Degree project

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Agency of others: The intentional binding paradigm in observed actions

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Abstract

Sense of agency (SoA) is defined as the subjective experience of being in control of our own actions. This attribution of control underpins all human action and is a vital aspect of the experience of being human. This systematic review sought to address whether intentional binding (IB), a proxy of SoA, can be found during observation of other-generated actions. This was done by investigating the current state of research in the field. Past studies are inconclusive in regards to what factors play into the formation of SoA and the motivation behind this review was to provide a conclusion regarding IB from observed actions. The studies featured in this review found that the IB effect was present in different procedures and contexts which highlights the flexible nature of SoA. Most importantly, this systematic review concluded that IB can and does occur during the observation of other-generated actions. Furthermore, this review found that social influence has an effect on SoA in both human- and robot-observations. We also found that the IB effect manifests in the absence of voluntary actions but to a lesser degree. However, the magnitude of the IB effect varied across studies where one found IB to be greater during action observation than self-generated actions, whilst another study found a weaker IB effect for action observation. Finally, this review provides a discussion on theories that best explain this phenomena, the neural evidence behind action observation, and what implications the findings could have for SoA as a whole.

Keywords: sense of agency, intentional binding, action observation, intentional binding paradigm, interval estimation paradigm.

Agency of others: the intentional binding paradigm in observed actions

Ironing a shirt, turning the ignition of a car, or flipping the pages of a book are actions that all have something in common. Beyond the sensory experiences such as the heat of the iron, the rattle of the engine, or faint smell of pine that resides between the pages, something else is there. Namely, an internal mechanism working behind the scenes, attributing an experience of control to the actions humans carry out. This phenomenon, known as sense of agency (SoA), is the subjective experience of being in control of our own actions (Haggard, 2017). Human beings are agents that have the capacity to intentionally bring changes to the external world through our actions. Without a SoA, our interaction with the environment would lose one key aspect in what it means to be human, namely our experience of controlling our actions.

SoA has been investigated using an implicit measure called the intentional binding (IB) paradigm, which refers to the observation that when a voluntary action produces a sensory outcome, action and outcome are perceived as being closer in time (Haggard et al., 2002). According to Haggard et al. (2002), agency is created from different stages of neural activity such as sensory feedback from body movements, motor preparation and specification of motor commands. Some researchers have proposed that a key feature is efferent information. When efferent information is not present, such as in passive movements or during observation of others, IB is reduced or absent. This highlights the central role of efferent information in the manifestation of SoA (Moore & Obhi, 2012).

Later studies have found that SoA can be experienced when observing the actions of others (Poonian & Cunnington, 2013). This introduces a problem that is largely dismissed in the literature. Namely, if sense of agency is our subjective experience of controlling our own actions, and if humans can experience SoA from the actions of other people, is SoA properly operationalised? This review will focus on two similar measures of intentional binding: the intentional binding paradigm and the interval estimation paradigm. The specific question that will be addressed is whether intentional binding, a proxy of SoA, can be found in observed actions. This thesis will begin by describing the current state of research in the field, the brain basis underlying SoA, as well as explain the most influential theories surrounding SoA. Furthermore, this thesis will discuss the implications of the neuroscientific findings within the field of SoA and propose suggestions for future research.

Background

Intentional binding

Haggard et al. (2002) introduced a measure, based on the work of Libet et al. (1983), called the intentional binding paradigm. This measure allowed researchers to demonstrate agency in an experimental setting. As previously mentioned, intentional binding refers to the fact that when a voluntary action produces a sensory outcome, action and outcome are perceived as being closer in time (Haggard et al., 2002). In the intentional binding paradigm, participants are asked to voluntarily press a button at a time of their choosing whilst viewing a clock hand that is continuously rotating around a clock face. After the voluntary key press, an auditory stimulus is presented with a delay which varies across different studies, with Haggard's original study (Haggard, 2002), featuring a 250 ms delay. The participant then explicitly reports where the clock hand was at the time of the button press. A shift in perception is then observed where the action and sensory consequence, i.e., the auditory tone, are perceived to be closer in time. This is what is referred to as the IB effect, also known as the temporal binding effect (Haggard et al., 2002). The IB effect has been shown to occur when self-made voluntary actions are executed, however, not when actions are involuntary. In a study by Haggard and Clark (2003), self-made voluntary actions, and involuntary actions induced by transcranial magnetic stimulation (TMS), were followed by a tone. These voluntary actions were compared to involuntary movements and no IB effect was observed. This supports the idea that SoA relies on a specific match between intention to act, action, and outcome.

Another variant of the intentional binding paradigm is the interval estimation paradigm. In this measure participants are instructed to explicitly estimate the interval between their own action and a subsequent tone. The estimated time is then contrasted to the actual time between action and tone which, if binding is present, shows a compression of perceived time such as in the IB paradigm (Poonian & Cunnington, 2013; see also Humphreys & Buehner, 2010; Wohlschlager et al., 2003). Here, perceptual time compression, i.e., the IB effect, is measured with interval estimation instead of the onset of an auditory tone such as in the intentional binding paradigm.

