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A causal view of the sense of agency

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ABSTRACT

If you expect that your action causes a near effect, you perceive the action and the effect as closer in time than they really are. This phenomenon is called *temporal binding* and is considered an implicit measure of the *sense of agency*, namely the sense of being the author of an action or action awareness. Recent studies, however, show that temporal binding occurs even without the agent executing any action and depends on the capacity to represent one event as the cause of another one. These studies demand the reexamination of the sense of agency, and of temporal binding as its diagnostic tool. I propose a *causal view of the sense of agency*, according to which action awareness arises when your action is represented as causing an effect. Because representing an action as causing outcomes affects time perception creating the illusion of event proximity, the causal view explains and operationalizes the sense of agency through the connection between causality and time, thus overcoming the indeterminacy of previous accounts. The causal view can pave the way to novel experimental perspectives in development and evolution and stimulate new thinking on the relationship between subjectivity, causal cognition, and time perception.

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Introduction

Temporal binding is a fascinating phenomenon showing that under some conditions, subjects perceive two events as closer in time than they really are. Temporal binding has been firstly investigated in the context of agency. It has been shown that during goal-directed actions subjects perceive the time between the action and the effect as shorter. This led most researchers to interpret temporal binding as a correlation of intentional actions and an implicit measure of the *sense of agency* (Haggard et al., 2002), namely the subjective experience of action or action awareness. Temporal binding is important experimental

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evidence for the classical view of the sense of agency, which is the view that explains the subjective experience of action with the mechanisms of goal-directed actions.

As the power of perceptual illusion consists in unveiling properties of the mind, temporal binding has been widely used to inquire into the sense of agency in both healthy subjects and subjects with psychopathologies (Haggard, 2017; Moore, 2016). Measuring mind-independent items such as action-effect timing has contributed to uncovering the psychological and neural mechanisms of the subjective experience of action in a variety of subjects and conditions. Recent studies, however, demonstrate that temporal binding can also occur without actions, and that it depends on representing an event as the cause of another one. These studies thus challenge the use of temporal binding as a correlation of the sense of agency. Temporal binding would thus constitute an implicit measure of causal representations, rather than a correlate of intentional actions. Should we stop using temporal binding as a measure of the sense of agency?

My short answer is no. The long answer is a proposal to make some adjustments to the concept of sense of agency. Precisely, I propose a *causal view of the sense of agency* claiming that we could define the sense of agency as the awareness of causing effects through actions, rather than defining the sense of agency as the awareness of executing goal-directed action. Defining sense of agency through causality would lead us to narrow down the type of action producing action awareness. There are different types of actions, requiring different degrees of control and ways of engaging with the external environments. The classical view of the sense of agency specified minimal requirements for actions producing awareness, with sense of agency arising from movements directed to a goal and the comparison between the goal and the actual outcome of the movement.

In contrast, the causal view of the sense of agency defines action awareness by appealing to actions that are represented as *causing* an outcome. On this view, while the congruency of the movement goal with the actual outcome plays a role in the formation of action awareness, it is not the crucial aspect of it. The crucial aspect is rather the subject's representation that a movement causes an outcome of some sort. Operationalizing the sense of agency through the connection between causality and time, the causal view is able to overcome the problems intrinsic to previous accounts.

One problem of the classical account of the sense of agency is that no conclusive evidence supports the connection between sense of agency and goal-directed actions. As I will show, the experiments inquiring into the subjective experience of action are more compatible with the causal view of the sense of agency that I am proposing here. These experiments suggest that wherever we can show that a subject represents her own action as

causally related with an effect, we can state that she has acquired awareness of causing consequences through actions, together with a subjective timeline to locate self-related events.

Another problem of the classical view of the sense of agency is that it proposes a non-parsimonious conception of the subjective experience of action, which is insensitive to variations of the mental implementation of behavior. On the classical view, the subjective experience of action is present whenever the individual executes a goal-directed action. By equating the subjective experience of action with the mere presence of a goal-directed action (without appealing to the individual mental state), this view thus offers a black box conception of the sense of agency, which prevents the understanding of its underlying mechanisms.

I start by describing key experiments on temporal binding in §1 and consider the properties of the causal representation involved in temporal binding in §2. In §3, I present the classical view of the sense of agency, for which the latter emerges with goal-directed actions, i.e., finalized movements that are sensitive to outcome contingencies. I also consider an alternative version of the classical view, which define the sense of agency as a correlate of full intentional actions, characterized by bidirectional relationships between stimuli and responses and by distinct representations of means and ends. I discuss the problems intrinsic to the classical views of the sense of agency and then propose a causal view of the sense of agency in §4. In §5, I envisage the use of temporal binding as a diagnostic tool to investigate the sense of agency through difference in event timing across early development and evolution. I conclude with describing the advantages of investigating differences in time perception in cognitive research, and of operationalizing subjectivity in relation to the requirements of action control.

Temporal binding with intentions and causes

Haggard and colleagues published the first study on the action-effect binding in 2002. Participants were as follows: 1) asked to press a key whenever they felt the urge to do so (intentional or voluntary action), 2) undergoing a transcranial magnetic stimulation (TMS) over the motor cortex, which induced a muscle twitch in the fingers (involuntary action), 3) undergoing a TMS over an area of the cortex where it would not induce movements (control condition 1), 4) waiting for a 100 ms beep and report the time when they heard the tone (control condition 2). The intentional action, the involuntary muscle twitch, and the sham TMS click inducing no effect, were all followed by a beep after 250 ms, and participants had to report (in separate blocks) the time of either the first (i.e., the voluntary, involuntary action or the TMS click) or of the second event (i.e., the beep). When comparing the timing of the action and the tone to baseline, the authors

found that only in the case of the intentional action, the perception of the movement initiation was delayed, whereas perception of the tone was brought forward. This effect was not present during the involuntary action and the two control conditions.

