to the finding of the effect that is investigated, though this effect might otherwise not be found. Explicit measures rely on participants' self-reports, and, as self-reports are very overt to participants, these methods might be especially prone to this phenomenon. The participant is quite likely to detect that the experimenter seeks to investigate their SoA and can thus simply report having a larger SoA, than what is actually the case. Though Time Interval Estimation is less reliant on self-reports, the measured values are still quite overt to the participants, as the measurement is the time duration between action and sensory consequence reported verbally. So, if a participant has detected the effect under investigation, it would be easy to monitor the temporal duration reported during baseline conditions, and then report a shorter duration for effect conditions. This could be less of an issue in Time Interval Reproduction tasks compared to Time Interval Estimation tasks, as it might be more difficult to monitor durations of reproduced intervals compared to verbally reported intervals, but it is still plausible that participants are able to monitor the reproduced durations. This means that participants can quite easily monitor their performance in separate conditions and compare these performances to each other thus influencing the results.

Divided Attention

The Libet clock method is more covert to participants, as they note the clock hands position that vary for each trial, making it hard to monitor one's previous judgments. But the Libet clock method contains a range of other methodological issues, the first being that it demands participants to exhibit divided attention (Engbert et al., 2007; Papanicolau, 2017). Participants are asked to simultaneously attend to the placement of the clock hand and to monitor when they choose to conduct a movement, which has been argued to be impossible, as the attention cannot be directed to two events at the same time (Engbert et al., 2007; Papanicolau, 2017). This will necessarily lead to inaccurate judgments of either clock hand placement or action onset/sensory consequence onset.

Flash Lag Bias

Another issue with the Libet Clock method is the flash-lag bias, which is the phenomenon that people tend to project the position of moving objects slightly ahead of their trajectory (Mackay, 1958; Dominik et al., 2024). Since the clock hand is continuously moving, this would imply that people judge the location of the clock hand a bit premature compared to both their onset of action (Dominik et al., 2024) and to their perception of the subsequent sensory consequence (Gomes, 2002; Klein, 2002; van de Grind, 2002). Though not having been investigated directly in intentional binding tasks, this should increase the binding effect of action toward sensory consequence and decrease the binding effect of sensory consequence toward action. Though equalizing the total amount of intentional binding, this bias will create noise in the data of Libet Clock experiments on intentional binding.

Prior Entry Effect

A bias of interest regarding the Libet Clock method is the prior entry effect, first noted by Titchener (1908). The prior entry effect represents the finding that attended stimuli are perceived as occurring earlier than unattended stimuli (Haggard & Libet, 2001). Thus, directing the attention to, for example sensory consequence onset, causes this event to be perceived as occurring earlier than if attention had not been directed. The issue regarding the Libet Clock method is that participants simultaneously pay attention to either their onset of action or the sensory consequence and the clock hand, and that it is impossible to know to what degree their attention is directed to either of these, thus the prior entry effect may affect perception of either element to varying degrees (Haggard & Libet, 2001). Haggard et al. (2002) notes that Shore et al. (2001) has found prior entry to shorten perception by 12 ms, which is less than the shortening caused by intentional binding (-97 ms in the 250 ms delay condition of Haggard et al., 2002), making it insufficient to explain the binding effect. But it could still, to some degree, affect the results in Libet Clock studies.

Complex to Perform

An additional issue with the Libet Clock method is that the task is quite complex and demanding to perform. Haggard et al. (2003) state that the task requires complex cross-modal time judgments and high levels of concentration, which is a result of the demand of simultaneous integration of several perceptual modalities (vision, proprioception and hearing) in various contexts (single event baselines, effect condition and control condition). Nonetheless, Haggard et al. (2003) found that participants with schizophrenia have approximately the same level of judgment errors on the single-event baseline conditions as healthy controls, and that the standard deviation of judgment errors were comparable between participants with schizophrenia and healthy controls, causing the authors to argue that participants with schizophrenia understood the task and performed it quite well. Since participants with schizophrenia have been found to have attentional deficits (Hahn et al., 2012; Spencer et al., 2011), they should constitute a proxy for validating that the general population can perform the task. But since the judgment errors of participants with schizophrenia are only compared to that of healthy controls performing the same task, it could be the case that both groups struggle with the complexity of the task. This could mean that the complexity of the task, and the amount of concentration needed, could induce unwanted noise in the data.

Correlations of Implicit and Explicit Measures

Zooming out from the Libet Clock method, a more general concern is that explicit and implicit measures have been found not to correlate (Dewey & Knoblich, 2014), and that implicit measures have been found not to correlate (Dewey & Knoblich,

2014; Siebertz & Jansen, 2022). This is an issue, as we would expect these measures to correlate, if they actually assessed the same entity, i.e. SoA.
The measures that were compared in these studies were sensory attenuation, Time Interval Reproduction and explicit ratings using a Likert scale (Dewey & Knoblich, 2014), and Time Interval Estimation and the Libet Clock method (Siebertz & Jansen, 2022). A possible reason for the lack of a correlation between Time Interval Reproduction and sensory attenuation is that sensory attenuation measures a broader physiological phenomenon than SoA (Grünbaum & Christensen, 2020), causing the two measures to assess different entities.
It could also be the case that Time Interval Estimation/Reproduction and the Libet Clock method assess something different than SoA, but intentional action has been found to be vital for binding in various studies (Haggard et al., 2002, Engbert et al., 2007; Haggard & Clark, 2003), making it unlikely that these methods are completely unrelated to intention and thus SoA. The same is the case for explicit measures, which, in addition to being susceptible to demand characteristics, rely on participants' introspective capabilities, which might be of varying quality. Nonetheless, it is unlikely that demand characteristics and varying introspective capabilities renders explicit measures completely unable to assess SoA.

Another explanation for the lack of a correlation between Time Interval Estimation and the Libet Clock method is that previously presented methodological issues create noise in the measures, though both methods might assess SoA. In addition to the previously presented methodological issues, both Dewey & Knoblich (2014) and Siebertz & Jansen (2022) used observational baseline conditions in the Interval Estimation task, which is problematic as observational baseline conditions does not involve voluntary action, making it unsure to what degree intentional binding was assessed (Gutzeit et al., 2023). So, the lack of a correlation between explicit and implicit measures, and of implicit measures internally, could be due to methodological issues with the currently available methods.

Lastly, a possible explanation for the lack of correlations is that the different measures tap into different processes of SoA, which is plausible with regard to the Two-Step Account of Agency (Syfonzik et al., 2008). The Two-Step Account of Agency suggest that SoA is mediated by processing of JoA and FoA (Synofzik et al., 2008), whereas the first should rely heavily on retrospective extrinsic processing as it conducts top-down processing of extrinsic cues, whereas the latter should rely heavily on predictive intrinsic processing as it conducts bottom-up processing of intrinsic cues. This would imply that explicit and implicit measures address different sub-processes of SoA, which could explain the lack of a correlation in some studies. Ebert & Wegner (2010) found that intentional binding and explicit ratings did correlate, but that explicit ratings were stronger for long action-sensory consequence delays, whereas intentional binding was stronger for short delays, suggesting that they address at least partially dissociable mechanisms of SoA, which Ebert & Wegner (2010) state is in support of the Two-Step Account of Agency.

Temporal Predictability

Another general concern regarding the currently available methods, is that they are confounded by temporal predictability, which has been found to affect intentional binding (Kirsch et al., 2019; Antusch et al., 2021). Temporal predictability is the ability to predict that an event will occur, which could be sufficient to create the effect of binding, without the involvement of intentional actions. Temporal predictability is often present in the action condition as the participants are able to anticipate, when they intend to conduct an action. This is often not the case for the observational baseline condition, as the participants are merely presented with two sensory consequences (e.g. Humphrey & Buehner, 2010). Some argue that temporal predictability, and not intentionality, is the primary factor for eliciting binding, as they found no difference of binding in voluntary and involuntary action-sensory consequence conditions, when controlling for temporal predictability by adding a cue that prompted upcoming events in the Libet Clock paradigm (Kirsch et al., 2019).

This has been challenged by other studies finding that, while temporal predictability can affect binding, intentionality is still vital for binding to occur (Engbert et al., 2007; Ruess et al., 2020; Antusch et al., 2021). Antusch et al. (2021) found that, by increasing temporal predictability, repulsion (the opposite effect of binding) was diminished in a task, where participants had learned that one of two tones was contingent on stimulation of one finger. Though not directly addressing intentional binding, this can be inferred as evidence that temporal predictability affects intentional binding, as it diminished repulsion, thus contracting the perceived temporal intervals as in the binding effect. However, Antusch et al. (2021) emphasize that, since they were unable to find contraction and only found repulsion in a task where intentional actions were not involved, intentional actions still seem vital for intentional binding to occur.

Engbert et al. (2007) replicated classical findings of intentional binding in an active but not in an observational condition, when introducing cues prompting upcoming events in both the active and observational condition, which also implies that intentional action is the primary factor for eliciting intentional binding.
Lastly, Ruess et al. (2020) found that intentional binding in the Libet Clock paradigm was influenced by the predictability of events and the duration of delay between action and sensory consequence in a pattern opposite to that of a Reaction Time Benefit Task. In the Reaction Time Benefit Task participants had to react as fast as possible, after the occurrence of a sensory consequence, which is a task where reaction time has been found to increase with duration, when the delay is predictable (Los & Van Den Heuvel, 2001; Steinborn, Langner, & Huestegge, 2017), and to decrease with duration, when the delay is unpredictable (Steinborn & Langner, 2011), making performance on the Reaction Time Benefit Task dependent on temporal predictability. Intentional binding was instead found to converge with explicit ratings regarding predictability and duration of delays, causing Ruess et al. (2020) to suggest that intentional binding is rather driven by SoA than temporal predictability.

In sum, though some research indicates that temporal predictability can have an effect on intentional binding (Kirsch et al., 2019, Antusch et al., 2021), a convincing array of research suggests that this is not the case, at least not to an extent that diminishes the notion that intention has an effect on binding (Engbert et al., 2007; Ruess et al., 2020, Antusch et al., 2021).

Perceived Causality

A second factor that has been argued to affect intentional binding is perceived causality between two sensory events (Moore et al., 2009; Suzuki et al., 2019; Buehner, 2012; Cravo et al., 2009; Buehner & Humphrey, 2009). Perceived causality is the learning that the occurrence of one event is dependent on the occurrence of another event, thus causing a perceived causal relationship between the two (Moore & Obhi, 2012). This account is in line with the Model of Apparent Mental Causation, as the causality between two events are inferred retrospectively. One way to investigate the involvement of perceived causality is to control whether the action that elicits a sensory consequence is committed by the participant or by a machine observed by the participant (Buehner, 2012), but the influence of causality has been established by a number of methods (Moore et al., 2009; Buhner &

Humphrey, 2009; Cravo et al., 2009; Buehner & Humphrey, 2010; Suzuki et al., 2019), though several methodological issues persist in these methods.