Brain basis of sense of agency

Sense of agency is defined as the subjective experience of being in control of one's actions (Haggard, 2017). Although no single structure in the brain is solely responsible for our experience agency, Haggard (2017) proposed that the key to understanding SoA might lie in further exploring the connectivity between frontal, prefrontal motor, and parietal areas. These areas are associated with the initiation of voluntary actions, the monitoring of perceptual events, body ownership, and work together to form our experience of agency (Haggard, 2017). Seghezzi et al. (2019) summarised the available neuroimaging findings within SoA and body-ownership. They described SoA to be generally associated with four specific clusters: the left supplementary motor area (SMA), left posterior insula, right postcentral gyrus, and the right superior temporal lobe.

An important feature of voluntary action is the preparatory activity in motor areas. An example of this type of activity is the Bereitschaftspotential (BP), or readiness potential, which is a slow negative electroencephalographic potential located in areas such as the SMA, and can be found in EEG studies, that occurs in relation to preparation of voluntary movement (Jahanshahi et al., 1995). Furthermore, the BP has been classically viewed as a marker of volition. Volition can be described as a person's process of preparing, initiating and executing an action under their own control (Haggard, 2017; see also Hallett, 2007). An area that is heavily discussed within SoA research is the SMA and its subsequent contributions to our experience of voluntary actions. Early research by Jahanshahi et al. (1995) on self-initiated movement proposed that the medial-premotor areas play a key role in the preparation of voluntary self-initiated actions. In addition, Jahanshahi et al. (1995) proposed that the SMA is the principal generator of the early phase of the aforementioned BP. Kühn et al. (2013) have suggested that there is a distinction to be made between the SMA and pre-SMA and their functions in relation to SoA. Namely, that the SMA proper is more closely tied to immediate action execution, whilst the pre-SMA is involved in processes related to planning and initiation of actions, more specifically, complex action sequences.

Like in most research fields, different approaches have helped us to further our understanding of the brain basis of different phenomena. SoA and IB are no different, where utilising other techniques than neuroimaging such as TMS has given us new insights. One example is Moore et al. (2010), who utilised TMS to suppress neural activity to investigate two specific sites in the motor cortices. Namely, the pre-SMA and primary motor cortex (M1), as previous research has highlighted the importance of these areas in relation to SoA and IB. When stimulating the pre-SMA, Moore et al. (2010) found that IB was significantly reduced, more specifically the ability to bind self-generated actions with their outcomes. This notion has further been supported by Seghezzi and Zapparoli, (2020) who also suggested that said region works to attribute SoA to the visual consequences of our self-generated movements. This observation indicates that the pre-SMA is vital for the predictive process and the intention to act. Furthermore, stimulation of M1 resulted in a reduction of IB to a lesser degree. The M1 is thought to be responsible for processing the actual signals related to motor execution, the generated motor command signals are then sent down to the spinal cord for movement execution. Moore et al. (2010) proposed that these two regions, i.e., pre-SMA and M1, could be a part of a wider network of structures that work together to support our experience of IB, rather than one specific component of IB.

Another area that contributes to SoA is the posterior parietal cortex (PPC). Desmurget and Sirigu (2009) proposed that the PPC integrates sensory signals caused by motor predictions and selection. Therefore, researchers concluded that motor awareness does not simply emerge from our movement, but rather as a consequence of increased parietal activity, i.e., due to the predictions humans make prior to movement execution (Desmurget et al., 2009). When looking at lesion studies of the PPC, Desmurget and Sirigu (2009) speculated that healthy people may rely on signals from the PPC to become aware of their intentions to move, whereas PPC lesion patients only become aware of their intentions when the SMA releases the motor command signal. This results in a delay in the subjective experience of their conscious intention to move. Furthermore, another area heavily discussed in regards to self-awareness in SoA is the insula and its role in affective self-awareness as well as integration of interoceptive signals (Craig, 2009).

To be able to compute one's own agency a combination of predictive and retrospective signals seems to be necessary, as only one type of sensory signal is not sufficient. Based on the studies of Chambon et al. (2015) and Eimer and Schlaghecken (2003), Haggard (2017) proposed that the angular gyrus may be involved in the process of monitoring errors that occur during action-selection, i.e., what should I do next, in the frontal areas. Thus the parietal cortex may work to match retrospective and predictive signals for initiated actions with their outcomes in SoA.

