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On Time, Causation, and the Sense of Agency

Abstract: *The experience of controlling events in the external world through voluntary action — the sense of agency (SoA) — is a subtle but pervasive feature of human mental life and a constituent part of the sense of self (Gallagher, 2000). However, instead of reflecting an actual connection between conscious thoughts and subsequent outcomes, SoA may be an illusion (Wegner, 2002). Whether this experience is an illusion, indicating no actual causal connection between conscious intention and physical outcome in the world, has been the focus of intense philosophical and scientific debate since the beginnings of these fields of enquiry. More recently, the fields of experimental psychology and cognitive neuroscience have begun to identify specific antecedents of the experience of agency — whether veridical or not (Haggard, 2008). Similar to the perception of causality, which depends on the temporal structure of the events, humans' experience of their agency is very sensitive to the temporal interval separating bodily actions from the external effects of those actions. Accordingly, just as studies on perception of causality in the outside world have paid much attention to the temporal configuration of events, many contemporary studies have also focused on the contribution of the temporal organization of events giving rise to SoA, and in turn how experienced agency might influence subjective time. Here, I review existing evidence suggesting that subjective time both influences and is influenced by perceived causality in general, and experienced agency in particular. Finally, I briefly speculate that these findings may support predictive coding theories of cognition and perception (e.g. Hohwy, 2013).*

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Journal of Consciousness Studies, **24**, No. 3–4, 2017, pp. 203–15

In early experimental studies on the perception of causality, Michotte (1963) identified the temporal relationship between two objects' motion as the most important determinant of the perception of cause and effect: in a series of experiments, participants saw two discs, one of which moved to touch the other disc, which subsequently 'launched' to movement as if propelled by the first object's touch. The key finding was that this 'launching effect' — perceptually experiencing that object A 'launched' object B into movement — depended on a specific temporal relationship between the two discs' movement. If the second disc begun moving before being touched by the first disc, people simply perceived two independently moving discs. Similarly, if the second disc did not move until much later after it was touched by the first disc, people also perceived two independently moving discs. However, when the temporal delay between the first disc touching the second and the second disc's movement onset was just right — depending on the specific configuration of the objects, usually under about a fifth of a second (*ibid.*, p. 22) — people unequivocally perceived that the first disc caused the second one's movement: with short time intervals, the two discs' motions were seen as causally connected.[1]

Later experiments investigating judgments of causality in similar perceptual tasks have found that when outcomes follow participants' actions probabilistically (e.g. actions produce outcomes on 75% of trials), increasing the delay from actions to their effects reduces judgments of the actions' causal power over the effects independently of the probabilistic contingency (i.e. the probability that an event follows an action; Shanks, Pearson and Dickinson, 1989). Therefore, time seems crucial for inferences about causality, even in the presence of uncertainty. It is important to note that while other factors, such as prior beliefs, can influence when and where causality is perceived, under suitable conditions the perception is very quick to occur — little or no conscious deliberation is required — but not automatic in the sense that people would have some underlying direct access to information about physical causality. Instead, causality is quickly inferred from the statistical regularities and temporal features of the

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1 In some variations of the basic 'Michotte display', completely removing the temporal delay between the discs' movement can also result in the perception of a single unitary object moving through the display, even if these objects are coloured differently (Michotte, 1963, p. 45), reminiscent of visual illusions of apparent motion (Wertheimer, 1912; Kolers and von Grünau, 1976).

observed events (Hume, 1748; Lagnado and Sloman, 2006). That is, objects and events must be temporally combined and structured in specific configurations for people to perceive causality: 'any adequate theory of causality judgement… must account for effects of both contingency and [temporal] contiguity' (Shanks, Pearson and Dickinson, 1989, p. 143).