Regarding the study of Buehner (2012), the temporal delays between action and sensory consequence were longer than those used in traditional binding studies (500-1300 ms vs. 250-650 ms) (Haggard et al., 2002), and self-causation was found to elicit greater binding than machine-causation in the short temporal delays in one of two experiments, suggesting that temporal delay duration might have an effect on self- vs. machine-causation. This is interesting with regard to the findings of Graham et al. (2015); that intentional binding is processed in two different mechanisms across temporal delay durations, since machine-causation was found to elicit stronger binding than self-causation primarily for longer durations (Buehner, 2012), which could suggest that perceived causality might mostly be a factor at longer durations.

An issue with several methods used in studies finding that causality rather than intentionality is the driving factor of binding is that intentionality is not controlled for. Buehner & Humphrey (2009) found that causality rather than intentionality was the primary factor for binding in an experiment, where participants learned that one tone was contingent on another tone in a non-causal condition. Participants additionally conducted a causal condition, where they were instructed to press a key, which caused tone 2, learning that tone 2 was contingent on action. It was found that intentional binding was increased, when participants were trained in the causal condition, suggesting that causality, and not voluntary action, is the primary factor for eliciting intentional binding, as the training prompted perceived causality. Buehner & Humphrey (2009) has been criticized for not controlling intentionality, as it is unknown if the training caused greater intention, which might have induced the increase in intentional binding (Moore & Obhi, 2012). Lacking control of intentionality is a critique that is applicable to other studies as well. Buehner & Humphrey (2010) argued that causality was the primary factor eliciting binding in a paradigm, where they additionally showed that binding was possible in the spatial domain. Participants were asked to watch one ball moving towards a bar, whereof another ball was attached and released, when the first ball hit. The participants underestimated the width of the bar, when there was a short delay between hit and release, but only when the second ball was launched in a direction congruent with the direction of the first ball. Buehner & Humphrey (2010) argue that these findings indicate that intentional binding is caused by causality instead of intention, as participants merely observed the balls moving, but it cannot be known if participants for some reason attributed intentionality to the launch of the first ball. Likewise, it is unknown if a greater binding effect would have been found in a condition where participants controlled the launch of the first ball.

Instead of being able to solely account for the occurrence of intentional binding, causality seems to influence binding in collaboration with intention (Cravo et al., 2009; Lush et al., 2019; Dienes et al., 2022). Cravo et al. (2009) found that binding was present when participants caused the launching of a disc, which collided with another object causing the other object to move. Both the launching being controlled by the participant and the causal relation between disc and object were necessary for binding to occur, suggesting that both causality and intentionality are demanded. Lush et al. (2019) tested high and low hypnotizable participants on the Libet Clock task, as they hypothesized that intentional binding is elicited in a Bayeshian fashion relying on the information from different cues. These different cues involve both metacognitive awareness of intentions and previous experience of causal relations, such as the experience that button presses cause a rapidly occurring sensory consequence (Lush et al., 2019; Dienes et al., 2022). The contribution of metacognitive awareness of intention can be assessed through precision of action judgment, which should be negatively correlated with hypnotizability (Lush et al., 2019), as people with low hypnotizability have more conscious intentions and as conscious intentions are more easily processed than unconscious intentions causing more precise action timing judgment (Dienes et al., 2022). The experience of causal relations should cause the interval between action and sensory consequence to remain relatively stable, causing precise action timing judgment to pull both action judgment and sensory consequence judgment towards action onset, which causes less action binding and more sensory consequence binding. Since highly hypnotizable people should have less metacognitive awareness of intentions, they should experience less conscious- and more unconscious intentions, thus exhibiting less imprecise action timing judgment, greater action binding, and less outcome binding. The results showed less imprecise action timing judgment and more action binding in lowly hypnotizable participants compared to highly hypnotizable participants, but the data was inconclusive regarding sensory consequence binding (Lush et al., 2019). Though the relative contribution of experience of causal relations and metacognitive awareness is unknown due to no evidence of sensory consequence binding, these findings support the notion that action binding is related to metacognitive awareness of intentions, making intentions important for intentional binding. The account suggested by Lush et al. (2019) seems to be in line with the Two-Step Account of Agency, as causality is likely to be related to external cues and top-down processing, whereas intentionality is influenced by intrinsic cues.

From the above studies it is evident that causality has an influence on binding (Buehner & Humphrey, 2009; Buehner & Humphrey, 2010; Cravo et al., 2009; Buehner, 2012), and some argue that causality alone is sufficient to elicit binding (Buehner & Humphrey, 2010; Buehner, 2012) though this is disputed (Moore & Obhi, 2012; Cravo et al., 2009; Lush et al., 2019; Dienes et al., 2022, Antusch et al., 2021). It seems more plausible that both intentionality and causality is involved in eliciting the binding effect (Cravo et al., 2009; Lush et al., 2019; Dienes et al., 2022).

Intentionality

For intentional binding to be an implicit measure of SoA, it needs to be related to intentionality, and this relationship has been challenged (Suzuki et al., 2019, Gutzeit et al., 2023; Kong et al., 2024), though some methodological concerns persist in the studies advocating for this. Suzuki et al. (2019) found that intentional binding happened irrespectively of intention, as intentional binding was found in two conditions, where participants watched a virtual hand press a key which caused a tone while either controlling this virtual hand or watching passively. Suzuki et al. (2019) argue that if intention was necessary for binding, then binding should have been found solely in the active condition. But at the same time, it is noted that participants could have experienced FoA for both virtual hand conditions, which enables the presence of intentionality in both conditions, as intentionality is not controlled for (Suzuki et al., 2019).

To overcome the issue of controlling for intentionality, Gutzeit et al. (2023) established a non-intentional effect baseline, where participants were asked to press a button to make a stimulus change color, but the stimulus appeared to change color irrespectively of the participants' keypress. The stimulus did however change color due to the keypress, meaning that the action of the participant had an effect without the participant realizing it, presumably causing no intention to be ascribed to the color change. Participants were then asked to reproduce the temporal interval between key press and color change. This was compared to a condition where they were aware of the effect of their action. The results showed that there was no difference of intentional binding between the two conditions, but that participants rated their agency to be higher in the perceived effect-condition, suggesting that binding can happen irrespective of intentionality (Gutzeit et al., 2023). A methodological concern is that participants did in fact have control of the color change, causing the possibility that they did actually experience agency in both conditions. Additionally, explicit and implicit measures do not correlate (Dewey & Knoblich, 2014), making agency judgment a rather unreliable argument to diminish this possibility because of. Intentionality could thus still have been present in the non-intentional effect baseline.

Kong et al. (2024) likewise concluded that intentional binding happens irrespective of intentionality, as their experiment found no difference of intentional binding between voluntary and involuntary movements. Importantly, a Bayes factor revealed low evidence for this conclusion in one of two experiments. The other experiment used a visual slider for time estimation, which is a novel method that might not be a good measure, as the visual slider could make it easier for participants to monitor their responses, causing the method to be prone to demand characteristics. Regarding intentionality, Antusch et al. (2021) suggest that their results indicate that intentionality is vital for binding to occur, as they did not find intentional binding in their experiment, where participants did not commit voluntary actions. The suggested explanation is that motor simulation is vital for binding, which would make intentional actions necessary. Since no motor simulation occurred in the experiment, no efference copy was created, causing repulsion instead of binding. This account can likewise explain why Haggard et al. (2002) found repulsion in their TMS induced movement condition.

Though several studies argue that intentionality is not vital for binding to occur (Suzuki et al., 2019; Gutzeit et al., 2023, Kong et al., 2024), they contain methodological issues. Besides, the importance of voluntary action is quite well reported (Haggard et al., 2002; Engbert et al., 2007; Voss et al., 2010, Antusch et al., 2023), making it unlikely that intentional binding is completely unrelated to intentionality.

The Novel Paradigm

To circumvent some of the issues of previous methods, it is suggested to combine the paradigm of intentional binding with another paradigm of temporal perception: the Kappa effect.

The Kappa Effect

The Kappa effect is a temporal illusion representing that the longer physical distance there is between two objects, the longer the temporal duration between them will be perceived as being (Cohen et al., 1953; 1955: Reali et al., 2019). Investigation of the Kappa effect was motivated by the discovery of the tau effect, where participants rate a spatial distance between two points as appearing longer, when there is a longer temporal duration between these two points (Helson & King, 1931). According to the tau effect, temporal perception has an influence on spatial perception, which caused Cohen et al. (1953) to suspect that spatial perception has an effect on temporal perception as well. In the experiment of Cohen et al. (1953) participants watched cycles of three flashes appearing sequentially on a horizontal line. The experimenter was able to adjust the distance separating the lights, while the participant was able to control the timing of the flash of the centre light with a lever. The task was to adjust the lever until the temporal interval between flash 1 to 2 was perceived equal to the temporal interval between flash 2 to 3. It was observed that the participants adjusted the temporal interval between the two flashes spaced farthest apart to be shorter than the time interval between the two flashes spaced closest, suggesting that the temporal interval occurring between the two flashes with the largest spatial distance was perceived as longest.

Combining Intentional Binding and the Kappa Effect

The novel paradigm consists of two conditions, where participants are presented with three sequentially occurring circles as in the experiment of Cohen et al. (1953). Instead of adjusting the temporal interval between flashes, the participants are presented with three circles with varying spatial distances on a computer screen and are asked to compare the temporal interval between Circle 2 and 3 (T2) to the temporal interval between Circle 1 and 2 (T1). This is a procedure that has been found to produce the Kappa effect (Reali et al., 2019). In an Intentional condition, participants press a key at the onset of Circle 1, thus controlling the onset of Circle 2. This should elicit an effect of intentional binding between Circle 1 and 2, thus contracting the perceived duration of T1. In a Non-intentional condition, participants press a key at the offset of a fixation cross prompting the beginning of a new trial, but before the onset of any circles. This should cause a binding effect outside T1 and T2. Additionally, participants report to which degree they experienced agency of Circle 1 and 2 in both conditions. See ‘Procedure’ for a full description of the novel paradigm.

One important advantage of this novel paradigm is that the varying spatial intervals mask the temporal intervals as the Kappa effect makes it difficult to disentangle temporal perception from spatial perception. Because of this, participants will be less prone to demand characteristics than in Time Interval Estimation/Reproduction and explicit measures. Besides including varying spatial intervals, varying temporal intervals will be introduced to further strengthen this masking.

The novel paradigm further circumvents several of the issues commonly associated with the Libet Clock method.

First, it is not prone to the flash lag bias, as participants are not asked to report the location of a moving object.

Second, it does not require divided attention, as participants are not asked to monitor a rotating clock hand while monitoring the onset of their action or a sensory consequence.

Third, it should not be as susceptible to the prior entry effect, as participants are only asked to pay attention to the circles, which should cause them all to be perceived earlier than if attention was not directed at them, thus equalizing the effect across circles. Since participants are not simultaneously paying attention to several things, the prior entry effect should not varyingly affect perception in different trials.