Theories on sense of agency

There are two prominent theories within SoA. Firstly, the predictive theory where the agent generates predictions of the causal relationship between different bodily movements and their sensory consequence. An example of this is the comparator model which suggests that humans have an internal mechanism that, through a feedback loop, compares predicted and estimated outcomes of our actions (Frith et al., 2000). Secondly, retrospective inference theories that suggest a general-purpose inferential mechanism that, through sensory information, confirms the causal origins of our actions and their effects (Synofzik et al., 2008). Support for both of these theories exists. For example, in support of the predictive theory, the IB effect can be observed where the sensory consequence is highly predictable but removed (Engbert & Wohlschlager, 2007; Haggard & Clark, 2003; Moore & Haggard, 2008). This indicates that the predictability of an outcome plays a key role in the forming of IB. In support of the retrospective models, studies have shown that there are instances where efferent information is not involved, but agents still claim to have caused events (Wegner et al., 2004). Furthermore, the fact that the IB has been observed to occur during observation of the actions of others (Poonian & Cunnington, 2013; Synofzik et al., 2008). The predictive model lacks explanation for this because no motor preparation or sensory effects are experienced during observed actions.

There are, however, limitations to both the predictive and retrospective theories of SoA. A limitation for the predictive theory is exemplified by the “helping hands” pantomime task (Wegner et al., 2004). In this task another person's hands are placed where the participant’s hands would normally appear. The participant then observes and listens as the other agent acts out verbal instructions from the experimenter. Even though the participant’s hands are passive and motor commands related to the action are being executed by another person, the binding effect still occurs. This demonstrates that internal predictions, which occur only during active movements, are not necessarily required for the experience of agency. These can instead be substituted by external cues, i.e., the experimenter's instructions (Wegner et al., 2004). Furthermore, if the predictive theory is correct, then there is no explanation for the fact that humans can experience IB when observing the actions of others. This, due to the fact that humans lack the internal prediction and motor preparation mechanisms to generate agency (Wegner et al., 2004).

The retrospective theories face similar problems. In the retrospective model, internal predictions and motor representations would play a miniscule role, leaving the rest of the process up to higher order inference mechanisms (Synofzik et al., 2013). If this theory is correct, our SoA would be prone to disruptions by factors in the environment. Furthermore, because inference mechanisms are slow when compared to predictive processes, delays in this process would lead to failures to distinguish if an event was self-caused or not (Synofzik et al., 2013).

It is clear that both of these theories face a plethora of problems when explaining SoA. Due to these issues, a new theory called optimal cue-integration has been proposed. This theory posits that "the brain constantly integrates several different authorship cues and weights to each cue according to its relative reliability in a given situation" (Synofzik et al., 2013, p. 4). Optimal cue-integration combines both the predictive and retrospective theories of SoA to explain a wider range of situations in which agency can be experienced. SoA, according to optimal cue-integration, is formed by mechanisms that rely on the most robust information of what has occurred during our actions. For example, when predictive cues are weak, retrospective cues such as action outcomes weigh heavier when forming the experience of agency. Because our SoA is reliably manifested in diverse contexts, the strength of this theory comes from its capacity to explain this reliability (Synofzik et al., 2013). In a study by Moore and Haggard (2008) researchers used the intentional binding paradigm to investigate whether conscious awareness of an action is based on an inferential process or a predictive motor control process. By varying the probability of an outcome, researchers found that both the actual outcome and the outcome predicted by the participant played a significant role. When predictability of the outcome was low, IB was found only on trials where the outcome, i.e., auditory tone, occurred. When predictability was high, IB was found even on trials where the action produced no outcome. That is, when participants expected a tone (high probability trials) binding was achieved even if the tone was removed. When participants didn't expect a tone (low probability trials) binding was achieved only when the tone occurred. Thus, this study falls in line with optimal cue-integration theory as it highlights the flexible nature of the formation of SoA.

Agency from the actions of others

Cortical activity during movement execution and action observation

A long standing question within the neuroscientific community is whether movement execution and action observation recruit shared brain networks. This question dates back to prior to the discovery of the mirror neuron in primates (Di Pellegrino et al., 1992; Gallese et al., 1996). In a meta analysis looking at this question, Hardwick et al. (2018) concluded that although some differences in the recruitment of the different cortices were observed, shared activation was found in cortical networks of areas ranging from bilateral premotor, parietal, and sensorimotor network during both action observation and movement execution. This suggests that the premotor areas, i.e., the bilateral pre-SMA and the SMA-proper, both play a key role in observed and executed actions. Furthermore, the parietal activity was mainly observed in the inferior parietal lobule. Which, as mentioned before, is involved in the process of action selection in SoA.

Thus, humans may rely on the recruitment of similar structures during action observation as to movement executions. Therefore, one might speculate that the same applies to observed actions during SoA of others, as similar regions are associated, which in turn opens up some exciting implications to SoA research.

Intentional binding and action observation

Research into SoA points towards an underlying mechanism that incorporates internal predictions, actions outcomes, and sensory information to form our perception of control over our voluntary behaviours. A question that arises from these studies is if this feeling manifests only from self-generated actions or if it can be formed when observing the actions of others. According to Kilner et al. (2007), the general predictive coding model of action observation posits that another agent's intentions are coded during action observation which allows observers to predict not only the sensory consequences of an action, but the goals of an action. If self-made and observed goal-directed actions are processed in this manner, it is possible that observers attribute agency over another agent's actions in a similar manner to how self-generated actions are attributed.