However, the relationship between time and causality is not restricted to actual temporal properties of events informing perceptions of causality. Perceived or judged causality between two events can also influence the subjective temporal properties of those events. For example, human participants anticipate that events occur earlier in time when they have learned that the events are caused by a mechanical agent, even at very short timescales (under 1.5 seconds between the two events; Buehner, 2012). Further, the effect of beliefs about causality on time perception is not limited to magnitude judgments, such as numerically estimated inter-event intervals; perceived causality between two events can shift the perceived temporal order of observed events (Bechlivanidis and Lagnado, 2016). In this study, participants observed modified 'Michotte displays', whose objective temporal order sometimes violated principles of causality (an object started moving before another object touched it). In these cases, participants sometimes ignored the objective temporal structure of the events, and reported seeing events in the temporal order implied by the assumed causal structure instead (*ibid.*). Perceived causality can also influence subjective estimates of event timing on a much longer timescale than the two studies highlighted above. In studies on historical events, Faro and colleagues have found that when people believe that two historical events are causally related, they estimate that these events occurred closer together in time than two events that they don't believe are causally connected (Faro, Leclerc and Hastie, 2005; Faro, McGill and Hastie, 2013).

These studies suggest that the flow of information between time and perceived causality (of external events) is bidirectional; perceived causality can inform judgments and perceptions of the temporal relationship between events, and the actual temporal distance between events can strongly modulate perceived causality. But does the bi-directional relationship also hold for time and people's perceptions about the causal powers of their own actions? Could such intimate self-knowledge be modulated by what happens when in the outside world, and could an individual's sense of agency (SoA) influence how time is perceived? If SoA is anything like inferences about causality in general, it is possible that SoA is also modulated by objective temporal properties of events, and that subjective time can be modulated by SoA.

1. Time Influences Experienced Agency

Although some early theories of how humans come to regard themselves as conscious agents took the view that people knew directly that one is an agent with causal powers (de Biran, 1942; see also Michotte, 1963, p. 11), more recent theories suggest that the sense of agency is inferred from the temporal, spatial, and psychological structure of intentions, actions, outcomes, and other related events. For example, according to the theory of apparent mental causation (Wegner and Wheatley, 1999; Wegner, 2002), the experience of causing actions by intending them is an illusion constructed retrospectively by the brain when three requirements are satisfied: the intention must occur before the action, and the intention and action must be compatible and causally exclusive — i.e. the thought should be the only possible cause for the action. This theory implies that the sense of agency is a *post hoc* construction formed only after the outcomes of the actions are known. However, more recent evidence suggests that SoA is modulated by factors necessarily operating before the outcomes are known to the agent (Chambon, Sidarus and Haggard, 2014; Sidarus and Haggard, 2016). Although apparent mental causation is therefore not a comprehensive model of the sense of agency, it highlights a common feature of many models of the sense of agency, namely that the experience of agency is not automatically known by the agent, but rather is influenced by many factors, including the temporal properties of events.

Apparent mental causation has received little empirical verification (but see e.g. Wegner, Sparrow and Winerman, 2004), possibly because the specific nature of subjective intentions has been difficult to determine and measure empirically. It nevertheless provides a useful analogy between the perception of causality in the external world, and the perception — or construction — of the sense of agency. Just as Michotte's experiments showed that external causality is perceived when the temporal properties of events are just right, SoA is also sensitive to the specific temporal configuration of events: in three studies using an arcade-style computer game, players reported feeling substantially lower SoA when a temporal interval (either 1/4 or 1/2 second) was introduced between the player's mouse movement and the game cursor's movement (Metcalfe, Eich and Castel, 2010). Further supporting the claim that sensitivity to this temporal interval is crucial for the sense of agency, individuals with schizophrenia — a disorder whose one core deficit relates to difficulties distinguishing self- and other-caused events — are not affected by a temporal lag between actions and outcomes in the same computer game (Metcalfe *et al.*, 2012). These studies, and others investigating how different manipulations in computer games influence the sense of agency (Metcalfe and Greene, 2007), support the general idea that the sense of agency is not directly perceived but rather inferred from multiple sources and cues (Synofzik, Vosgerau and Lindner, 2009). Specifically, the sense of agency — the subjective experience of causing and being in control of actions and their effects — is decreased by longer intervals separating one's voluntary action, and their subsequent effect.