Fourth, it is less complex to perform, as participants are not simultaneously asked to monitor a rotating clock hand, while conducting an action and monitoring onset of action and subsequent sensory consequence. In the novel paradigm, participants are simply asked to conduct an action, watch three circles, and then judge T2 in comparison to T1.

Beyond issues of the Libet Clock method, the novel paradigm also circumvents the issue of temporal predictability, which is especially present in studies, where the baseline condition consists of the observation of two unpredictable sensory events (e.g. Humphrey & Humphrey, 2010). This is circumvented as either a fixation cross or the action of the participant cues the onset of circles in both conditions, causing the participant to be able to predict the coming circle-onset.

Lastly, the novel paradigm includes explicit ratings to investigate SoA in terms of the Two-Step Account of Agency, where explicit ratings should incorporate external-cue-informed top-down processing (JoA), while including an implicit measure through the combined intentional binding/Kappa effect paradigm, which should incorporate internal-cue-informed bottom-up processing (FoA).

Aim of the study

The aim of this study is to test this novel implicit measure of SoA on a healthy population, and to compare the findings with an explicit measure of SoA, to investigate if the novel paradigm can successfully be used to assess SoA.
It is hypothesized that: 1) An effect of intentional binding will be found on trials where the participants control the onset of Circle 2, compared to trials where the participants control the onset of Circle 1, i.e. respectively the Intentional and Non-intentional condition.
2) The effect of intentional binding will be amplified on trials where the spatial distance of Circle 2 and 3 are larger than between Circle 1 and 2, as the Kappa effect increases the perceived temporal duration of T2.
3) The effect of intentional binding will decrease on trials where the spatial distance of Circle 2 and 3 are shorter than between Circle 1 and 2, as the Kappa effect increases the perceived temporal duration of T1.
4) Participants will have a higher rating of explicit agency of causing onset of Circle 1 on trials where they control the onset of Circle 1.
5) Participants will have a higher rating of explicit agency of causing onset of Circle 2 on trials where they control the onset of Circle 2.
6) The amount of intentional binding and explicit agency will correlate positively.
7) The amount of intentional binding and the ability to detect which circle the participants were in control of will correlate positively.

Method

Participants

Thirty-five participants (n = 18 women) with a mean age of 26.3 (SD = 5.7) were recruited for this experiment. Thirty-four participants spoke Danish as their first language and were thus tested in Danish, while one spoke English and was tested in English.
All participants had normal or corrected-to-normal acuity, did not suffer from neurological disease or schizophrenia, and were not related to parents or siblings with schizophrenia. The reason for controlling acuity is that faulty acuity can prevent participants from accurately perceiving the circles, which might cause noise in the data. No participants with neurological disease or schizophrenia were included, as

the study aimed to investigate the novel paradigm in the general healthy population before investigating it in relation to different diseases. Neurological diseases have been found to affect intentional binding (Wolpe et al., 2014), causing testing conducted on this population unable to generalize to the general healthy population. Likewise, participants with schizophrenia and participants with first-degree family with schizophrenia were excluded, as schizophrenia has been found to be related to aberrant behavior on intentional binding tasks (Haggard et al., 2003; Voss et al., 2010).

Participants were recruited via flyers shared on the faculty of Communication and Psychology and at the Department for Politics and Society at Aalborg University, and by flyers shared on campus at Aalborg University. Additionally, the flyers were shared via SoMe (Facebook and Instagram).

Participants were not monetarily compensated for their participation. Written informed consent was obtained for all participants. According to the rules of AAU, no ethics board approval was needed, as the project was conducted by a student. The ethical board case that waived further reviewing is AAU084-1060247.

Apparatus

The experiment was run on a Dell Optiplex 9020 computer attached to a Benq LCD screen (1920x1080 pixels, width: 54 cm, height: 30 cm, diagonal: 62 cm). Refresh rate was set to 100 Hz and the brightness of the screen was set to 61cd/m2. Participants sat at a distance of 90 cm from the screen.

Stimuli

Stimuli consisted of three circles created using the Polygon feature in PsychoPy (v2023.2.2) (Peirce et al., 2019). The size was 0.51˚ visual angle, and the circles were white presented on a black background.

Procedure

Intentional Binding and the Kappa Effect

The experiment was a two-alternative-forced-choice task (2AFC) created on Pyschopy (v2023.2.2). Each trial started with a fixation cross sized 0.64˚visual angle appearing for 800 ms, whereafter the three circles appeared on a row either from left to right or from right to left. The direction of appearance was randomized, and each direction occurred half the time. In an Intentional condition, Circle 1 appeared for 50 ms after the offset of the fixation cross and a subsequent delay of 150 ms. Participants were asked to press the spacebar as soon as they saw circle 1. After a 200 ms delay, Circle 2 appeared for 50 ms. The response time and the 200 ms delay thus defined the temporal interval between Circle 1 and 2 (T1). After a variable temporal interval, Circle 3 appeared. The temporal interval between Circle 2 and 3 (T2) was either equal to T1, or 20%, 40% or 60% shorter or longer. Participants were then asked to rate whether T2 was longer or shorter than T1. If they believed T2 was longer they were asked to press the arrow up-key, if they believed it was shorter they were asked to press the arrow down-key. The circles were additionally separated by varying spatial distances, where the locations of Circle 1 and 3 were fixed, but Circle 2 could appear in the middle or halfway closer to either Circle 1 or 3 (see Figure 5).

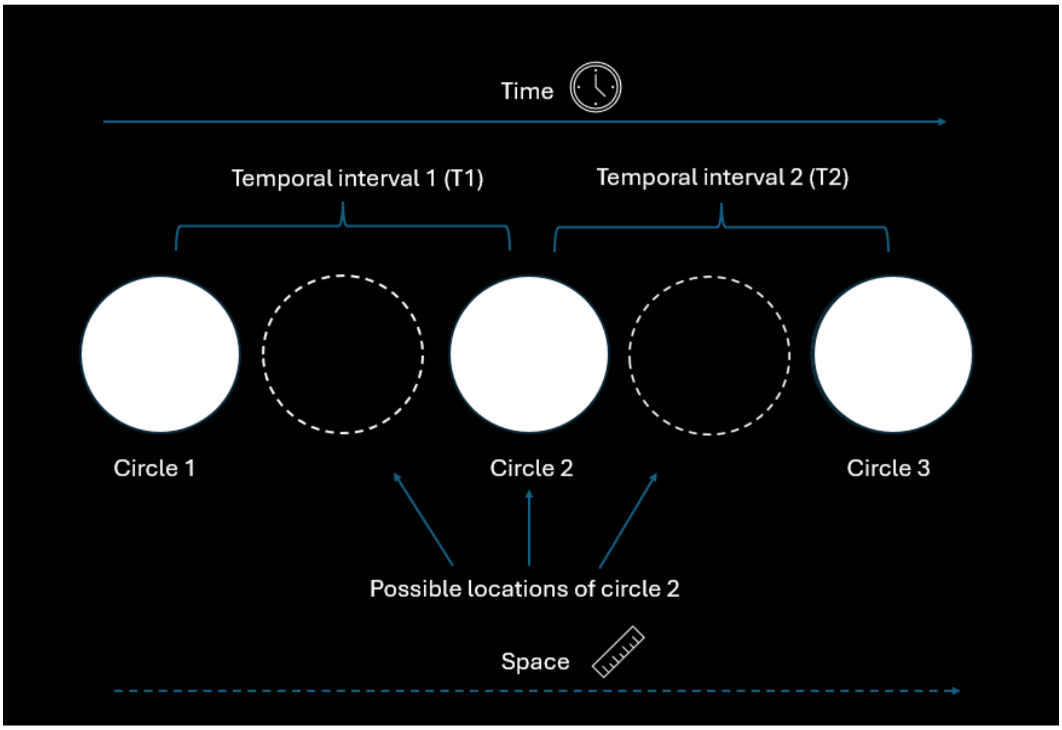

Figure 5: The three circles were separated by two temporal intervals (T1 and T2) and two spatial intervals, as Circle 2 could have 3 possible locations. In this figure it is located in the middle. Time is progressing from left to right, meaning that Circle 1 was presented first, then Circle 2 and lastly Circle 3.

The intentional action, i.e. the keypress, at the onset of Circle 1 should cause intentional binding, thus contracting the temporal perception of T1. The Non-intentional condition was the same as the Intentional condition, but instead of pressing the spacebar at the onset of Circle 1, participants were asked to press the spacebar at the offset of the fixation cross. After a delay of 150 ms, Circle 1 appeared, whereafter a delay of 200 ms followed, and Circle 2 appeared. T2 was determined as T1 +- 0%, 20%, 40% or 60%, as in the Intentional condition (See Figure 6). In the Non-intentional condition, participants committed an intentional action before Circle 1, causing an intentional binding effect to happen outside both T1 and T2.