To study this, Poonian and Cunnington (2013) used the interval estimation paradigm and found the IB effect in conditions where an action was observed, and a stronger effect in the conditions where the action was self-generated. During a second experiment in the same study, a non-agent condition was added where a button gets pushed seemingly by itself. It was found that stronger binding occurs during observed actions than during non-agent conditions, suggesting that humans infer agency over the consequences of our own actions and the actions of others in a comparable way. The researchers suggest that when observing the actions of another agent, a causal attribution is made, linking the actions and outcomes to an agent. However, contrary evidence has been found in Suzuki et al. (2019) where a non-agent condition did not produce a difference in IB in a virtual reality environment. Because of these antithetical findings, this systematic review seeks to establish whether the IB effect can be elicited not only in situations where an agent performs self-generated actions, but during observation of the actions of others.

Methods

The studies used in our review were obtained through database searches in Web of Science and MEDLINE EBSCO. The searches were performed prior to March 3, 2023, with the following search string; ("Intentional binding" OR "temporal binding") AND "Sense of agency" AND "action observation*" which resulted in 305 articles from Web of Science and 2 from MEDLINE EBSCO.

Inclusion & exclusion criteria

Studies that investigated action observation and intentional binding were included. Firstly, the articles found from our search went through selection based on title and abstract. During this stage, articles that were not relevant to our question were excluded. Furthermore, articles that included unhealthy or non-adult human participants were excluded. Articles not written in English were also removed. The primary focus of the included articles was whether or not intentional binding can be elicited during observed actions.

After screening all the titles and abstracts of our initial 305 articles, 246 were excluded, with two of those being duplicates. This resulted in 59 remaining articles. Out of these 59 articles, two could not be retrieved. The remaining 57 articles were then fully read and additional 51 were excluded. Out of those 51, 40 articles were removed because their contents were not relevant to the question posed in this systematic review. Five were excluded as they included non-healthy human participants or non-adult human participants. One article was removed because the article itself was not written in English. And lastly, five articles were removed because they featured the wrong measure. This resulted in six articles included in the qualitative synthesis, all of which were found through the database search.

Data extraction

The PICO model was employed to address our choice of categories for the data extraction from the articles. The age from healthy human adult participants were extracted. The relevant interventions used were: intentional binding or interval estimation paradigm to measure sense of agency. Data from comparisons of the same participants under different conditions is what is being investigated, behavioural measures were extracted.