This and other studies (see Moore and Obhi (2012), and Shiloh (2019) for reviews) have demonstrated a perceptual attraction between actions and effects through time when the action is intentionally performed. The received view is that action-effect binding is a correlate of intentional action. For this reason, the temporal shift in perception between action and effect is often called "intentional binding".

The binding effect is considered an indirect measure of the sense of agency. To understand the rationale of this interpretation, consider a fictional individual Gina pressing a key that produces a tone (Figure 1(a)). Gina pressed the key *intentionally*, that is she deliberately initiates and executes the action. Gina executes the key press by expecting a sensory outcome (the tone), and this expectation produces an anticipation of the tone perception. She perceives the initiation of the action (the click on the keypress) and the ensuing sensory effect as closer in time compared to when these events objectively occur (Figure 1(b)). Therefore, Gina possesses sense of agency, she possesses subjective experience of the observed effect (the tone) that she has produced.

Temporal binding is now a robust, replicable phenomenon representing the fact that individuals possess subjective experience of event timing. Subsequent studies, however, have shown that the binding effect does *not* depend on the presence of an action, but rather on representing causal relations (Buehner, 2012; Buehner & Humphreys, 2009; Shiloh, 2019; Suzuki et al., 2019). These studies have investigated the role of causality in the binding effect, and shown that representing an event as the cause of another one is *necessary* for shortening the perceived time interval (i.e., the duration) between them.

One seminal study tested temporal binding through a stimulus anticipation task, in causal and non-causal conditions (Buehner & Humphreys, 2009). The conditions were identical in appearance and in their perceptual and motor demands. The only difference between them was that in the non-causal condition, subjects were instructed that their response (R1) to the first stimulus (T1) was simply preceding the second stimulus (T2). In the causal conditions, the subject was told that her action was *causing* T2, thus she mentally linked R1 to T2. The results showed that linking causally the two cues led to powerful and reliable shifts in event perception.

Additional studies support that action-effect binding can arise irrespective of whether the cause is an intentional action or a mechanical event (Buehner, 2012; Shiloh, 2019; Suzuki et al., 2019) and show that the binding effect can occur also without actions. Importantly, intentions can have an additive role on temporal binding, insofar as the time compression experienced during action execution is

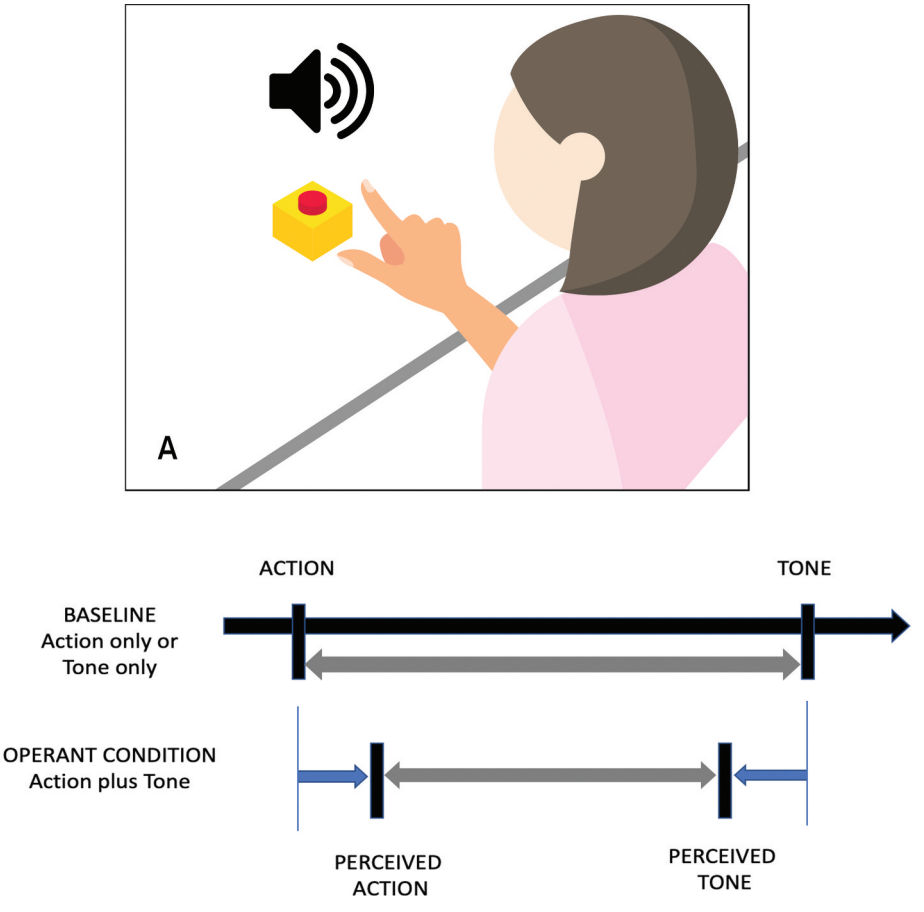


Figure 1. Example of action-effect association: The subject intentionally presses a key and produces a tone. (b) Temporal binding: schematic representation of action-effect binding occurring in situations like (A). In the upper part of the picture, the temporal interval between action and its sensorial outcome measured during baseline condition is presented: Typically, the subject either executes an action or listens to a tone and then report the time of these two events independently. In operant conditions (lower part of the picture), the subject makes a voluntary key press on every trial. The key press is followed at time t by an auditory tone. In separated blocks, the subject is asked to judge either the time of the action or the time of the tone. Results show that the subjects perceive action and tone as closer in time in operant conditions compared to baseline.

usually stronger than during non-agentive situations. The reasons for this difference are still matter of investigations, but it is worth mentioning some hypotheses.