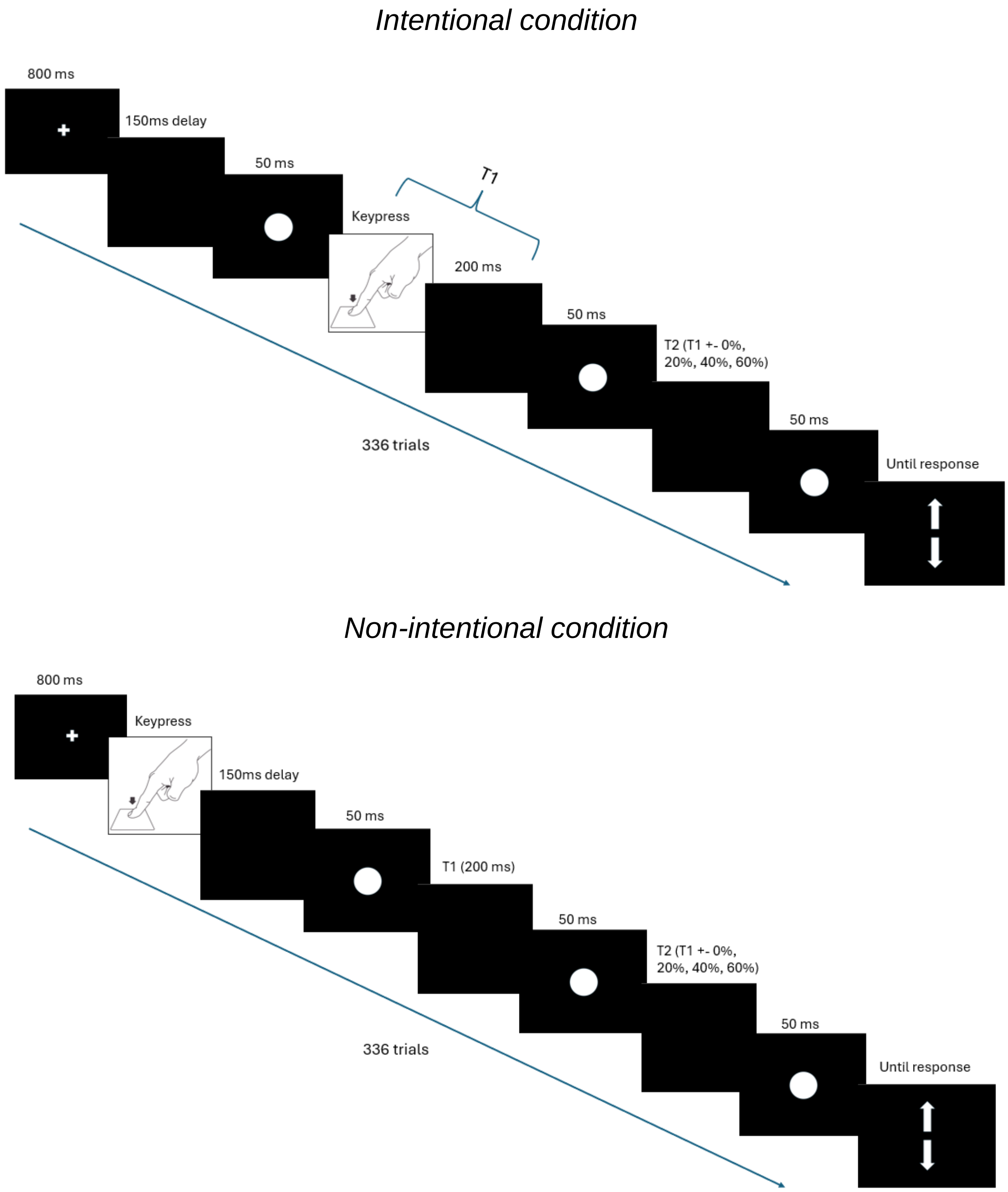

Figure 6*:* Respectively the Intentional and Non-intentional condition. In the Non-intentional condition the participants conducted a keypress before T1, whereas in the Intentional condition the keypress was conducted within T1. Note that Circle 2, could have 3 possible locations as depicted in Figure 5.

The conditions were administered in a counterbalanced fashion across participants. Participants performed two blocks of 12 training trials and two experimental blocks of 336 trials. In the training trials T2 was only set to be either 90% shorter or longer than T1, and Circle 2 only occurred in the middle. In the experimental trials each block lasted approximately 25 minutes. As piloting showed that participants had difficulty remembering the instructions, a piece of paper with the information: '↑ = Temporal interval 2 is longest (in Danish: Tidsinterval 2 er længst)', and '↓ = Temporal interval 2 is shortest (in Danish: Tidsinterval 2 er kortest)' was placed next to the keyboard for the participants to look at when in doubt.

Explicit Ratings

After completion of both experimental blocks, participants were asked to rate: 'To what extent did you experience that you caused the appearance of circle number 1?', and 'To what extent did you experience that you caused the appearance of circle number 2?' (In Danish: 'I hvor høj grad oplevede du, at det var dig der forårsagede, at cirkel nummer 1/2 dukkede op?'.
The participants were asked to rate on a scale from 1 to 10, where 1 was equal to 'I did not at all cause the appearance of circle number 1/2', and 10 was equal to 'I definitely caused the appearance of circle number 1/2' (in Danish: 1 = 'Jeg forårsagede slet ikke at cirkel 1/2 dukkede op', 10 = 'Jeg forårsagede helt sikkert at cirkel 1/2 dukkede op').
The participants were asked to complete an explicit agency questionnaire for each condition. They were first administered one for the block they had just completed, as we suspected their judgment of the first blocks of trials would be affected by the completion of the second blocks of trials.

Data Analysis

To measure intentional binding and the Kappa effect, psychometric functions were created using PyCharm (v2023.3) for each participant, to assess the Point of Subjective Equality (PSE), which represents the point at which the observer is equally likely to choose that T2 was either shorter or longer than T1. This was done for each location of Circle 2. Thereafter mixed ANOVA was conducted on the PSE-values for each possible location of Circle 2 using SPSS (v29.0.0.0). The Explicit Ratings were likewise investigated using mixed ANOVA, and lastly a possible correlation between an intentional binding effect and the Explicit Ratings was

assessed, since previous studies has shown varying results in this regard (Dewey & Knoblich, 2014; Siebertz & Jansen, 2022; Ebert & Wegner, 2010).
The formula used to create psychometric functions were:

$$f(x) = L / (1 + e^{-k(x-x0)})$$

, representing a logistic function, which is commonly used for calculating psychometric functions (Treutwein & Strasburger, 1999; Strasburger, 2001). In the formula, 'L' is the supremum, i.e. the highest value on the Y-axis, 'k' is the logistic growth rate, i.e. the steepness of the slope, 'x' is the input value, and 'x0' is the midpoint of the function, i.e. the PSE.
The X-axis consisted of the varying temporal durations of T2, thus consisting of seven points (-60%, -40%, -20%, 0%, 20%, 40%, 60%), while the Y-axis represented the probability of the participant choosing T2 as the longest from 0 to 1. When PSE values are negative, it means that there is a 50% probability that T2 will be perceived as longest even though it is actually shorter than T1, which is a pattern that is expected to represent intentional binding.

The correlational analysis was done by calculating the difference between PSE values of each location, by subtracting PSE values of the Intentional condition with the PSE values of the Non-intentional condition. These were compared to the Explicit Ratings of control of Circle 2. If the implicit measure and the explicit measures correlate, this should be expressed in the data as a positive correlation of PSE differences and Explicit Ratings of Circle 2 in the Intentional condition, as higher Explicit Ratings should converge with more intentional binding represented as a larger PSE difference. Additionally, a correlational analysis was conducted on PSE differences and differences of Explicit Ratings, calculated as experienced control of Circle 2 minus experienced control of Circle 1. This latter correlational analysis was conducted to investigate whether the ability to detect the circle of control correlated with performance in the implicit measure. Again, a positive correlation is expected in the Intentional condition, as higher Explicit Rating differences should represent a higher ability to detect the circle under control, which should converge with more intentional binding, i.e. higher PSE differences.

Results

First, a visualization of how the data were handled is presented through psychometric functions created by collapsing all data. Thereafter, the results of an effect of intentional binding and Kappa are presented, whereafter the results of the Explicit Ratings are presented. Lastly, the results of correlations between implicit and explicit measures are presented.

Psychometric functions

To calculate PSE values, a psychometric function was created for each participant. As the data of four participants did not fit a psychometric function, these data were not included in the analysis, leaving 18 participants in the group that had the Intentional condition administered first and 13 participants in the group that had the Non-intentional condition administered first. Below are presented psychometric functions created by collapsing data from all participants (n = 31), into two psychometric functions for the Intentional condition and Non-intentional condition to provide a visualization of how data was handled (see Figure 7).

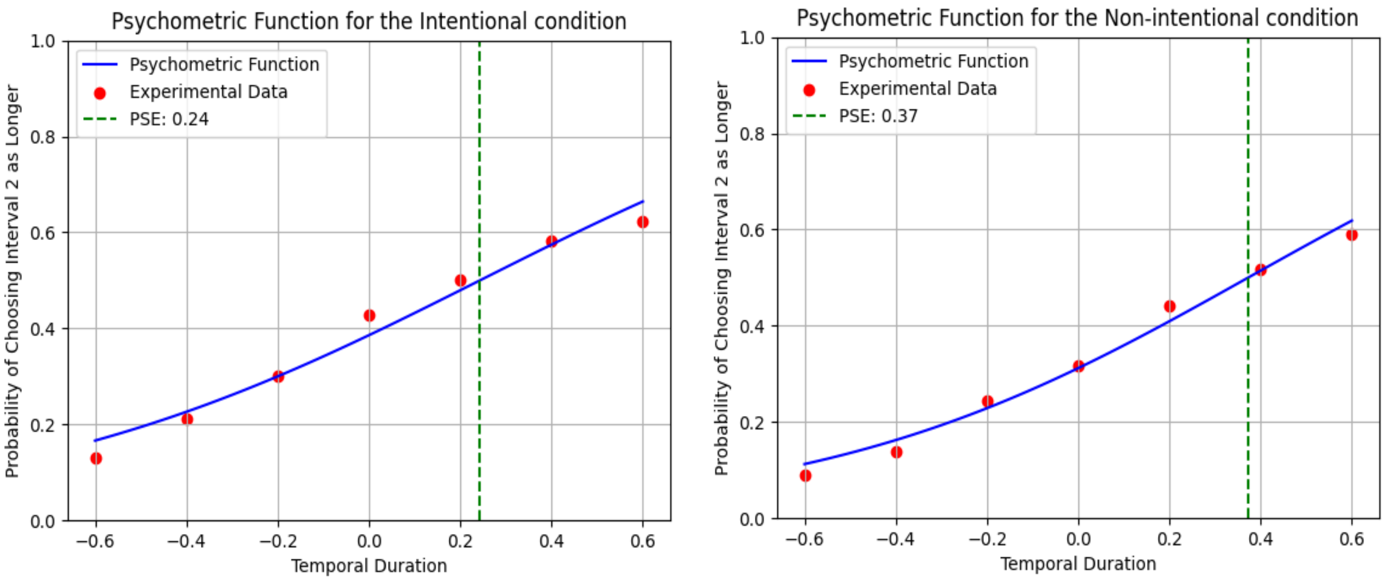

Figure 7: Psychometric functions created by collapsing data of all participants into functions of the Intentional- and Non-intentional condition. The X-axis represents the temporal durations of T2 from -60% to +60% of T1, while the Y-axis represents the probability from 0 to 1 of choosing T2 as longer.

The PSE value of the Intentional condition, when collapsing data across participants, is x0 = .24, steepness of the slope is k = 1.91, the Y-value at the lowest

X-value is Y = .17, while at the highest X-value it is Y = .66. The PSE value of the Non-intentional condition, when collapsing data across participants, is x0 = .37, steepness of the slope is k = 2.12, the Y-value at the lowest X-value is Y = .11, while at the highest X-value it is Y = .62. Though not applicable to analysis, these values would suggest that participants in the Intentional condition had lower PSE values than those in the Non-intentional condition, which could imply intentional binding. The steepness of the slopes suggest that participants were slightly more sensitive to the temporal durations in the Non-intentional condition compared to the Intentional condition. Note however, that these values are not applicable for the analysis, and that they are simply used for a visualization of how the data were handled.

The following analysis will concern PSE values calculated from psychometric functions created for each participant.

Intentional Binding and the Kappa Effect

To test for an effect of intentional binding and the Kappa effect, mixed ANOVA was conducted on PSE values with Group (2 levels; representing the order in which the Intentional Binding conditions were administered), Intentionality (2 levels; representing the Intentional- and Non-intentional conditions) and Location of Circle 2 (3 levels).

There was no main effect of Location of Circle 2 [$F(1.27, 36.78) = 1.01$, $p = .342$, $\eta_p^2 = .03$], implying no evidence that the Kappa effect was present across Groups and Intentionality conditions.

There was no main effect of Intentionality [$F(1, 29) = .68$, $p = .416$, $\eta_p^2 = .02$], which implies no evidence for intentional binding across Groups and Locations of Circle 2.