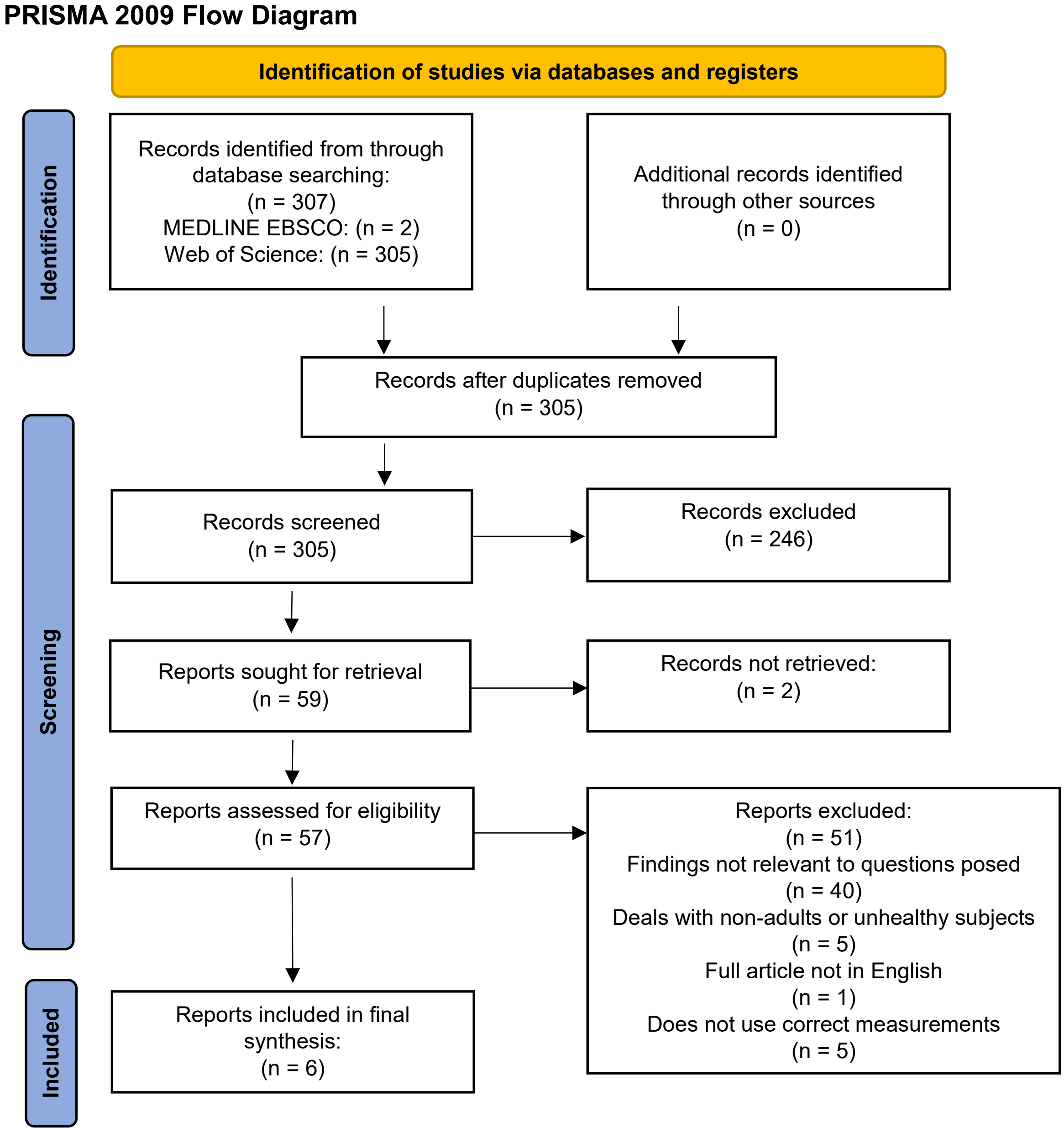

Figure 1. Summary of the literature review process

Results

Overall, the findings of the following studies indicate that the IB effect can be achieved during observation of other-generated actions. One study found that observing the actions of another human agent increases the magnitude of the IB effect when compared to a robotic agent. Furthermore, the absence of an agent still resulted in binding when efferent information was present. A discrepancy from the results of different studies was the magnitude of the IB effect for self- and other-generated actions. One study found that the magnitude of the IB effect was greater during observation of other-generated actions when compared to self-generated actions whilst other studies found a weaker effect.

Social transmission of experience of agency: An experimental study (Khalighinejad et al., 2016)

Participants and methods

In this study, 71 healthy right-handed participants aged 18-35 (mean age 23 years), were recruited. Khalighinejad et al. (2016) used the intentional binding paradigm to investigate if viewing a human agent was necessary in order to achieve IB during action observation. The design featured two groups, one which interacted with another human agent of the same gender, and one paired with a robotic hand which was described as an intentional agent. Both of these groups were divided into an observational group which could observe the actions of their co-actor, and an individual group which could not observe their co-actor.

Results

The researchers found that intentional binding was achieved in both groups and the IB effect was statistically equal in human- and robot-observation. With repeated trials, multivariate analysis showed that the perceived time of action and tone progressively shifted towards the time of the outcome, this effect was stronger in the observational group. This suggests that participants attributed more importance to the outcome of actions as trials progressed, opposed to the action itself. Furthermore, it suggests that social influence has an effect on SoA.

Intentional binding in in self-made and observed actions (Poonian & Cunnington, 2013)

Participants and methods

This study featured two experiments and two participant groups. In experiment one the group consisted of 18 participants, seven males with a mean age of 22.6 years and an age range of 20-39. In experiment two, the participant group consisted of 18 participants, five males with a mean age of 24.6 years and an age range of 19-41. This study used the interval estimation paradigm to measure IB and featured four conditions. First, the control condition with an estimation of an interval between two tones. Second, the action condition where participants made an estimation between a self-made keypress and tone. Third, the observed condition in which participants estimated an interval between an observed keypress and tone. Fourth, a no-agent condition where participants estimated an interval between a keypress and a tone in which the key pressed itself.

Results

They found the IB effect in conditions where an action was observed; however, the effect was weaker when compared to self-generated actions. Furthermore, they found that stronger binding occurs during observed actions than during non-agent actions. They concluded that humans infer agency over the actions of others in a similar manner as to self-generated actions.

Intentional binding without intentional action (Suzuki et al., 2019)

Participants and methods

This experiment featured three experiments and three different participant groups. Experiment one consisted of 51 participants (mean age: 24.14, 30 females). Experiment two consisted of 20 participants (mean age: 26.65, 12 females). Experiment three consisted of 30 participants (mean age: 21.17, 23 females). This study used an interval estimation paradigm where participants wore a virtual reality (VR) headset and viewed a button being pressed. Participants also wore a vibrating motor that was attached to the participants index finger to provide tactile stimulation. Furthermore, explicit measures of agency were taken after each trial.

Experiment one consisted of three estimation conditions: active, no hand, and a fake hand. During the active condition participants estimated the intervals between a virtual button press and the tone that followed. In the no hand condition participants observed the button being pressed on its own. During the fake condition participants observed a virtual hand of another participant pressing the red button. Experiment two removed the no-hand condition. In experiment three, researchers instead showed the participants their own arm against a greenscreen rather than the virtual hand model to explore whether the IB was reduced in the VR-environment.