The majority of the studies suggest that during action execution the subjects possess higher predictive control on the temporal and contingent factors relating to the occurrence of the first event (say "key press") and the second event (say the tone). The binding effect does occur also with unpredictable or surprising effects, but the magnitude of the temporal shift decreases as a function of the uncertainty that the subject experience in the

particular situation. This hypothesis is compatible with studies, such as Poonian (2015) and Suzuki et al. (2019), which maintained temporal and predictive factors constant across conditions, and found equivalent binding both for intentional actions and external events.

The causal representation involved in the binding effect

Most experiments on temporal binding have assumed that the temporal shift between action and effect is due to the underlining mechanisms of intentional actions. Nevertheless, causality as a necessary condition has been unproblematically accepted by researchers investigating temporal binding, probably because it is intrinsic in the concept of agency that acting implies some form of causality. Those studies have often merged the role of causality and intentions, because intentional actions are also causal.

Nevertheless, it is unclear what it means that intentional actions are also causal: Do intentional actions only require the subject to operate in line with the causal relations present in the world? Or do intentional actions also require the subject to possess awareness of causality? These are truly different questions, insofar simply operating in line with the causal properties of the external environment does not require to possess representation or awareness of causal relations and does not produce temporal changes in event perception.

The case of temporal binding can thus help with addressing these questions. Temporal binding can occur also without an action, and the perceptual attraction between events depends on representing a causal relation, not on the mechanisms underlying an intentional action. Since representing causality is necessary for temporal binding, I shall explain differences in time perception by referring to causal representation. I then clarify the relation between causal representation, intentional action, and the sense of agency.

What are the properties of the causal representation involved in action-effect binding? Experimental results suggest that temporal binding depends on local and context-specific factors, such as contiguity and contingency (Blakey et al., 2019). Based on a Humean account of causality, some scholars (e.g., (Buehner, 2012; Desantis et al., 2012) have connected the binding effect to temporal contiguity: given that we are more likely to infer a causal relation when we perceive proximity between two events, we are also more likely to have perceived proximity when we know that two things are causally related.

In support of this interpretation, some studies (Haggard et al., 2002; Ruess et al., 2017) found a decrease in temporal binding with less contiguity (e.g., delay of 600–800 ms between events), and its absence with longer delays. Nevertheless, another study found that, if the delay is compatible with the subjects' expectation, temporal binding does not disappear with

less contiguity (Ruess et al., 2018). The role of expectation is also compatible with studies showing that beliefs of agency or causality can have a top-down effect on the presence and magnitude of temporal binding (Majchrowicz & Wierzchoń, 2018).

Another factor affecting temporal binding is predictive contingency, namely the expectation of observing a specific effect as a function of one's own behavior. Some studies manipulate the occurrence of the action outcome, and show that highly predictable outcomes increase the binding effect (Moore and Haggard 2008). Interestingly, when the subject had the chance to represent her own action as having causal power over a possible effect, unpredictable or absent effects do not abolish temporal binding, bringing support to the view that the prior confidence in the existence of a causal relation overrides variation in both contiguity and contingency (Desantis et al., 2012).

Other factors likely modulating the magnitude of binding are temporal control (the expectation of observing an effect at a specific time as a function of one's own behavior) and temporal prediction (the expectation of observing an external effect at a specific point in time). Note, however, that the precise role of each of these factors has not always been clearly disambiguated through experimentation (see Hughes et al., 2013 for a review). Taken together, this body of work suggests that, although the combination of low-level factors is a primitive source of the formation of a causal representation, the temporal shift in event perception primarily depends on the higher-level mental construct of causality (Legaspi & Toyoizumi, 2019), which modulates the way we perceive the occurrence of experienced events.

As a matter of confirmation, the binding effect does not occur with non-causal associative learning. No significant changes in time perception occur when the subjects simply experience that two events have occurred together. Temporal shift in event perception is triggered by a causal representation, but not by targets that are equally predictable because merely associated with the predictor (Buehner, 2012; Buehner & Humphreys, 2009; Shiloh, 2019; Suzuki et al., 2019). In other words, it is not sufficient for a movement to be followed by a target stimulus – the action must cause it. That is why even a nonintentional mechanical cause results in binding. Attributing causal relations with or without action is a necessary component of the binding effect.

If possessing a causal representation is necessary for temporal binding, and intentional actions are sufficient for binding to occur, then intentional actions (at least those producing binding) depend on possessing a causal representation.[1] This reasoning would lead to claim that if the sense of agency is defined in terms of causal representation, then temporal shift in

event perception can be used to investigate the sense of agency. If this line of reasoning is accepted, one would possess sense of agency, if he forms a mental representation that his own action causes consequences.

A consequence of defining the sense of agency in terms of causal representation would be the reexamination of the type of intentional actions, which are relevant for action awareness. One could not be willing to proceed to a re-conceptualization of the sense of agency only for the sake of saving temporal binding as (one of) its empirical measure. Although this is in principle a legitimate position, I think that there are advantages for using differences in time perception as a way to inquire into the awareness of action as connected to causal representations.

One advantage is that we can still learn a lot on the subjective experience of action from the results of the intentional binding experiments conducted in the last 20 years. If we interpret the sense of agency through causal representations in fact, those studies can highlight contextual factors and sub-personal mechanisms modulating and underlying the subjective experience of causing effects in the world. Thus, an advantage of defining the sense of agency in terms of the bidirectional relationship and between causality and time is providing an account of the sense of agency that is empirically testable and that have been partly tested through previous experiments on temporal binding. A causal view of the sense of agency would exploit the bidirectional connection between causality and time to uncover properties and mechanisms of the subjective experience of action.

Consider an additional advantage of a causal view of the sense of agency, which relies on the bidirectional connection between time and causality. From a theoretical point of view, the causal view of the sense of agency postulates a distinction between the outer behavior of the subject and her subjective experience, between the objective fact that the subject executes an action and her subjective sense of being the author of that action. Acknowledging the distinction between outer behavior and subjective experience, the causal view of the sense of agency prevents the black boxing of the subjective experience of action, it is sensible to variations in the mental implementation of behavior and eventually paves the way to empirical investigations of the construct of sense of agency.