There was a main effect of Group [$F(1, 29) = 8.04$, $p = .008$, $\eta_p^2 = .22$], suggesting that the order in which the Intentionality conditions were administered had an effect on PSE values, where the Group that had the Intentional condition administered first (IBF) had a lower average PSE value ($M_{IBF} = .25$, $SD_{IBF} = .19$, CI_{IBF} [.15, .35]), than the Group that was administered the Non-intentional condition first (NIBF) ($M_{NIBF} = .47$, $SD_{NIBF} = 0.23$, CI_{NIBF} [.35, .59]), though not in itself implying intentional binding in either Group.

There was no interaction between Group and Location of Circle 2 [$F(2, 29) = .1.79$, $p = .177$, $\eta_p^2 = .03$], implying no evidence that the Kappa effect was present in either Group.

There was no interaction between Intentionality and Location of Circle 2 [$F(1.51, 43.75) = .51$, $p = .555$, $\eta_p^2 = .02$], implying no evidence that the Kappa effect was present in either Intentionality condition.

There was an interaction between Group and Intentionality [$F(1, 29) = 6.92$, $p = .013$, $\eta_p^2 = .19$]. Post hoc pairwise comparisons with Bonferroni correction revealed a difference in PSE values between Intentionality conditions for the Group that had the Intentional condition administered first ($p = .003$), where PSE values were lower in the Intentional condition (IB) compared to the Non-intentional condition (NIB) ($M_{IBF\text{-}IB} = .17$, $SD_{IBF\text{-}IB} = .22$, $CI_{IBF\text{-}IB}$ [.03, .31]; $M_{IBF\text{-}NIB} = .34$, $SD_{IBF\text{-}NIB} = .2$, $CI_{IBF\text{-}NIB}$ [.25, .44]), suggesting that intentional binding was present for this Group.
No difference in PSE values was found between Intentionality conditions for the Group that had the Non-intentional condition administered first ($p = .275$), where PSE values in the Intentional condition compared to the Non-intentional condition were ($M_{NIBF\text{-}IB} = .51$, $SD_{NIBF\text{-}IB} = .37$, $CI_{NIBF\text{-}IB}$ [.35, .68]; $M_{NIBF\text{-}NIB} = .42$, $SD_{NIBF\text{-}NIB} = .2$, $CI_{NIBF\text{-}NIB}$ [.31, .53]), implying no evidence that intentional binding was present for this Group (See Figure 8).

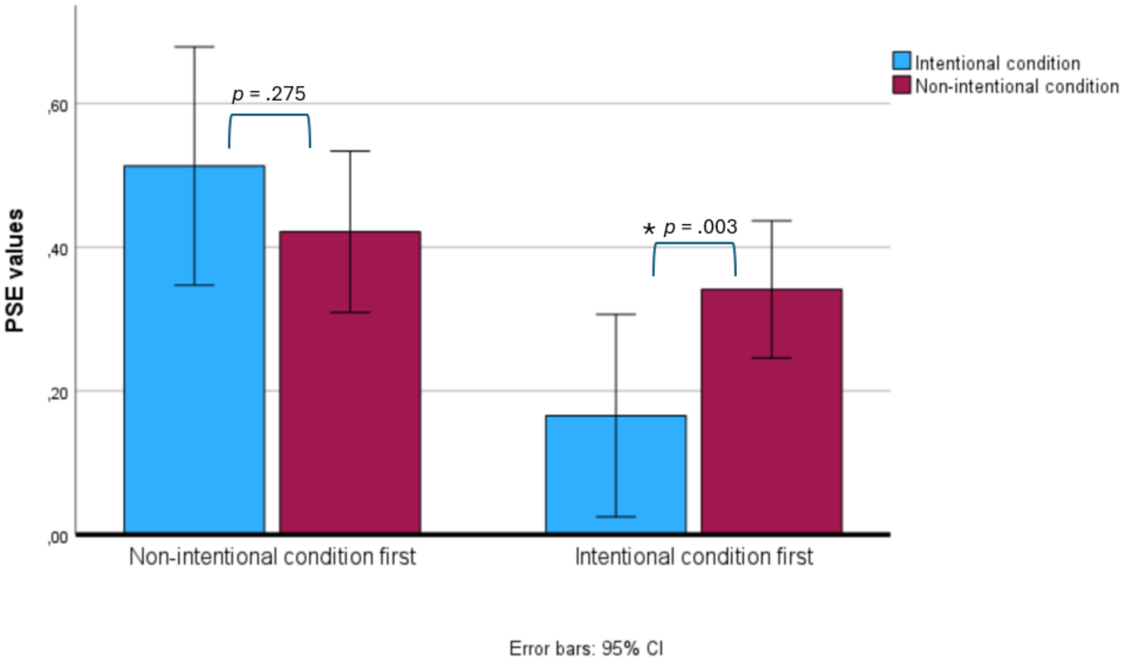

Figure 8: PSE values in relation to Intentionality regarding which conditions were administered first. There was a difference in PSE values between Intentionality conditions in the Group that had the Intentional condition administered first. Error bars represent 95% CI.

There was no interaction between Group, Intentionality and Location of Circle 2 [F(2, 29) = 2.71, p = .075, η_p^2 = .09].

Mean PSE values are presented in Table 1.

	Location 1 Mean (SD)	**Location 2** Mean (SD)	**Location 3** Mean (SD)
Intentional condition administered first			
Intentional condition	.17 (.19)	.1 (.25)	.23 (.33)
Non-intentional condition	.37 (.19)	.35 (.24)	.30 (.27)
Non-intentional condition administered first			
Intentional condition	.56 (.57)	.74 (1.05)	.24 (.71)
Non-intentional condition	.42 (.27)	.44 (.25)	.41 (.22)

Table 1: PSE values of the Intentional- and Non-intentional condition of the three locations of Circle 2 in the two groups that had either the Intentional- or Non-intentional condition administered first.

In sum the results suggest that there was an effect of intentional binding, but only for the group that performed the Intentional condition first, thus partially yielding support to hypothesis 1. The Kappa effect was not present, which does not yield support to hypothesis 2 and 3.

Explicit Ratings

To test for differences in Explicit Ratings, mixed ANOVA was conducted on Group (2 levels), Intentionality (2 levels) and Rated Circle (2 levels; representing the rating of either Circle 1 or 2).

As expected, there was no main effect of Intentionality [$F(1, 29) = 3.58$, $p = .068$, $\eta_p^2 = .11$], implying no evidence that the ratings were different across the Intentional- and the Non-intentional condition across Groups.

Also expectedly, there was no main effect of Rated Circle [$F(1, 29) = 2.4$, $p = .132$, $\eta_p^2 = .08$], implying no evidence that ratings of Circle 1 and 2 were different across Intentionality conditions and Groups.

There was no main effect of Group [$F(1, 29) = 2.22$, $p = .147$, $\eta_p^2 = .07$], implying no evidence that ratings were different in the Group that performed the Non-intentional condition first compared to the Group that performed the Intentional condition first.

There was no interaction between Intentionality and Group [$F(1, 29) = 0.62$, $p = .805$, $\eta_p^2 = .002$], implying no evidence that ratings differed across Circle 1 and 2 between Intentionality conditions across Groups.

There was no interaction between Rated Circle and Group [$F(1, 29) = .79$, $p = .383$, $\eta_p^2 = .03$], implying no evidence that ratings were affected by which circle was rated across Groups.

There was an interaction of Intentionality and Rated Circle [$F(1, 29) = 57.004$, $p = <.001$, $\eta_p^2 = .66$]. Post hoc pairwise comparisons with Bonferroni correction showed that Explicit Ratings differed between Intentionality conditions for Circle 1 ($p = <.001$), where Explicit Ratings of Circle 1 in the Non-intentional (NI) and Intentional (I) conditions were respectively $M_{NI} = 8.55$, $SD_{NI} = 2.59$, CI_{NI} [7.57, 9.53]; $M_I = 3.39$, $SD_I = 3.85$, CI_I [1.8, 4.5].
Explicit Ratings also differed between Intentionality conditions for Circle 2 ($p = <.001$), where Explicit Ratings of Circle 2 were $M_{NI} = 2.74$, $SD_{NI} = 2.76$, CI_{NI} [1.62, 3.62]; $M_I = 6.39$, $SD_I = 3.58$, CI_I [5.63, 8.22]. This suggests that participants reported experienced agency of the circle that they were in control of in both Intentionality conditions across Groups.

There was an interaction of Intentionality, Rated Circle and Group [$F(1, 29) = 57.44$, $p = .04$, $\eta_p^2 = .14$]. A post hoc pairwise comparison with Bonferroni correction showed that the Group that performed the Non-intentional condition first experienced significantly more control of Circle 1 in the Non-intentional condition (M = 8.54, SD = 2.7, CI [7.04, 10.03]) compared to the Intentional condition (p = <.001, M = 1.69, SD = 2.5, CI [-.36, 3.75]). This Group likewise experienced significantly more control of Circle 2 in the Intentional condition (M= 7.46, SD= 3.33, CI [5.49, 9.44]) compared to the Non-intentional condition (p = <.001, M= 1.85, SD= 1.63, CI [.32, 3.37]).

The Group that performed the Intentional condition first experienced significantly more control of Circle 1 in the Non-intentional condition (M = 8.56, SD = 2.6, CI [7.28, 9.83]) compared to the Intentional condition (p = <.001, M = 4.61, SD = 4.25, CI [2.86, 6.36]). This Group also experienced significantly more control of Circle 2 in the Intentional condition (M = 6.39, SD = 3.58, CI [4.71, 8.07]) compared to the Non-intentional condition ($p = .002$, M = 3.39, SD = 3.24, CI [2.86, 6.36]). This suggests that both Groups experienced most control of Circle 1 in the condition where they could control Circle 1, and that they experienced most control of Circle 2 in the condition where they could control Circle 2.

Additionally, post hoc pairwise comparisons with Bonferroni correction showed that Circle 1 (C1) was rated higher (M = 8.54, SD = 2.7, CI [7.04, 10.03]) than Circle 2 (C2) (M = 1.85, SD = 1.63, CI [.32, 3.37]) in the Non-intentional condition, when it was performed first (p = < .001). It was also the case when it was performed second (p = <.001, $M_{C1} = 8.56$, $SD_{C1} = 2.6$, CI_{C1} [7.28, 9.83]; $M_{C2} = 3.39$, $SD_{C2} = 3.24$, CI_{C2} [2.86, 6.36]).

Inversely, Circle 1 was rated lower (M = 1.69, SD= 2.5, CI [-.36, 3.75]) than Circle 2 (M= 7.46, SD= 3.33, [5.49, 9.44]) in the Intentional condition, when it was performed second ($p = .002$), however no significant difference appeared, when it was performed first ($p = .232$, $M_{C1} = 4.61$, $SD_{C1} = 4.25$, CI_{C1} [2.86, 6.36]; $M_{C2} = 6.39$, $SD_{C2} = 3.58$, CI_{C2} [4.71, 8.07]) (See Figure 9).