Results

This study found that the IB effect occurs during action observation. Furthermore, it was found that in the absence of a voluntary action, i.e, the button moved by itself, the magnitude of the IB effect manifested to a lesser degree when compared to when the participants voluntarily pressed the button. However, comparing the condition where participants observed an arm performing a button press, and the condition where only the tactile information was replayed, no difference in binding was observed.

Subjective agency and awareness of shared actions (Strother et al., 2010)

Participants and methods

In experiment one, 12 participants (age range: 19-39, four females) volunteered to be a part of the study. Participants were paired and seated side by side viewing a digital clock hand on a computer monitor while it continuously rotated around a clock face. Each participant placed their right index finger on one side of the spacebar and were instructed to, at a time of their choosing, press the key. If one participant was not first to press the key, they were instructed to let their finger passively follow the movement of the key downwards. After a keypress from either participant, a tone was played after a delay of 200 ms. Participants then covertly reported the location of the clock hand at either the time of the keypress or the tone and whether or not they were responsible for the keypress. Experiment two featured the same task, methods, and participants as experiment one except only one participant was instructed to perform a button press within a given block, creating an initiator and passive follower situation.

Results

When an action and the subsequent tone was believed to be produced by oneself, both were reported to have occurred earlier than actions and tones judged in the baseline. Researchers found evidence in favour of the IB effect in shared actions both in experiment one and two. Both experiments showed a decrease in perceived time compression for both self-generated and other-generated actions. Moreover, a vast amount of trials featured greater perceived time compression for judgements made after other-generated actions, indicating a stronger IB effect for actions produced by another agent.

Attribution of intentional causation influences the perception of observed movements: Behavioural evidence and neural correlates (Moore et al., 2013)

Participants and methods

The participant group consisted of 19 participants, 16 of which were female, with a mean age of 22. The measure used to investigate IB was the interval estimation paradigm. Whilst in a fMRI scanner, participants viewed a video recording of a person pressing a button. Four conditions were investigated. First, two causal conditions where the observed keypress resulted in an auditory tone. One in which the participants were told that a person intentionally pressed the button, and one in which they were told it was unintentional and generated by a motor. Second, two non-causal conditions which directly matched the two causal conditions but featured no tone after the keypress.

Results

Intentional binding was found during observation of another person's actions. Findings indicate that intentional causation is key to the generative process of IB but is not self-specific. Moreover, achieving IB from action observation relies on similar mechanisms as self-generated actions. Researchers found the IB effect during observed movements regardless of whether participants believed the action to be intentional or unintentional.

Goal sharing with others modulates the sense of agency and motor accuracy in social contexts (Hayashida et al., 2021)

Participants and methods

The experiment consisted of 26 healthy participants with a mean age of 20.8, out of which 20 were female. Participants were divided into a cooperative group and an independent group. Participants within these groups were then divided into same-gendered experiment pairs and the measure used was the interval estimation paradigm. Participants in the cooperative group alternated in being the observer and the actor in a cooperative task that involved moving a geometric figure to the centre of the screen, which awarded points if successfully achieved. In the independent group, pairs alternated in being the observer and the actor but were instructed to not work together. They were instead told to achieve a high individual score. In both groups an auditory tone was played after each participant's keypress and the interval between action and tone was reported after each keypress by both participants.

Results

Hayashida et al. (2021) found evidence of the IB effect in observed actions and that goal sharing improved motor accuracy and significantly enhanced the IB effect in both self-generated and observed actions when compared to non-goal sharing. Researchers proposed that goal sharing with other individuals in the context of specific social situations can modulate SoA as well as improve motor accuracy.

Table 1. Summary of included papers

Article	Participants	Stimulus presented	Measurements	Findings of observed action
(Hayashida et al., 2021)	26 healthy participants mean age 20.8	Other human agent	Interval estimation paradigm	Intentional binding found during action observation when sharing a common goal.
(Khalighinejad et al., 2016)	71 healthy participants aged 18-35	Other human agent Robotic arm	Intentional binding paradigm	Intentional binding effect found in action observation during joint action task.
(Moore et al., 2013)	19 healthy participants mean age 22	Other human agent	Interval estimation paradigm	Intentional binding effect found in movement observation.
(Poonian & Cunnington, 2013)	Experiment one: 18 healthy participants, mean age 22.6 Experiment two: 18 healthy participants mean age 24.6	Video recording of human agent	Interval estimation paradigm	Found intentional binding effect in observed actions.
(Strother et al., 2010)	12 healthy participants aged 19-39.	Other human agent	Interval estimation paradigm	Intentional binding found in self- and other-generated actions.
(Suzuki et al., 2019)	Experiment one: 51 healthy participants, mean age 24.14.	Three dimensional model of human	Interval estimation paradigm	Intentional binding found in self- and other-generated actions.

	Experiment two: 20 healthy participants, mean age 26.65. Experiment three: 30 healthy participants, mean age 21.17.	agent in VR setting.		