One can also accept the causal view of the sense of agency but refuse to consider temporal binding as a measure of the sense of agency, that is as a measure of the subjective experience of action. If temporal binding reflects the possession of a causal representation, why shall we think that assessing temporal binding gives us any measure of the sense of agency?

I think that the temporal shift between action and its effect can be considered as a marker of the sense of agency, because to represent one's own action as causing effects, one must discriminate the action and the effect as discrete events in the world. Representing an action as a cause

requires integrating various low-level contextual features, some of which are primarily used for discriminating the properties of one's own movement. With one's own action, the subject does rely on the proprioceptive properties of the issued movement, temporal control, and a self-centered spatial perspective to represent that action as issued in an egocentric mode.

Because representing an observed action as a cause relies on a discrimination that is always perspectival and perceiver-oriented, temporal binding in the context of the execution of an intentional action can be taken as a measure of the sense of agency if the latter is defined as the awareness of causing effects through actions. A similar proposal has been recently made by Hoerl et al. (2020). While it is always possible for the subject to be mistaken on the discrimination of a movement as egocentrically produced, consequently possessing sense of agency for actions that are not self-generated or vice versa, I take this to be a characteristic of the fragile nature of the sense of agency, and not a shortcoming of the causal view that I am advancing here.

I will spend the rest of the paper describing the advantages of the causal of view of the sense of agency and of temporal binding as its implicit measure against alternative views. I will first describe the classical view of the sense of agency as connected to goal-directed actions. Then, I will describe how the sense of agency could still be operationalized by temporal binding if we narrow down the type of intentional actions that are relevant to action awareness and discuss the advantages of this proposal in both theoretical and experimental terms.

Sense of agency and variety of intentional actions

According to a classical phenomenological, action-oriented view of the mind (Gallagher, 2000; Gallese & Sinigaglia, 2010; Legrand, 2007; Zahavi, 2005) the sense of agency emerges with goal-directed movements. I mostly discuss the account formulated by Gallagher (2000), for its undeniable influence in cognitive science and philosophy of mind, and because it clearly attempts to provide a mechanistic, action-based understanding of sense of agency.

Sense of agency depends on sensorimotor processes and an ecologically embedded body, without the organism being *cognitively aware* of having a subjective experience of action that counts as such (Gallagher, 2000). Sense of agency is pre-reflective, because it does not result from a deliberate process of thinking of who is the author of an action or of the reasons why the action has been executed. According to this classical view, a pre-reflective sense of agency is defined as an implicit awareness of initiating and performing movements, and producing and detecting certain effects in the world (Gallagher, 2017). The sense of agency is considered a fundamental component of consciousness, of having a *minimal* awareness of a body that

is capable of causing certain effects (Gallagher, 2000; Seth et al., 2011). This awareness has been explained through a forward model (Figure 2(a)). The model includes – the intended state (i.e., the motor goal); – the motor command, that is the kinematic information necessary for the movement; and – the outcome of the movement. The comparison between goal, command and outcome underpins the subjective experience of actions and movements.

The intended state is a motor representation that guides the execution of the action. Executing a goal-directed action, which is a movement guided by a motor representation containing information of the outcome, and then comparing the motor representation with the actual outcome generates sense of agency, the sense that I am the one who executed the action (Gallagher, 2000, 2017; Gallese & Sinigalia 2010). Sense of agency is associated with the coupling between the expected action outcome and the actual outcome produced by the action. It is based on the mechanism that precedes actions (motor preparation) and translates goals into actions [Note that executing an action also includes a sense of ownership (or presence) of the body based on afferent components, namely the various peripheral signals that inform the state of the body] (Figure 2 (left side)).

The sense of agency has also been described through a predictive coding framework (Fletcher & Frith, 2009; Seth et al., 2011). Briefly, predictive coding regards how the individual makes sense of reality by representing probable causes of events. The mind infers the causes of events by minimizing the mismatch originating from the comparison between top-down, preexisting representations (i.e., priors about how things are expected to be) and bottom-up ascending information (i.e., how things really are). According to predictive coding, the sense of agency originates from the minimization of the mismatch or errors between expectations about the outcome of an action, and the actual outcome (Figure 2 (right side)).

According to this classical view, goal-directed actions generate a minimal action awareness. Sense of agency is thus attributed to any individual able to perform, modify, and redirect movements, and is typically considered to be an unconscious awareness. Some scholars, however, have casts doubts on the claim that the sense of agency is the result of goal-directed actions (Verschoor & Hommel, 2017), and explicitly criticize this account for its disadvantage of preventing "the development of testable models about its underlying mechanisms, which basically has rendered the scientific concept of subjectivity, and thus of the self a black box" (Verschoor & Hommel, 2017, page 131).

This criticism consists in challenging the idea that the sense of agency is a correlate of goal-directed movements, and in proposing that more sophisticated intentional actions (sometimes called full intentional actions) are a pre-requisite for the development of action awareness. Full intentional actions are actions for which the subjects *intend* to execute