2. Voluntary Actions Influence Subjective Time

Similar to perceptions of causality between external events, the human sense of agency is influenced by temporal properties of events, such that the sense of agency is strongest when actions precede their effects with no or very short delays (Metcalfe, Eich and Castel, 2010). However, evidence also shows that voluntary actions, and the ensuing sense of agency, can influence subjective time. Before reviewing this evidence, I briefly introduce one influential approach for measuring subjective timing of intentions, actions, and effects.

2.1. Chronometry of voluntary action

In a seminal set of experiments, Benjamin Libet and colleagues asked volunteer participants to observe a clock face with one rapidly rotating hand (one rotation about every three seconds), and to make simple hand movements whenever they wanted to (Libet *et al.*, 1983). After each hand movement, the participant reported the onset of the feeling of wanting to move (W judgment) and when they thought they had actually moved the hand (M judgment) by reporting the recalled position of the clock hand at the time of the event. These judgments constituted the subjective chronometric evaluations of events, which could in turn be compared to objective timings of the events. While the participants were performing the task, the electrical activity of their brains was recorded with an electroencephalogram (EEG), and the muscular activity at the hand was recorded with an electromyogram (EMG). As a result, Libet *et al.* were able to compare the time course of the brain's electrical activity (EEG) with the participant's judgment of when they first wanted to move (W), and also the objective timing of the actual hand movement (EMG) to the subjective judgment of when the participants thought they had moved (M). The key finding was that the W judgments were reliably preceded by a slow ramping up of brain activity detected with the EEG (the readiness potential; Kornhuber and Deecke, 1965), from which the authors concluded that the intention to produce voluntary actions, and therefore the decision to move, is determined by unconscious brain processes before the person is aware of wanting to move. This interpretation of the results was fiercely critiqued (see e.g. commentary in Libet, 1985), and recent computational models suggest that the readiness potential reflects random neuronal noise instead of a unitary unconscious mechanism determining when to act (Schurger, Sitt and Dehaene, 2012). The second finding from the initial study was that participants' judgments about when they had moved their hand (M judgment) reliably preceded the hand movements by about 80 milliseconds. Most importantly for the present discussion, however, the study provided an innovative (but controversial; see commentary in Libet, 1985) method for assessing the subjective timing of events, and relating those subjective chronometric judgments to objective temporal properties of events.

2.2. Intentional binding

Libet's clock task was later adopted to studying the time course of action awareness in more detail, and how agency might influence the perceived timing of actions and effects: instead of only asking about the subjective timing of intentions and actions, Haggard, Clark and Kalogeras (2002) asked if operant (effect-causing) voluntary actions can modulate the subjective timing of events in the intention–action–effect chain of events. They modified the Libet task to include, on some trials, events caused by the action (a short beep following the action by 250 milliseconds), and on some trials replaced the voluntary hand movements with involuntary hand movements caused by transcranial magnetic stimulation (TMS) pulses to the participant's parietal cortex. With this design, whereby on some trials the hand movement (either voluntary or involuntary) caused an effect (auditory beep), and on other trials these events were present in isolation, Haggard *et al.* investigated if one possible mechanism by which the brain produces an experience of controlling external events — the sense of agency — relates to subjective temporal binding of voluntary actions and their effects. Indeed, they discovered that operant voluntary hand movements — ones that were followed by a beep — became temporally bound to their apparent effects. That is, on trials where a voluntary action caused a beep, the judgments of when the action occurred were shifted forward in time toward the beep, and judgments of when the beep occurred were shifted backward in time, toward the action that caused it. For involuntary operant trials, where the TMS-produced hand movements were followed by tones, they instead found temporal repulsion, whereby the judgments moved further away from each other in subjective time, in comparison to baseline (action-only or effect-only) trials. From these results, the authors suggested that 'the brain contains a specific cognitive module that binds intentional actions to their effects to construct a coherent conscious experience of our own agency' (*ibid.*, p. 385).