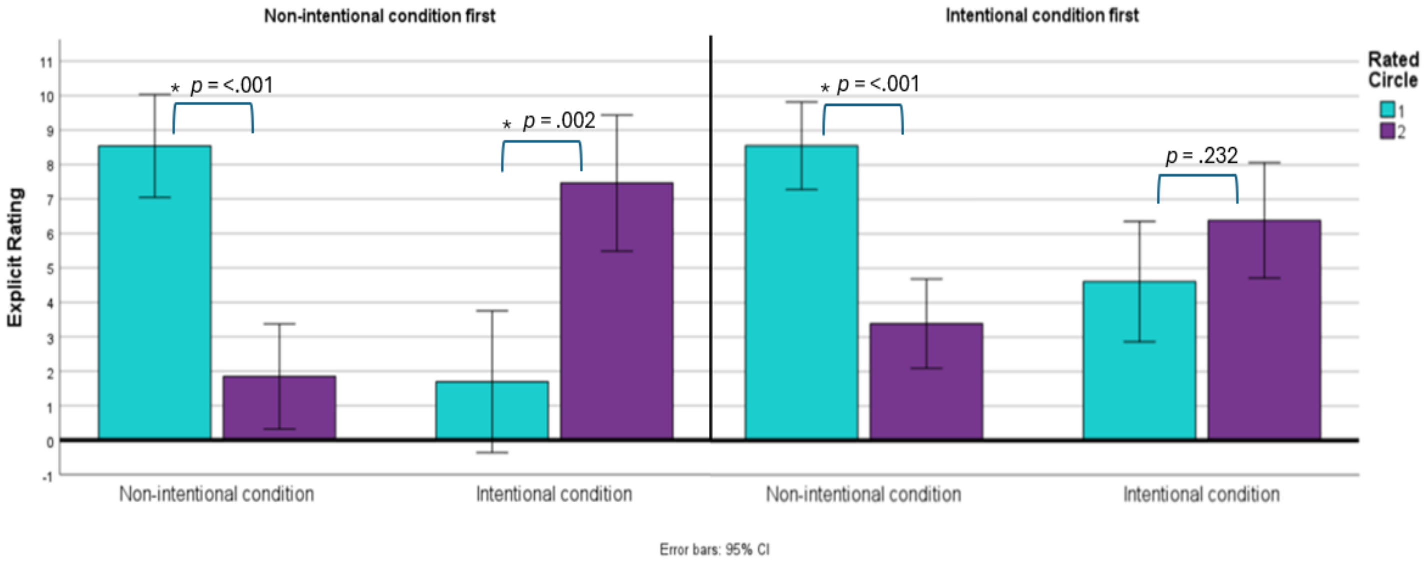

Figure 9: Explicit Ratings in relation to Intentionality and Rated Circle. Ratings for the Group that had the Non-intentional condition administered first are presented on the left, while ratings for the Group that had the Intentional condition administered first are presented on the right. Participants experienced more control of the circle that they could control compared to the circle that they could not control, though this pattern was not found in the Intentional condition for the Group that had the Intentional condition administered first. Error bars represent 95% CI.

This suggests that participants experienced significantly more control of the circle that they could control compared to the circle that they could not control for both Groups in the Non-intentional condition, but this pattern was not found in the Intentional condition for the Group that performed the Intentional condition first. This is peculiar as participants of this latter Group yielded intentional binding, which should prompt a difference of experienced agency of Circle 1 and 2, if both measures assess SoA.

Lastly, a post hoc pairwise comparison with Bonferroni correction showed that the Group that performed the Intentional condition first experienced significantly more agency of Circle 1 in the Intentional condition (M = 4.61, SD = 4.25, [2.86, 6.36]) than the Group that performed the Non-intentional condition first (p = .035, M = 1.69, SD = 2.5, [-.36, 3.75]). This is interesting, as this suggests that the Group that performed the Intentional condition first was more misled about their control of Circle 1 in the Intentional condition than the Group that performed the Non-intentional condition first, as they did in fact not have control of Circle 1 in this condition.

Mean values of Explicit Ratings are presented in Table 2.

	Circle 1 Mean (SD)	**Circle 2** Mean (SD)
Intentional condition administered first		
Intentional condition	4.61 (4.25)	6.39 (3.58)
Non-intentional condition	8.56 (2.6)	3.39 (3.24)
Non-intentional condition administered first		
Intentional condition	1.69 (2.5)	7.46 (3.33)
Non-intentional condition	8.54 (2.7)	1.85 (1.63)

Table 2: Explicit Ratings in relation to Intentionality for the Group that had the Intentional condition administered first and the Group that had the Non-intentional condition administered first.

In sum, the results suggest that participants experienced most control of the circle that they could actually control, and on most occasions participants experienced more agency of the circle that they could control compared to the circle that they could not control, thus partially yielding support to hypothesis 4 and 5. But this was interestingly not found in the Intentional condition of the Group that had the Intentional condition administered first. Additionally, the Group that was administered the Intentional condition first was found to experience more agency of Circle 1 in the Intentional condition than the Group that was administered the Non-intentional condition first, though they did in fact not have control of this circle, causing suspicion that the Group that was administered the Intentional condition first was misled about their control of Circle 1 in the Intentional condition.

Correlation of Implicit and Explicit measures

To investigate if the measures of the novel paradigm correlates with a measure of judged agency, a correlational analysis was performed on the differences between PSE values and on Explicit Ratings of Circle 2 in the Intentional condition. Differences of PSE values were calculated by subtracting PSE values of the Intentional condition from PSE values of the Non-intentional condition. If lower PSE values in the Intentional condition compared to PSE values of the Non-intentional condition represents an implicit measure of SoA, a bigger difference should represent a larger SoA.

No correlation was found between PSE difference and Explicit Ratings of Circle 2 across Groups [$r(29) = -.15$, $p = .412$], suggesting that implicit and explicit SoA did not correlate across the two Groups, that was administered either the Intentional- or Non-intentional condition first.

Neither was a correlation found for the group that was administered the Intentional condition first [$r(16) = -.03$, $p = .914$], suggesting that implicit and explicit SoA did not correlate in this Group, though these participants were found to exhibit intentional binding in previous analysis.

Likewise, no correlation was found for the Group that was administered the Non-intentional condition first [$r(11) = -.16$, $p = .601$], suggesting that implicit and explicit SoA did not correlate in this Group either (see Figure 10), which is not surprising as this Group was not found to exhibit intentional binding in previous analysis.

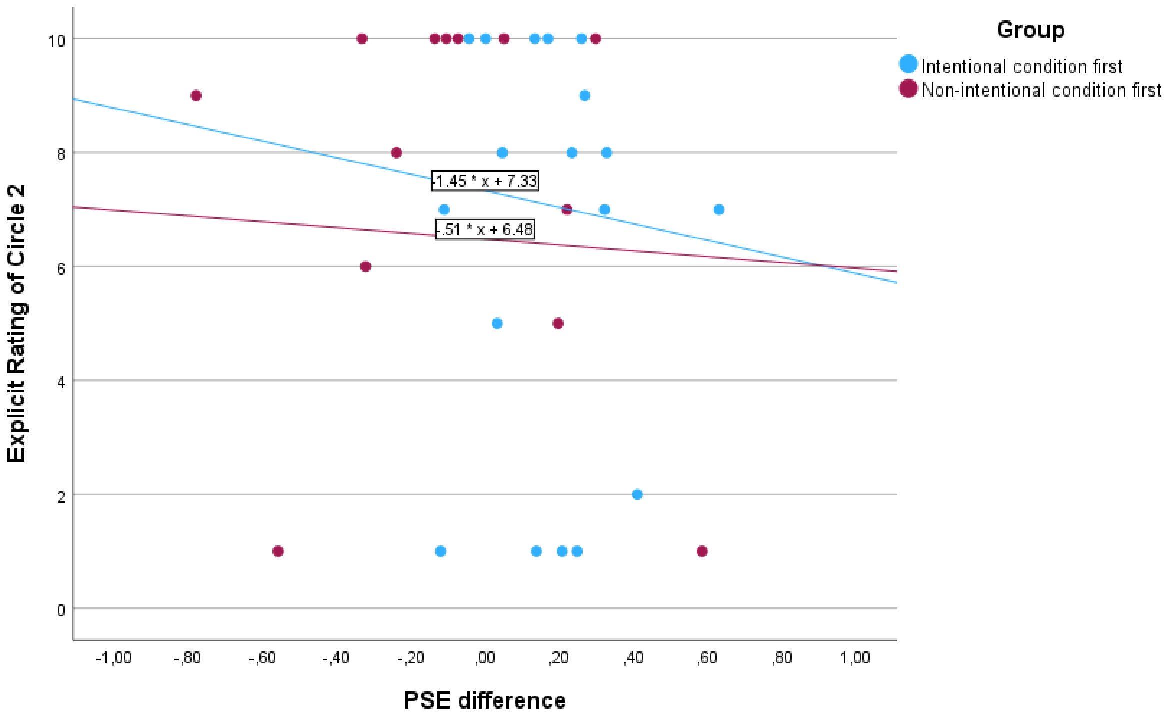

Figure 10: Scatterplot with linear function of Explicit Rating of Circle 2 as a function of PSE difference in relation to Group. The Group that had the Intentional condition administered first yielded a linear function of $y = -1.45x + 7.33$, while the Group that had the Non-intentional condition administered first yielded a linear function of $y = -.51x + 6.48$. Pearson's r was non-significant for both, respectively (-.03, p = .914) and (-.16, p = .601).

In sum, these results suggest that a greater effect of intentional binding did not converge with a greater rating of explicit agency, implying that implicit and explicit SoA does not correlate, thus not yielding support to hypothesis 6.

To further explore the link between implicit and explicit SoA, the differences of PSE values were correlated with differences in Explicit Ratings, calculated as the Explicit Rating of control of Circle 2 minus the Explicit Rating of control of Circle 1 in the Intentional condition. This was done to analyze whether the ability to detect which circle was under control correlated with the implicit measure. If participants were able to detect which circle they were in control of, they should experience low control of Circle 1 and high control of Circle 2 in the Intentional condition, thus causing a large difference between Explicit Ratings of Circle 1 and 2.

No correlation was found between PSE differences and the differences of Explicit Ratings across Groups [$r(29) = -.09$, $p = .616$], suggesting that the ability to detect which circle was under control did not correlate with intentional binding across the two Groups, that was administered either the Intentional- or Non-intentional condition first.

Neither was a correlation found for the Group that was administered the Intentional condition first [$r(16) = .03$, $p = .896$], suggesting that the ability to detect which circle was under control did not correlate with Intentional binding, though this group yielded an effect of intentional binding in previous analysis. Since previous analysis showed that this Group did not show a difference in Explicit Ratings of Circle 1 and 2, this is not surprising.