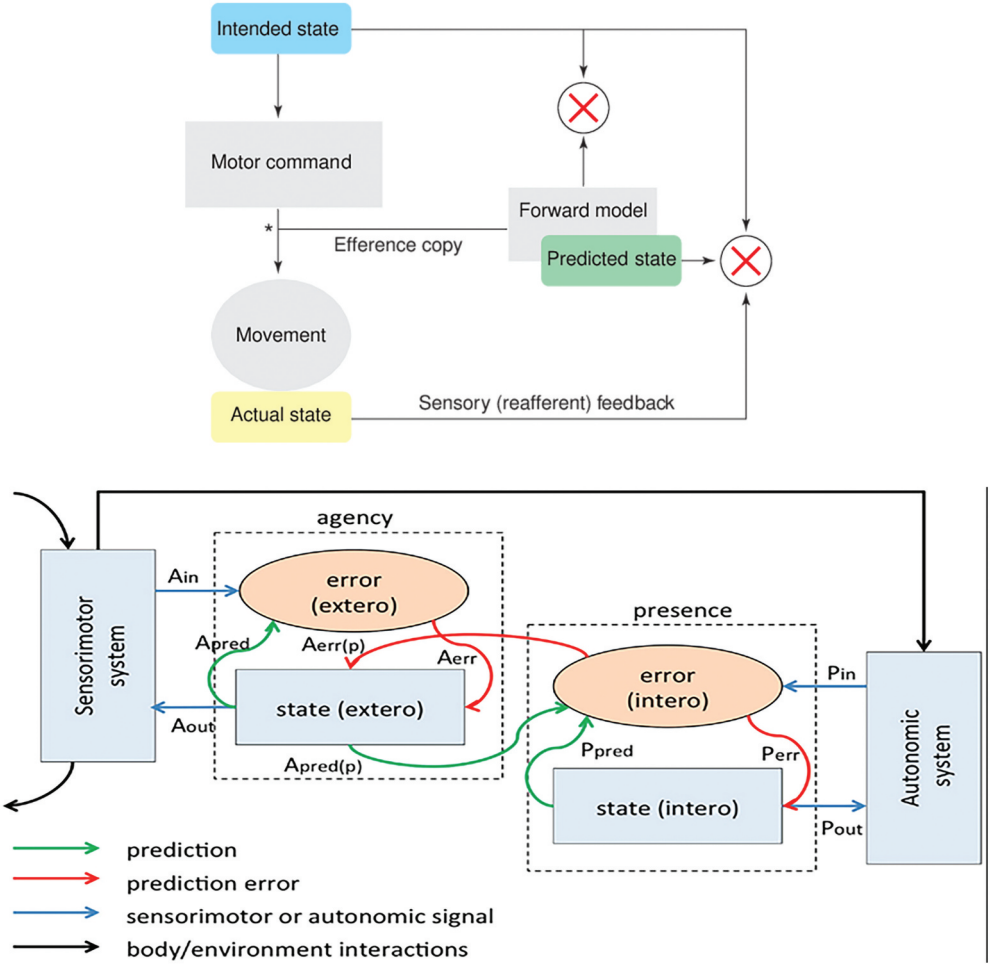


Figure 2. (a) (left side) The forward model represents the processes that generate two aspects of the self in normal experience. Matching at the feedback level provides a sense of agency for movement; match at the forward comparator provides a sense of ownership for movement. Caption and picture taken by Gallagher, 2000. (b) (right side) Predictive coding (Bayesian inference) schema of subjective agency. Both agency and presence (or ownership) components comprise state and error units; state units generate control signals (Aout, Pout) and make predictions [Apred, Ppred, Apred(o)] about the consequent incoming signals (Ain, Pin); error units compare predictions with afferents, generating error signals [Aerr, Perr, Aerr(p)]. In the current version of the model, the agency component is hierarchically located above the presence component, so that it generates predictions about the consequences of sensory input generated by motor control signals. Picture modified from Seth et al. 2019.

a goal, namely select movements on the basis of a flexible association between actions and outcomes. Said in other words, intentional actions require the possession of distinct, decomposable representations of means and ends.

The difference between different types of intentions possibly leading to actions has been theorized in various philosophical works. I am thinking, for example, of John Searle (1980), Elisabeth Pacherie (2006) and Butterfill and Sinigaglia (2014). Given the empirical nuance of the paper, here I will depict the difference between goal-directed actions and full intentional actions in a developmental perspective, and use results of empirical psychology to clarify the distinction.

According to the classic view, newborns from very early in development possess minimal action awareness, because they are able to perform movements finalized to a goal and are sensitive to outcome contingencies. Infants as old as two months are able to modify the sucking rate with the pacifier in response to the manipulation of the auditory consequences of this behavior (Rochat & Striano, 1999), or to adjust the sucking rate in response to the mothers' voice as ongoing conditional feedback (DeCasper & Fifer, 1980). Infants from three months are also able to perform typical goal-directed actions such as grasping and reaching objects, which clearly involve executing finalized movements while being sensitive to multimodal sensory feedback (Diamond, 1990; Rochat et al., 1999).

Thinking that full intentional actions are a necessary pre-requisite for action awareness would lead to a completely different picture. Human infants are thought to develop full intentional actions quite gradually (see Hauf, 2007 for a review). From around 6–9 months, they start to perceive adult's movements as intentional (Jovanovic & Schwarzer, 2007) and to predict them (Falck-Ytter et al., 2006). In the same window of time, they start to produce sequences of movements to achieve a goal.

Consider one study where 10-month-old infants were required to grasp a ball in order to fit it in a tube 1 cm larger in diameter than the ball, or to throw it in a tube, 25 cm larger than the ball (Claxton, et al., 2003). Results show that at this age infants, like adults, are able to reach for the ball faster if they were going to subsequently throw it, while they were slower when they were going to fit the ball in the tube, evidencing some forms of motor *planning* in their reaching behavior (Figure 3(a,b)). Taken together, studies suggest that means-end behavior starts at around 9 months of age (for a review see Babik et al., 2019) and continues to develop gradually throughout the entire second year, while infants learn to solve complex tasks and transfer their knowledge across various contexts.