The observed temporal binding of intentional actions and their sensory consequences was dubbed 'intentional binding', because the binding effect was restricted to voluntary effect-causing movements, and because similar involuntary movements resulted instead in temporal repulsion of the judged timing of action and effect (*ibid.*). Although the relationship between explicit judgments of agency and intentional binding is still somewhat unclear, as some studies have found that they are only weakly if at all correlated (Dewey and Knoblich, 2014; one suggestion is that they somewhat independently measure explicit and implicit aspects of the sense of agency, respectively, Moore *et al.*, 2012), this modulation of time perception has been used in a large number of studies yielding valuable insight into the nature of SoA and temporal awareness of actions and their outcomes (Moore and Obhi, 2012).[2]

Although a great number of studies have examined the various influences on intentional binding, the underlying mechanism of this modulation of subjective time has received less attention (Moore and Obhi, 2012). One study used judgments of simultaneity of electric shocks following voluntary and involuntary action to examine if modulation of an internal clock might account for intentional binding

2 Recent evidence has also called into question whether intentional binding is restricted to voluntary actions, or if it instead reflects a more general effect of perceived causality on timing judgments (Buehner, 2012).

(Wenke and Haggard, 2009). According to internal clock models of time perception, judgments of interval durations result from readouts of the number of 'ticks' generated by an internal clock during a given interval (Gibbon, Church and Meck, 1984). Modulations to interval judgments can then be explained in terms of changes to the tick-rate of the clock, or how these ticks are recalled from memory (Wearden, 2008).

Wenke and Haggard (2009) hypothesized that voluntary actions and their effects seem closer in time because voluntary actions slow an internal clock, and therefore lead the two events to be separated by fewer ticks. If this was the case, then two events presented during the action–effect interval would be separated by fewer ticks following voluntary actions (*ibid.*). In the experiment, participants produced a tone with either a voluntary key-press or an involuntary key-press (the finger on the key was depressed by a machine). During the key-press–tone interval, they received two closely placed electric shocks on the hand that pressed the key, and, following the tone, judged whether the two shocks were simultaneous or not. In support of the slowed-clock hypothesis, participants required more time between the two shocks in the voluntary action condition, in contrast to the passive movement condition, to be able to correctly judge them as not simultaneous. These results were interpreted as suggesting that the electric shocks were separated by fewer ticks in the voluntary action condition, making the temporal discrimination more difficult. These results therefore suggest that intentional binding results from a temporarily slowed internal clock, which in turn allows actions and their effects to be separated by fewer ticks of the internal clock, making them appear as closer together in time.

In line with these results, another study found that voluntary actions change visual perception of illusory motion in a manner that would be expected by an online subjective shortening of intervals following action (Vuorre and Metcalfe, in preparation). In this experiment, participants observed two static frames of visual stimuli that could result in specific visual illusions of motion if the frames were separated by a short interval (apparent motion and Ternus illusion; Wertheimer, 1912; Kolers and von Grünau, 1976; Ternus, 1926). The participants either passively observed the displays, or observed them following a voluntary hand movement. Results showed that participants still perceived the illusions at longer inter-frame intervals when the stimuli followed voluntary actions, suggesting that voluntary actions cause a temporal rate shift, not only in the tactile domain in a bodily location near the movement, as suggested by Wenke and Haggard (2009), but also in global temporal awareness, and reinforce the hypothesis that intentional binding might reflect a temporary slowing down of an internal clock. More generally, these findings are consistent with the theme of the current paper: experienced causality and agency can modulate estimates of temporal intervals, judgments of when events occur, and even perceptual phenomena that are dependent on the subjective flow of time, such as tactile temporal simultaneity judgments and visual illusions of motion.

3. Role of Prediction

A common theme above has been that perceptions of causality, agency, and time are to a degree inferential, in the sense that these perceptions are sometimes influenced by information that is not indicative of the objective passage of time, degree of agency, or causality. An illustration of the inferential nature of time perception, for example, is the intentional binding effect, whereby one's voluntary actions change how time is perceived, although information about one's actions — and their effects — is not really about time. Note that by 'inference' here I do not mean conscious deliberation, but rather something akin to unconscious integration of multiple sources of information, some of which are not objectively informative of the to-be-judged quantity. It is also only in this weak sense that SoA can be considered an illusion: SoA is influenced by information that doesn't necessarily pertain to the objective degree of agency, so one may sometimes experience SoA in the absence of actual agency, because some of these potentially non-veridical sources of information lead one to believe so (e.g. Wegner, Sparrow and Winerman, 2004).