Discussion

The goal of this systematic review was to address the question of whether intentional binding can be found during observation. Although some studies feature different methods and are researching different topics within SoA, our interests lie only in action observation. All of the studies found evidence that the IB effect can manifest during observation of other agents. The prevailing theme within the results was that observed other-generated actions resulted in a IB effect of lesser magnitude when compared to self-generated actions. However, one study found an IB effect of a greater magnitude for observed actions in a vast number of trials (Strother et al., 2010). The main point of contention between the articles is not whether the IB effect can be found during observed actions, but the magnitude of the IB effect and what conditions are optimal for its emergence. The articles analysed in this systematic review presented stimuli with diverse properties to participants in different contexts. For example, Khalighinejad et al. (2016) had participants view both actual human stimuli and a robotic hand, Suzuki et al. (2019) used a VR setting, and Moore et al. (2013) used a video recording. A question worthy of discussion is: what factors contribute to the magnitude of the IB effect in observed actions? Two of these factors seem to be the type of agent, and beliefs of the observer.

Non-human agent observation and top-down effects

Moore et al. (2013) suggested that there are top-down effects on social perception during action observation that, if effects vary between participants, could confound results. An example of such an effect would be if a participant was primed to believe that an action was intentional or unintentional prior to action observation. We propose that a similar effect is occurring in Khalighinejad et al. (2016) where, contrary to the researchers' predictions, there was no difference in binding between observing a human or a non-human agent. The researchers told participants that the robotic hand had anthropomorphic features and that they were interacting with an 'intentional' and 'human-like' agent. Similar to what Moore et al. (2013) describes, this anthropomorphic description as well as the prime of intentionality could produce a top-down effect which potentially skewed the participants perception of the non-human robot arm to such a degree that no difference in binding between human vs. robot occurred. While there is some evidence which shows that priming has an effect on IB during self-generated actions (Moore et al., 2009), priming having an effect during action observation has, to our knowledge, not been found. Even so, the findings of other studies indicate that IB for other-generated actions is diminished when participants are informed that the observed agent is robotic (Wohlschlager et al., 2003; Barlas, 2019). Because the findings of Khalighinejad et al. (2016) differ from these studies, and neither Wohlschlager et al. (2003) or Barlas (2019) explicitly told their participants that the hands were intentional actors, this top-down effect could be the confounding variable that skewed the results.

Mirroring of observed actions

We have previously highlighted how sensorimotor networks, bilateral premotor, and parietal areas shared activation patterns during action observation and movement execution. The question then becomes: how do the results of these studies relate to findings within the human mirror system such as discussed by Hardwick et al. (2018)? A possible explanation for this process is the previously mentioned article by Kilner et al. (2007) who proposed a general predictive coding model for action observation. This model states that the observing agent not only predicts the sensory consequences of other-generated actions, but also the goals of said agent.

This notion was supported and built upon by Poonian and Cunnington (2013), who proposed that when humans observe the actions of another agent a mirror mechanism activates. During this process the observing agent maps or mirrors the observed actions onto areas involved in the execution of said action. Further evidence for this idea was supported by Moore et al. (2013) who found shared activity patterns for intentional vs unintentional movements during action observation. Researchers found involvement during action observation in areas such as: the superior parietal cortices, insula and in particular the involvement of the primary motor cortices. These areas are commonly associated with the process of SoA for self-generated actions and based on these findings are also involved in the attribution of feelings of SoA during action observation of other agents. This supports the idea that a similar mechanism may be involved during IB for action observation and action execution.

Optimal cue integration theory

None of the studies featured in this systematic review had procedures that were in complete alignment. One of the most notable differences were the diverse range of stimuli presented to the participants such as: other human agents, video recordings of human agents, robotic arms, and VR-recordings of human agents. Regardless of the stimuli presented, the IB effect still manifested in most of these conditions. Furthermore, Moore et al. (2013) found that whilst the sensorimotor network was not overtly active when participants passively observed the actions of others, a reduction in activity or covert activity was observed which could be the result of IB occurring for observed actions. Moore et al. (2013) therefore suggested that sensorimotor information may not be an essential cue for binding to occur. Both of these findings, i.e., manifestation of IB from different stimuli as well as sensorimotor information not being essential, fits in line with the optimal cue integration theory where no single cue is essential for the formation of SoA (Synofzik, 2013).

As previously mentioned, Moore et al. (2009) investigated the effect of priming on intentional binding. In an experiment, participants performed either an active movement involving a key press, or an involuntary passive movement which was generated by the experimenters. During passive movements internal predictions about motor outcomes are not generated which, from an optimal cue integration perspective, maximises the effects of external cues such as priming. This maximisation was observed by Moore et al. (2009) and the authors concluded that primes modulated perceived intervals for both active and passive movements, with the effect of primes being greatest in the passive movement conditions. This finding, if present during observation of other-generated actions, fits in line with the optimal cue integration theory and could theoretically explain the results found in Khalighinejad et al. (2016).