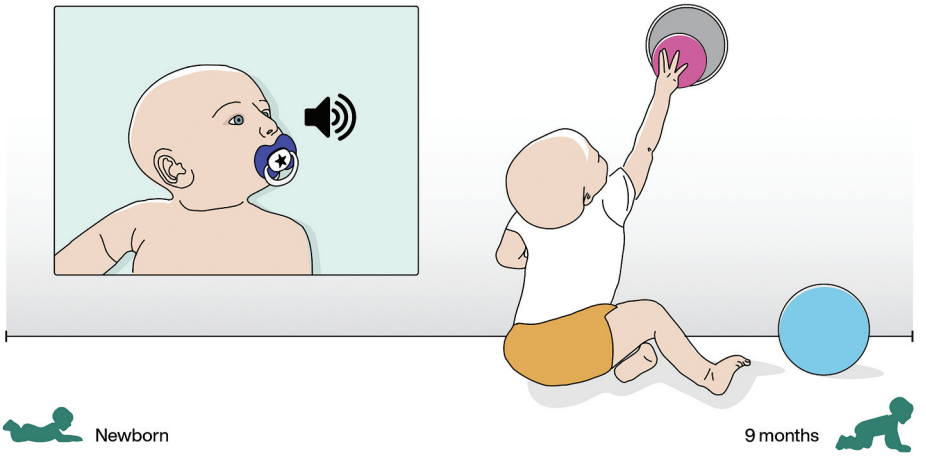
Full intentional action has also been conceptualized through the assumptions of ideomotor learning, according to which intentional actions require flexible relations between their motor and sensory components. Only by using representational resources for distinguishing between motor plans and sensory outcomes can the agent intentionally and flexibly select a specific movement on the basis of its predicted end-state (Figure. 3(b)).

A causal view of the sense of agency

The classical view attributes sense of agency to newborns who are capable of executing actions guided by motor representations, and which contain information on action outcomes. Nevertheless, if no evidence supports the link between sense of agency and the goal-directed behavior of the organism, this account becomes a mentalist, adultist, and non-parsimonious interpretation of infant experience. The sense of agency in newborns cannot be justified by analogy with the adult experience, because infants may lack the necessary cognitive architecture for it (Zaadnoordijk et al., 2019). Further, by stating that sense of agency is intrinsic to any goal-directed action, the classical view proposes a black-box, preformist explanation of action awareness, which is insensitive to variations of the mental implementation of behavior also in the case of adults.

Consider again Gina's case: when she acts by pressing a key and producing a tone, she is *objectively* executing an action associated with an effect. The representation of the motor command specifies the way (through force, direction, and kinematics) she produces changes on the key, and guides the pressing action which is compared online with the sensorimotor feedback to ensure fast and efficient motor control. Nonetheless, being objectively the author of an action is different than having subjective experience of that action because Gina might be *subjectively* unaware of being the author of any distinctive action. Gina may associate the key press with the tone because of previous experiences with the same object, but she may lack the subjective experience of executing the action with that object for various reasons. For example, she may be under the effect of drugs that make her blind to what she is currently doing, or she could be in a condition of sleepwalking.

The classical view entails that Gina has a sense of being the author of the action that she executed only because she is objectively executing an action. However, this explanation does not differentiate between the action behavior performed by Gina and Gina's subjective experience of action; it does not problematize which aspect of an action produces sense of agency in the Gina's mind. Further, it gives no reason to believe that simply associating action with outcome produces action awareness. Evidence shows that the comparison between action command and sensory outcome underpins the subjective experience of actions and movements in human adults, but human adults are typically able to attribute causal effectiveness to their action. The capacity of typical human adults to consider one's own action as the cause of subsequent effect acts therefore as a confounding factor and make the classical view of the sense of agency unsupported by evidence.



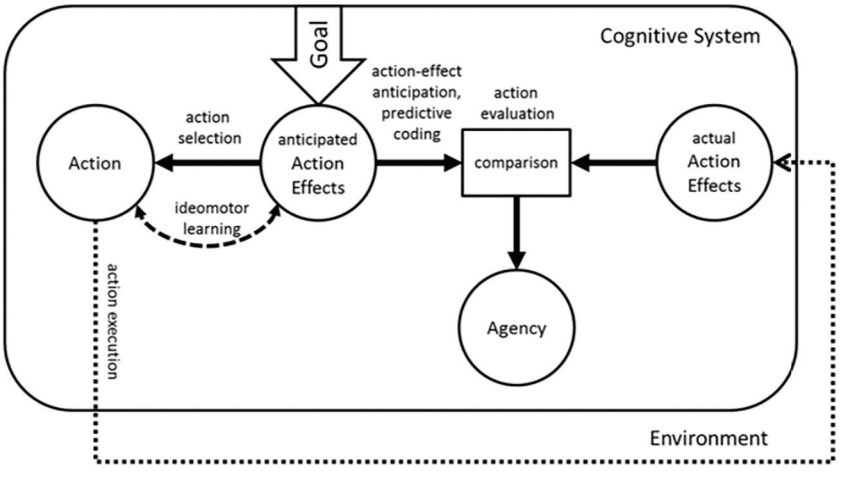


Figure 3. (aa) Newborn capable of goal-directed action. The newborn is capable of modifying the sucking rate with the pacifier in response to the mother's voice as ongoing conditional feedback. ab) Infant capable of intentional action. Infants at 9 months able to plan an action (grasp a ball to fit in a tube) and execute the movements by anticipating the desired outcome (the way the ball fit in the tube). (b) Ideomotor mechanism underlining intentional actions: agency integrates not only the evaluative component of comparing the motor pattern with the action effects, but also the selection of the action based on a bidirectional association (ideomotor learning) between the action and the anticipated action effects (which constitute the goal or intention of the action). Contrary to Figure 2(a), where the intended state is simply the motor representation of the action itself, which activates the congruent motor command, here the motor command is activated by a representation of the anticipated (predictive coding of the) final states, which is different from the motor representation of the action itself. Under appropriate conditions, the action is executed and compared with the actual effects. Agency results from a cognitive system, which is able to integrate and compare the selective and evaluating components of action.