Lastly, no correlation was found for the Group that was administered the Non-intentional condition first [$r(11) = .08$, $p = .796$], suggesting that the ability to detect which circle was under control did not correlate with Intentional binding (see Figure 11), which is not surprising as this Group did not exhibit intentional binding in previous analysis.

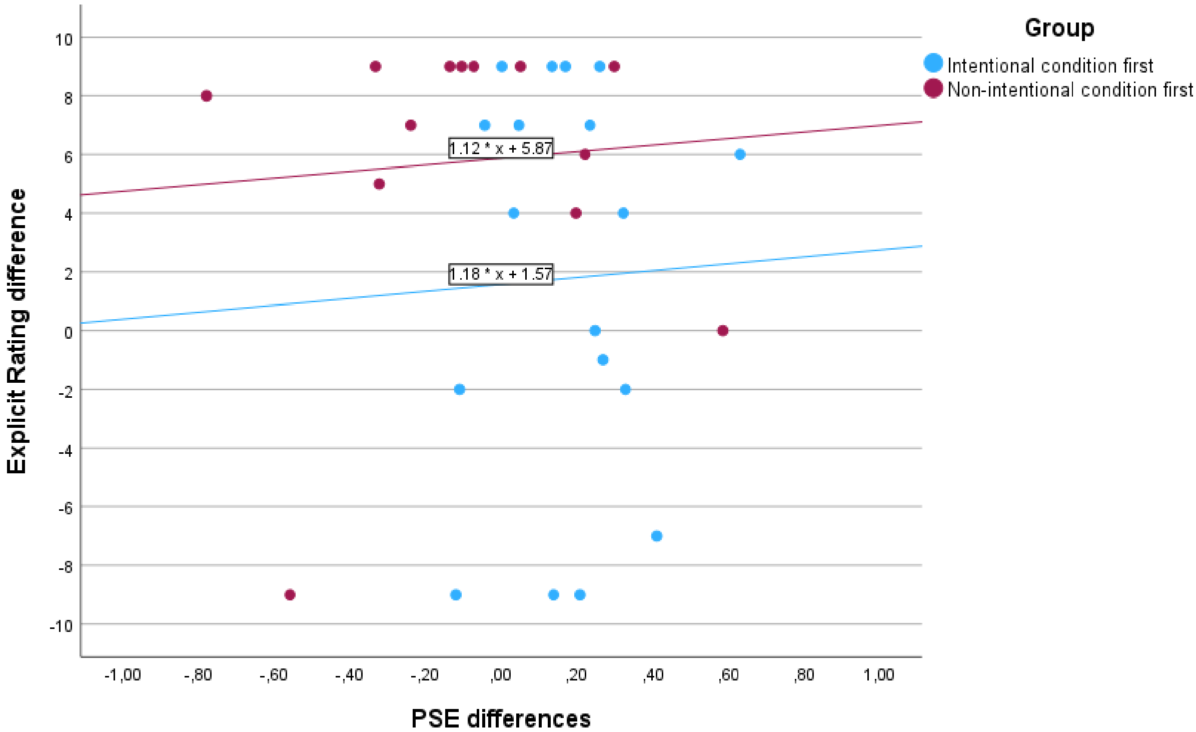

Figure 11: Scatterplot with linear function of Explicit Rating difference as a function of PSE difference in relation to Group. The Group that had the Intentional condition administered first yielded a linear function of $y = 1.18x + 1.57$, while the Group that had the Non-intentional condition administered first yielded a linear function of $y = 1.12x + 5.87$. Pearson's r was non-significant for both, respectively (.03, p = .896) and (.08, p = .796).

This suggests that a greater effect of intentional binding did not converge with a greater ability to detect which circle the participant was in control of, thus not yielding support to hypothesis 7.

Discussion

The goal of this study was to examine a novel paradigm to assess SoA that combines intentional binding with the Kappa effect. This was investigated by testing the novel paradigm on 35 participants to obtain PSE values, whereof lower PSE values in the Intentional condition compared to the Non-intentional condition should represent an effect of intentional binding, which should be increased and decreased under various conditions due to the Kappa effect. Additionally, the performances on the novel paradigm were compared to the participants' reported experiences of agency.

The results suggest no evidence of the Kappa effect, but an effect of intentional binding, though interestingly only in one group. The results further suggest that most participants did experience agency of the appropriate circles, but the amount of intentional binding did not correlate with either the amount of experienced agency or the ability to detect control. Additionally, the results suggest that the participants who were administered the Intentional condition first were misled regarding their control of Circle 1 in the Intentional condition. These results and limitations of the study will be investigated in the following chapters.

Lack of a Kappa effect

One explanation for the lack of a Kappa effect is that introducing an intentional action to a Kappa effect paradigm might have disrupted the Kappa effect. The reasoning for this is that, in the Intentional condition, participants are expected to be able to very swiftly shift from conducting an action at the onset of Circle 1 to monitoring the occurrence of the following circles. This could tax the attentional resources to a degree that merely observing the circles do not, causing diminished spatial perception, which causes the Kappa effect to be disrupted. Additionally, it is possible that the action at the offset of the fixation cross in the Non-intentional condition could disrupt the Kappa effect in a similar way, though perhaps to a lesser degree, as participants had slightly more time to shift from conducting an action to observing the circles in this condition, due to the 150 ms delay between action and Circle 1 and no action demands after onset of Circle 1. This would explain that no Kappa effect was found in the Non-intentional condition of the group that performed the Non-intentional condition first. It would be interesting to see if introducing a longer delay between action and Circle 1 in the Non-intentional condition would prompt a Kappa effect, as the longer time to shift attention from action-conduction to observing the circles should decrease the attentional demands that are suggested to disrupt the Kappa effect.

Another explanation is that the occurrence of the circles was too short (50 ms), which is conceivable as other studies finding evidence of a Kappa effect have used longer appearance periods (100 ms) (Reali et al., 2019). If the stimulus duration was too short, participants might have been unable to properly perceive the circles, which would obstruct the Kappa effect, as it would have made it hard to notice their exact location on the screen. Other studies have found evidence of a Kappa effect using 50 ms stimulus durations (47 ms in De Pra et al., 2023, and 50 ms in Kuroda et al., 2016), but it could be that when not merely observing stimuli, but also conducting motor actions affecting the stimuli, the stimulus durations of 50 ms are too short, as greater attentional resources are demanded. Perhaps prolonging stimulus duration would create better time to process the spatial locations of the circles, which might elicit the Kappa effect.

Lastly, an explanation for the lack of a Kappa effect is that participants were not adequately sensitive to the chosen temporal durations of T2. T2 was defined as -60% to +60% of T1 with increments of 20%, which yielded Y-values of Y = .17 and Y = .66 at respectively the lowest and highest X-values in the Intentional condition. The same values for the Non-intentional condition were Y = .11 and Y = .62. This results in Y-value differences of Y = .49 for the Intentional condition and Y = .51 for the Non-intentional condition. These differences are quite low as the Y-axis goes from 0 to 1, where a perfect fit has a difference of Y = 1. Thus, the low differences suggest that participants were not very sensitive to the varying temporal durations, which could mean that the span from the lowest to the highest value was too low. Future studies should apply a larger span to see if the psychometric functions will exhibit a larger Y-value difference.

To sum up, the Kappa effect might have been disrupted by the participants’ ability to control the onset of Circle 1 and 2 in conjunction with relatively short stimuli duration, and by participants' low sensitivity to the varying temporal durations of T2.

Intentional Binding Only in One Group

It is interesting that intentional binding was only found in the Group that was administered the Intentional condition first. A possible explanation is that the administration of the Non-intentional condition first introduced disruptions to the perceived contraction of T1 in the Intentional condition. Participants reported having trouble performing the keypress at the correct time in the secondly administered Intentionality condition, which is likely a result of the participants becoming very confident with the procedure of the first condition they were administered, as they completed 336 trials in each block, causing the procedure of the firstly administered block to be hard to unlearn when beginning the secondly administered block. It was observed by the experimenter, that participants that performed the Non-intentional condition first kept pressing the spacebar at the offset of the fixation cross in the Intentional condition, though they were supposed to press the spacebar at the onset of Circle 1. In some instances, this caused participants to be confused as to why the screen kept being blank after Circle 1, which was caused by the fact that they did not elicit the onset of Circle 2. In other instances, the short delay between fixation cross and Circle 1 (150 ms) caused the keypress, which was intended at the offset of the fixation cross, to happen very briefly after the onset of Circle 1, thus falsely causing a very short reaction time after onset of Circle 1, resulting in shortening of both T1 and T2. Both instances can have disrupted the intentional binding effect.

Another possible cause of the lack of intentional binding in the Group that performed the Non-intentional condition first is that the many trials caused attentional exhaustion. Participants reported being quite exhausted after completion of both blocks, as the total number of trials completed was 672 and as the task, though it was quite simple, required participants to sustain attention for a long period of time. It is conceivable that the Intentional condition was a bit more cognitively demanding than the Non-intentional condition, as the keypress was required at the onset of Circle 1, which required the participant to very swiftly shift attention from conducting the keypress to monitoring T1. In the Non-intentional condition, a 150 ms delay allowed the participant a bit of time to transit from conducting an action to monitoring T1 and T2. It is possible that participants, who were administered the Non-intentional condition first, were cognitively exhausted from the first block, and when performing the second block, which was a bit more demanding, they could not sustain their attention. As these participants became cognitively exhausted, they were less sensitive to the varying temporal durations, causing them to rely more on guessing than actual sensory detection. This possibility is supported by the fact that the participants, who had to be removed from the data set due to behavior unable to fit a psychometric curve, all stemmed from the Group that performed the Non-intentional condition first.
The high attentional demand is unfortunate, as one of the suggested arguments for using this novel paradigm is that it is less complex for participants to perform than previous methods (Haggard et al., 2003), thus sustaining cognitive and attentional resources less. Since this novel paradigm is attentional demanding, it might be challenging to perform for people with schizophrenia, as they have been found to have attentional deficits (Hahn et al., 2012; Spencer et al., 2011). This is an issue as research in SoA is vital for understanding influence phenomena in people with schizophrenia. But before ruling out that people with schizophrenia cannot perform well on this novel paradigm, it should be tested on this population, as previous research has found that participants with schizophrenia performed quite well on the

cognitively demanding Libet Clock task (Haggard et al., 2003), and as this novel paradigm is plausibly less demanding than the Libet Clock method.

Difference of Experienced Agency of Circle 1 and 2 due to Administration Order

It is peculiar that the participants that had the Intentional condition administered were not found to differ in their ratings of experienced agency of Circle 1 and 2 in the Intentional condition, as they were the only Group to elicit intentional binding, which suggests that they did experience SoA of Circle 2. It was found that this Group had a higher rating of experienced control of Circle 1 in the Intentional condition, when compared to the participants that had the Non-intentional condition administered first, which cause suspicion that the participants that had the Intentional condition administered first was misled regarding their control of Circle 1 in the Intentional condition.