Possible implications for Sense of Agency

Suzuki et al. (2019) found the same magnitude of IB for self-generated actions as for observed actions. However, implicit and explicit measures of IB were dissociated, a finding which has previously been documented by other studies (Dewey & Knoblich, 2014; Obhi & Hall, 2011). If we assume the IB effect, can be experienced from other-generated actions and that it is a valid measure of SoA, what does that entail for SoA as a whole? SoA is defined as a subjective experience of being in control of one's own actions, this means that SoA is self-specific and by definition cannot be experienced by other people (Haggard, 2017). If the evidence shows the opposite, which according to the studies included in this systematic review seems to be the case, this could raise questions about the definition of agency per se. Furthermore, if implicit and explicit measures of SoA do not align with each other, there is yet another problem. Namely, that humans cannot explicitly report an experience of SoA when its supposed proxy can be measured implicitly.

The implications of these findings lead to what we see as three potential outcomes. First, either the evidence presented in these studies is false. Second, the idea of intentional binding being a proxy of SoA must be dispensed with. Third, the definition must be changed in order to incorporate the actions of others. Exploring these points; first, there is always the risk that the findings of studies come to the wrong conclusions or that their statistical analysis was inaccurate. However, we maintain that this is unlikely because the phenomenon was found across all articles. None of the studies included in this review stand out as poorly designed and all of them use well established paradigms for investigating IB. Furthermore, they made use of contemporary methods of data analysis. Second, the idea that IB does not reflect SoA is not uncommon. Some researchers believe that instead of being linked to agency or motor predictions, IB is linked to causality in general (Buehner and Humphreys, 2009; Buehner, 2012; see also Wohlschläger et al., 2003). However, as pointed out by Synofzik et al.

(2013), even if it is the case that IB is linked to causality and not agency, the phenomenon could still contribute to binding by accentuating a subject's perception of temporal contiguity. Thirdly, in our view, the current operationalisation of SoA cannot account for the phenomena of IB from observed actions. From our perspective in order to have a coherent understanding of IB and SoA that can be researched and explored, this definitional problem needs to be addressed by scientists and philosophers.

Limitations

Out of the studies featured in this review, only Khalighinejad et al. (2016) had a participant group with over 50 participants while the majority of the articles had under 20. This has potential negative consequences for the reliability of the studies featured. Furthermore, only one of the articles featured an fMRI measure that investigated the neural basis of action observation, while the others solely investigated behavioural findings. In turn, this means our conclusions drawn regarding the mirror system are limited. Because this systematic review only includes six articles to draw conclusions, this opens up for potential errors in individual studies that could affect the conclusions drawn. Furthermore, because only six articles were found, we maintain that the question posed in this systematic review has not yet been properly addressed by the scientific community. Even so, the fact that all the studies point towards one conclusion leads us to believe that our conclusions are well substantiated within the scientific literature regardless of the amount of studies investigating this question. Another explanation of this total unanimity in results could be an error with our methods, such as narrow search terms which excluded relevant studies.

Societal and ethical considerations

These findings raise some interesting implications for how humans infer agency over the actions of others and therefore our interactions with the world around us. The findings of studies such as Khalighinejad et al. (2016) indicate that humans can experience the IB effect from not only other humans, but inanimate objects in our surroundings. As society becomes more technologically advanced and humans become more integrated with computer interfaces in areas such as artificial intelligence, the topic of sense of agency becomes more relevant societally. For example, the perceived degree of control over the actions of robotic agents that perform instructions or even in the absence of instructions. Thus, future research is needed for a better understanding on how feelings of SoA might emerge in human-robot interactions.

The topic of sense of agency has legal considerations as well. For example, studies such as Christensen et al. (2019) have looked into emotional states and how they influence our experience of control, especially during situations of legal responsibility. Uncovering more information about the process of sense of agency in action observation might lead us to insights about how humans attribute control over the actions of other people in different types of situations. As mentioned by Haggard and Tsakiris (2009), a proper understanding of SoA is also of legal relevance. If individuals with diminished SoA ought to be punished less than those with full agency, a full understanding of SoA in different contexts becomes of utmost importance. For example, an assault by a person sleep-walking. Relating this to the question of observed actions, this becomes important regarding situations such as responsibility for accomplices of crimes.

Conclusion

In summary, the results of these studies provide convincing evidence that the IB effect can and does occur in observed actions and in a variety of different conditions. This systematic review provides insights into the flexible nature of intentional binding. In addition to this, the findings show that there is convergence between the behavioural and neuroimaging data with regards to action execution and action observation. Furthermore, the data reveals recruitment of similar brain structures for action execution and action observation, specifically the superior parietal cortices, insula, and primary motor cortices. The significance of these findings is that they raise questions regarding our current definition and understanding of intentional binding, and by proxy SoA. Future empirical research should investigate the degree to which top-down effects such as priming can influence intentional binding. Furthermore, scientists must deal with the problems that can potentially occur because of the limiting definition of SoA.

Word count: 7230 words

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