By ascribing sense of agency to organisms expecting that their actions are causally effective, the causal view of the sense of agency takes into consideration the subject's mental states and recognizes causal representation as

the content that makes a difference. Thus, the causal view is beneficial compared to the classical one, because it offers an explanation for how the sense of agency emerges. Contrary to simple action-effect association, causal representation produces a measurable subjective experience, that is time contraction. The connection between causal representation and shorter duration makes the sense of agency, intended as representing one's own actions as causing an effect, a parsimonious explanation for the agent perceiving certain actions as compressed in time.[2]

The causal view of the sense of agency can overcome the mentalistic and non-parsimonious character of the classical view of the sense of agency, which attributes subjective experience of action to any organism able to execute goal-directed actions. By postulating a clear relationship between action, mental state and time perception, the causal view identifies the type of actions, which produce sense of agency, postulating a distinction between the action behavior of the subject and its subjective experience of action.

The causal view of the sense of agency attributes subjective experience of action to organisms, which are able to execute intentional actions involving distinct action and outcome representations, which the subject causally relates. In this respect, the causal view is in line with the accounts, which consider full intentional actions as a necessary pre-requisite for acquiring a subjective experience of action. Being able to actively and flexibly select actions by predicting their possible outcomes is a crucial step in cognitive development, and a crucial aspect of mental life. But how exactly do intentional actions connect to sense of agency?

Many accounts have left unexplained why intentional actions are crucial to generate action awareness. One possibility is that acquiring distinct representations of means and end is instrumental to the communication of goals in a socio-cultural context (Hommel, 2013; Masicampo & Baumeister, 2013). However, connecting sense of agency with communication remains vague: what type of communication would trigger the emergence of action awareness? Appealing to language (as Carruthers (2011), Dennett (2014), and Frith and Metzinger (2016) seem to do) risks making sense of agency cognitively too demanding. It would exclude young infants and also non-human animals from the experience of their own agency, or unjustifiably make the question of sense of agency irrelevant from a psychological perspective.

In contrast, the causal view of the sense of agency illustrates the connection between intentional actions and action awareness. An agent acquires sense of agency if he flexibly combines a means to an end and selects a means on the basis of its expected capacity to yield an end. Because the agent represents the means as causally related to a possible outcome, he experiences a time compression between them. Accordingly, Gina acquires

sense of agency, when she represents the pressing of the key as causing an effect such as the tone. Thus, the causal view of action also overcome the indeterminacy present in some previous accounts.

It is worth noting that full intentional actions have been sometimes connected to causal representation in the philosophical literature. Woodward (2011) for example, has claimed that one way to assess that a subject does possess a causal representation is the extent to which she is able to decouple the means and the end, and to flexibly combine means and end to achieve some goals. Peacocke (2011) has expressed a similar view, which I adapt to my example. If a subject is able to act by representing causality, his intentional action would not be based on a simple behavioral rule (such as *to get the tone, press the key*). Rather, the representation would include a causal statement (such as *there is some property of acting on objects such that it's because pressing the key is acting on objects that pressing the key yields a (contiguous) sensorial event such as the tone*[3]).

In sum, representing causal relations between events restructures previously acquired information about them, and gives rise to subjective changes in event timing. Representing a causal link between action and effect produces the subjective experience of action or action awareness. Also, because linking events causally implies acquiring a temporal contraction among them, causal representations affect time perception by deforming the gravity of the temporal space, moving actions closer to their consequences, and causes closer to their effects. The intimate connection between causality and time is instructive to understand how acquiring causal expectations affects agent's perception and behavior; the acquisition of a causal prior coincides with the emergence of a self with a sense of being a cause in the world and interestingly, this sense is associated with the raise of a temporal illusion.

Action awareness and causal representations in development and evolution

Because possessing a mental representation with causal content affects time perception, sense of agency can be analyzed in terms of changes in event timing. If temporal binding is a function of the agent's causal representation, then assessing temporal binding in the context of an action can be used as a marker of the sense of agency. Temporal binding can be used as a *marker of the subjective*, which can offer information on whether and when individuals acquire awareness of causing effects. More specifically, a marker of the subjective would show that *ceteris paribus*, changes in behavior result from what the specific situation looks like *for* the subject, from the perspective of her mind.

The causal view may pave the way to investigations of the sense of agency intended as causing effects, illustrating the role of representing causal relations as the crucial aspect for understanding action awareness, subjective time perception, and the structure of the word. This would justify the investigation of temporal binding in developmental and evolution, exploring when infants acquire sense of agency through representation of causal relations, and the taxonomic distribution of it among other species.

According to the current literature, infants do not acquire visual impressions of causality earlier than 6 months, when they start to perceive the launching effect (Leslie & Keeble, 1987), while causal perception for more complex stimuli (e.g., unusual trajectories) arises at least at 10 months of age (Oakes & Cohen, 1990). It is instead more difficult to assess when they learn to represent causality, because many developmental studies can be explained through operant conditioning, making unclear whether infants are using causal representations for solving problems based on causal relations (Danks, 2009). From about 1 to 2 years of age, infants acquire a flexible repertoire of intentional actions. If in this period infants show a contraction of the time of their actions, this would demonstrate that they have action awareness, and that they are aware of causing changes through their actions.

The phenomenon of temporal binding has been tested with children as old as 6 to 8 years (Blakey et al., 2019; Lorimer et al., 2020). I can suppose that there are practical obstacles in conducting similar experiments with younger individuals. Even though I do not think that measuring differences in event timing in infants is an easy task, I think that it could be viable. Surely, using the Libet clock to measure the perceived time of events, as the majority of temporal-binding studies have done, could *not* be the best option. The Libet clock may not be suitable for testing perceptual differences of event timing in agents with poor linguistic capacities. Also, paying attention to the clock while performing a movement may be cognitively demanding, because it requires a load of visual attention that can distract the subject from the process of action execution (Engbert et al., 2007).

An alternative could be the *motor synchrony task* (Cravo et al., 2011), where participants are required to evaluate the time of occurrence of a target stimulus in an action or non-action condition: participants would perceive two cues, one (a beep) after executing an action (or after a fixation point disappears on a screen), and another temporally independent cue (a flash). They would then indicate whether the two cues were simultaneous or not. This technique has proved effective to measure differences in time perception, and the temporal-binding phenomenon has been thereby replicated. I imagine that a simplified version of the motor synchrony task could be used for testing the binding effect in infants from 2 years of age.