A possible explanation for this is that these participants were subject to a mechanism similar to that of Backward Causation as suggested by Maeda et al. (2012), where SoA is retrospectively inferred, though the sensory consequence happened before the action. In terms of the current experiment this would suggest that participants retrospectively inferred that they controlled the onset of Circle 1, though their keypress was conducted after the onset of Circle 1. Maeda et al. (2012) investigated participants with schizophrenia, but a somewhat similar mechanism was described by Stetson et al. (2006) regarding healthy participants, where shortening of the temporal delay between action and sensory consequence was found to cause the illusion that the sensory consequence happened before the action, thus implying that SoA can also be modified retrospectively in healthy participants. The reason that only the Group that had the Intentional condition administered first was susceptible to this might be that the Group that had the Non-intentional condition administered first had gained experience with actual control of Circle 1 in the Non-intentional condition before conducting the Intentional condition, causing them to have a priori knowledge of the experience of control of Circle 1. As they knew how control of Circle 1 ‘should feel’, they were not as prone to Backward Causation as the other Group.

The findings of Maeda et al. (2006) and Stetson et al. (2006) support the notion that retrospective processing can affect SoA, which is also supported by the current findings.

Lack of Correlation of Implicit and Explicit measures

The lack of a correlation between implicit and explicit measures contributes to similar findings of earlier studies (Dewey & Knoblich, 2014). The question is then: why do implicit and explicit measures correlate in some instances (e.g. Ebert & Wegner, 2010), but not in others? Grünbaum & Christensen (2020) emphasize that the current implicit measures have low construct validity. Construct validity refers to whether different psychometric measures assess the same underlying construct, in this case SoA. The lack of a correlation suggests that this is not the case. Grünbaum & Christensen (2020) additionally emphasize that a problem of the current SoA research is that it lacks in acknowledging that SoA is constructed by several sub constructs. Grünbaum & Christensen (2020) divide SoA into four different sub constructs based on a two 2x2 model, with a column of bodily and external agency as well as a column of ability and phenomenal agency (See Figure 12).

	Bodily	External
Phenomenal	Construct 1 - Bodily + Phenomenal	Construct 3 - External + Phenomenal
Ability	Construct 2 - Bodily + Ability	Construct 4 - External + Ability

Figure 12: A representation of the model suggested by Grünbaum & Christensen (2020), where SoA can be divided into four constructs assessed by different methods. Classical intentional binding paradigms and explicit measures used to assess agency in intentional binding tasks relate to Construct 3.

Implicit measures using classical intentional binding paradigms (e.g. Haggard et al., 2002) assess the external + phenomenal construct, as they assume that SoA are represented by the experience of being the agent of consequences in the external world, while relying on a measure of phenomenal agency assessing the experience of SoA rather than the cognitive ability associated with SoA. Explicit measures in the external category belong to the same construct, causing them to supposedly assess the same aspects of SoA (Grünbaum & Christensen, 2020).

The Comparator model has been used to explain SoA in experiments of classical intentional binding paradigms (e.g. Haggard, 2005). But the issue is that the

Comparator model can only account for the motor aspects of the phenomenal experience, causing it to be able to explain the bodily experience of agency, (the experience of being in control of one's own body parts), but not the external agency (experience of motor actions causing an effect in the external world). The reason for this is that, when conducting an action that elicits an effect on the external world, some external objects will come into play, which the predictive processing of the Comparator model cannot account for. For example, it requires causal knowledge of how an engine in a car works for a person to experience phenomenal agency of starting the engine by twisting the key in the ignition lock, as there is a delay between twisting and humming of the motor (Grünbaum & Christensen, 2020). This is not possible to explain with pure predictive processing of intrinsic cues, as causal inference of external cues is needed (I need to know how a car works for me to experience agency of starting the engine by twisting the key). It is conceivable though, that predictive processing and causal inference (related to retrospective processing) collaborate in a Bayesian fashion to elicit SoA in the external + phenomenal construct, so if predictive processing yields scarce evidence, the system puts more weight on processing of causal inference, i.e. retrospective processing. The fact that predictive and retrospective processing both influence classical implicit measures is supported by several studies (Moore & Haggard, 2008; Moore et al., 2009; Voss et al., 2010).
Thus, besides being confounded by factors such as temporal predictability, perceived causality and several biases, classical implicit measures are also confounded by the fact that we do not know to what degree they rely on predictive and retrospective processing.

Regarding the contradictory findings of correlations between implicit and explicit measures, it is conceivable that different implicit measures rely to varying degrees on predictive- and retrospective processing, causing them to be reliant on both FoA and JoA in relation to the Two-Step Account of Agency, as these are related to predictive bottom-up processing of internal cues and retrospective top-down processing of external cues, as earlier stated.
Though belonging to the same construct of external + phenomenal agency (Grünbaum & Christensen, 2023), explicit measures rely primarily on retrospective processing, as they relate to participants' conceptual judgment of agency.

Therefore, the contradictory findings can be explained by the fact that when implicit and explicit measures both rely heavily on retrospective processing, they will correlate, but when implicit measures rely primarily on predictive processing, they will not correlate.

Regarding this explanation, the reason for a lack of correlation between the novel paradigm and the Explicit Ratings is that the novel paradigm relies primarily on predictive processing, whereas the Explicit Ratings rely on retrospective processing. This reasoning makes sense regarding the finding of a correlation between the implicit- and explicit measure in the study of Ebert & Wegner (2010), as the implicit measure was found to be enhanced by congruence between bodily movement and subsequent movement of an external object, suggesting that the system was heavily reliant on retrospective processing in this task. Since both the implicit- and explicit measures were very reliant on retrospective processing, they were found to correlate.

This explanation is speculative, but it is possible to investigate with the method of Moore & Haggard (2008), as the relative contribution of predictive- and retrospective processing is assessed, which can then be compared to an explicit measure that should be primarily reliant on retrospective processing. Though not assessing this novel paradigm, this could indicate if the above explanation for contradictory results regarding correlations of implicit and explicit measures holds true.

To sum up, while the Explicit Ratings and intentional binding assess the same construct, they might varyingly rely on two sub processes, and as intentional binding rely mostly on one process in the current experiment, while the Explicit Ratings rely mostly on the other process, they do not correlate.

Limitations

One limitation of this novel paradigm is that it is unknown to what degree it relies on predictive and retrospective processing causing uncertainty as to what it actually measures as mentioned above. Future studies should be concerned with uncovering the contribution of predictive and retrospective processing in different methods of intentional binding, and perhaps, instead of focusing on developing one single measure for SoA, future research should focus on creating a protocol of various measures, thus incorporating all aspects of SoA, as the entirety of SoA might not be possible to assess through just one measure.

A related issue is that it is unknown to what degree the different methods are subject to confounding variables, and, while this novel paradigm aims to circumvent some of these confounding variables, it cannot control for perceived causality between events. This means that it is unknown whether it was simply the belief that the onset of Circle 2 is contingent on the onset of Circle 1 that caused the effect of intentional binding. This could indeed be the case, as Cohen et al. (1953; 1955) propose that the Kappa effect is due to participants perceiving the three circles as one moving object, which would imply a causal relationship between all three circles. It seems unlikely though, that this perceived causality should have a stronger effect in the Intentional condition of the Group that had the Intentional condition administered first compared to the Group that had the Non-intentional condition administered first, as there is no reason why this Group should be more prone to perceived causality between Circle 1 and 2 than the other Group. Additionally, there is no reason why the Group in question should experience increased perceptual causality between Circle 1 and 2 than between Circle 2 and 3 in the concerned condition. The most plausible cause of the finding of intentional binding in the Group that had the Intentional condition administered first is thus that the intentional action of the participants at the onset of Circle 1 caused a contraction of the temporal interval between Circle 1 and 2, suggesting that a true effect of intentional binding was found. Nonetheless, future studies should address the issue of controlling for perceived causality between events in intentional binding paradigms, so it can be uncovered to what extent intentional binding methods actually assess SoA.

The novel paradigm has a limitation in the procedure of the Intentional condition as participants are asked to press the spacebar at the onset of Circle 1. It is not possible to press the spacebar at the exact onset of Circle 1, causing a temporal discrepancy between onset of Circle 1 and onset of Circle 2 between conditions. This happens as Circle 1 and 2 are only separated by a 200 ms delay in the Non-intentional condition, while they are separated by a 200 ms delay + reaction time of the participant in the Intentional condition. In previous intentional binding paradigms, the participant conducts an action at a self-chosen time, causing reaction time to be irrelevant. This issue is hard to circumvent, when combining intentional binding with the Kappa effect, as timing of the keypress and onset of Circle 1 is difficult to perfectly match. Nonetheless, intentional binding was found in one Group of participants, which is impressive regarding the fact that this procedural limitation actually lengthens T1 in the Intentional condition compared to T1 in the Non-intentional condition, making an intentional binding effect more difficult to elicit.

Lastly, this leads to a limitation regarding the degree of intention with which the keypress is committed, as Engbert et al. (2007) criticize the Libet Clock method of confounding intentionality, because participants could be acting due to certain clock hands positions instead of in a truly self-generated manner. The same critique can be raised against this novel paradigm, as participants are asked to act at the onset of Circle 1, thus causing them to respond to a sensory event rather than due to self-generated intentions. A counterargument is that no matter if participants act in a completely self-generated way or due to a sensory event, it usually requires some amount of intention to act, and as participants pay close attention to the onset of Circle 1, it is unlikely that they act completely unconsciously. Nonetheless, the novel paradigm could require intentional action to a lesser degree than Time Interval Estimation/Reproduction, where participants conduct the action in absence of sensory events.

Conclusion

This project aimed to investigate a novel paradigm for assessing SoA. It was found that one Group elicited intentional binding, suggesting that the novel paradigm is able to assess SoA. However, it was found that one Group did not elicit SoA, and that neither Group were sensitive to the Kappa effect, causing the paradigm unable to assess SoA in the way that was expected.

Additionally, it was found that the explicit measure did not correlate with the novel paradigm, neither when assessing the participants' experience of controlling the circles or their ability to detect the circle under control, suggesting that the novel paradigm and the explicit measure assess different aspects of the SoA.

In addition, it is unknown to what degree intentional binding, which is the foundation of the novel paradigm, is actually able to assess SoA, as previous studies have been unable to control for a variety of confounding variables, and as the novel paradigm is not able to control for perceived causality between the circles.

Before this novel paradigm can be applied as a reliable measure of SoA, the issues with the lacking Kappa effect and intentional binding occurring solely in one Group must be resolved. Additionally, the nature of intentional binding needs more investigation, as perceived causality undoubtedly contributes to some of the effect of intentional binding, causing it of importance to investigate to what extent.

Though the project proved unable to offer a reliable novel measure of SoA, it aided in the development of the knowledge on SoA, as it was able to successfully measure intentional binding while circumventing a range of earlier methodological issues, and as it replicated findings of earlier studies regarding a lack of correlation between explicit and implicit measures, suggesting that the entirety of SoA might be too complex to assess through just one measure.

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