Another intriguing possibility would be to investigate temporal binding in other animal species. Comparative studies of action-effect binding could highlight whether the organisms can form causal inferences and help to clarify the connection between causal representation, intentional actions and the emergence of the sense of agency. Note that one proposal for testing the phenomenon of binding in other animal species has already been made at the time of writing (Tramacere & Allen, in press).

By showing that causal representations produce a temporal shift in action-effect binding, while non-causal associative learning does not, temporal binding could test whether other species possess representations of causal relations, and therefore sense of agency. Ideal candidates for testing temporal binding would be the species which already proved to be flexible and creative problem solvers. Apes, some species of monkey, corvids, parrots, and mammals, such as dogs, dolphin and elephants show means-end reasoning (Krasheninnikova, 2018), skilled tool using capacities (Seed et al., 2011), and high rates of innovation behavior in ecological conditions (Reader & Laland, 2002); all abilities that objectively require to operate and generalize along relevant causal features. Do these skills also rely on causal representations?

By adjusting the *motor synchrony task* from Cravo et al. (2011) to the perceptual and cognitive characteristics of the species, it may be possible to address this question. I will adventure here in a concrete proposal with nonhuman animals. I envisage a preparatory phase, where the subject responds with a key press only when she perceives that two selected cues occurred simultaneously. In the experimental phase, the subject undergoes an action and a non-action condition. In the action condition, she executes a press triggering the two cues, separated from each other by one out of various stimulus onset synchronies (SOA).

In the non-action condition, the cues appear after a fixation point disappears on the screen, again separated by one out of various SOA. After each trial, the subject responds with a key press only if she perceived the two cues occurring simultaneously. A major number of simultaneity judgment in the action versus the non-action condition would suggest that the subjects experience a temporal contraction between the action and the effect, thus proving to possess awareness of action causation.

We have seen that infants can act in line with causal relations during the first year of life, when they acquire the capacity to execute goal-directed actions. They practice a flexible repertoire for intentional actions from 1 to 2 years of age, while from 2 years of age children are able to extract causal relations from observed behavior and to immediately apply them. So far, this capacity to intervene causally has been observed only in great apes (Völter et al., 2016). Despite being skillful problem solvers in tasks that require them to grasp causal relations in object–object interactions (Taylor

et al., 2010) or to reason about hidden causes (Taylor et al., 2012), other "intelligent" species, such as crows (Taylor et al., 2014) did not seem to be capable of causal intervention.

What types of causal representations are involved in these capacities? Which of these capacities are explainable through the acquisition of causal representations? I believe that the causal view here described may be instrumental to address at least some of these questions.

Conclusion

I have argued that one possesses the sense of being the author of an action or action awareness if he represents the action as *causally* linked to its effect. I have thus formulated a causal view of the subjective experience of action based on conceptual and experimental grounds.

Connecting the subjective experience of action to causal representations brings some new elements to the field of phenomenology and the philosophy of mind. Many accounts of the mind have focused on the relationship between perception, action and the world, with causality being a fundamental building block of this complex of interactions. However, contemporary phenomenological frameworks have disregarded causal representations in the explanations of the subjective experience of action. Further, since the discovery of temporal binding in the contest of action execution, sense of agency has been exclusively explained in sensorimotor terms.

Findings that temporal binding occurs also with external conditions could stimulate new thinking, by problematizing *how* the acquisition of progressively more complex actions relies on mental states with both causal *and* subjective content. The causal view of the sense of agency that I propose here has exactly this goal. This view implies that representing the causal connection between your action and the consequence of the action gives rise to an expectation that manifests in the mind in terms of a subjective experience of action.

Through the analysis of the perceptual properties of event timing, the causal view of the sense of agency also gains experimental tractability and paves the way to the longitudinal and cross-species investigations of causal states through measure of time perception. The empirical investigation of the sense of agency can constitute an important novelty in the field of developmental and comparative psychology, because it brings classical phenomenology to the attention of scientists, who could analyze causal representations in terms of time perception.

The causal view of the sense of agency analyzes subjectivity in relation to the mental requirement of action control and in the light of that fundamental idea which is causality. This view is in line with novel investigations from various disciplines suggesting that causality is a *passe-partout* for understanding the origin of self-awareness and the

sense of time (Arstila et al., 2019). When an organism becomes aware of causal relations, it can access the existence of itself and other objects as part of a structured world that extends beyond the immediate senses, and that conforms to an ordered and subjectively experienced succession of time.

Examining the mind from the perspective of causal representation is ultimately conducive to deepening our comprehension of how the human mind evolved. Understanding causal relations and creating a wide range of causal interventions are key factors behind our transition from stone tool using hominins to humans of science and civilization.

Notes

1. It is also possible that intentional binding (perceived time compression in the context of actions) and causal binding (perceived time compression in the context of non-agentive conditions) are two different and independent mechanisms. However, this does not seem to be the case, since in both causal and intentional conditions, the binding phenomenon depends on an overlapping set of variables.
2. An advocate of the classic view of the sense of agency as pre-reflective may claim that the causal view and the classic view are not targeting the same phenomenon, that is the two views are not trying to explain the same type of action awareness. An advocate of the classic view could also find unproblematic that action awareness is a non-parsimonious construct, and that it is not amenable to scientific investigation. I concede that. The causal view of the sense of agency I am proposing here has a clearer empirical orientation, and it is indifferent to the existence of something like a pre-reflective action awareness.
3. Peacocke (2011) attributes causal representations to agents who are able to represent or believe in a general property P explaining why an event of type B is followed by an event of type A, and are in the position to hold that (other things being equal) if the A-event had not occurred, then the B-event would not have occurred.

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No potential conflict of interest was reported by the author(s).

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