Therefore, it may be that the perception of causality is an inference, in the sense described above, mostly based on learned associations between co-occurring events (Hume, 1748; Michotte, 1963), or that the sense of agency is inferred from various cues available to the agent (Synofzik, Vosgerau and Lindner, 2009). In either case, evidence suggests that the relationship between experiences of time and agency is bidirectional; that is, experienced causality and agency are informed by time, and perceptions of time are informed by experienced causality and agency. Although a mechanistic understanding of these effects is still lacking, they are suggestive of unifying theories of cognition and perception whereby prior top-down expectations shape the stream of experience — the so-called 'predictive coding' and

‘Bayesian brain’ hypotheses (Friston, 2010; Clark, 2013; Hohwy, 2013).

An early explanation of the intentional binding phenomenon suggested that it might reflect an approximation of Bayesian inference in the presence of uncertainty about event timing (Eagleman and Holcombe, 2002). Under this Bayesian framework, because individuals have learned through experience that causally connected events tend to happen close together in time, and that their actions are likely to cause outcomes in the world, individuals can — on average — improve the estimated timing of events by combining these prior expectations with noisy incoming sense-data. In other words, when asked to estimate the timing of an action and its sensory consequent, people would tend to judge that these two events occurred closer together than two passively observed events, because of the prior assumption that their actions are likely to cause outcomes, and that causes and effects are likely to occur close together in time. In this framework, the subjective experience of event timing and agency is a combination of the current stream of incoming sensory information and top-down expectations. This framework may be adopted to explain the intentional binding effect (Eagleman and Holcombe, 2002), but importantly can also be reversed to explain the bi-directional influence between perceived time, causality, and agency, as explored above. In the case of judgments of agency, for example, in ambiguous situations as to whether ‘I’ caused some outcome in the environment, the temporal proximity of my action to an event in the world may be used to erroneously infer that ‘I’ did it, even when in fact the action and a sensory event are not actually causally related (Wegner and Wheatley, 1999). Similarly, when people have little information about actual causal relations between external events, they use information about temporal covariation to guide their estimates of causality (Lagnado and Sloman, 2006).

Generally, the notion of combining prior information with noisy sensory inputs is in accordance with theories of cognition and perception as probabilistic, predictive inference (Friston, 2010; Clark, 2013; Hohwy, 2013). According to these theories, cognition and perception arise from unconscious inference about the possible external causes of sensory inputs, using Bayes’ rule. This inference requires an internal model in the form of a probability density, which assigns prior probabilities to hypotheses. These probabilities are then updated in light of incoming sense-data to yield posterior probabilities of hypotheses, which then dictate the resulting perceptual experience (for a clear extended discussion of this idea, see Clark, 2015, pp. 39–41). One suggestion then, generalizing from the intentional binding example above, is that the bidirectional relationship between perceptions of time and causality (or agency) results from a prior positive correlation, in people's internal models, between two events occurring close together in time and them being causally related. That is, one would, all other things being equal, expect that these properties are more likely to occur together. The prior correlations would parsimoniously translate to directional influences, the direction depending on whether one is trying to guess the time interval between two events, or whether the two events are causally related.

Although many of the empirical findings reviewed here are broadly in line with the idea that perceptions of time can inform and be informed by perceptions of causality and agency, future research should attempt to move toward formal modelling of how such information exchange occurs. An intriguing avenue for future research in this field would be to investigate whether predictive coding theories could, in fact, explain the relationship between time perception, sense of agency, and perceptions of causality.

4. Conclusion

Experiences of causality, agency, and time are nearly omnipresent in human cognition: rarely a moment goes by without us noticing that a moment has passed, and that one event during that moment caused another event in a future moment. Accordingly, we can also rapidly evaluate whether 'I' was the cause of some or other event in a continuous stream of events. This article has reviewed evidence suggesting that subjective time and (self-)causality are connected in a bidirectional manner: when the situation calls for it, humans can use information from one domain (e.g. time) to inform judgments in another domain (e.g. agency). Evidence suggests that this two-way connection between time and causality is a primitive one, that its use does not require conscious deliberation, and that information from one domain can influence conscious experience in another domain. The evidence reviewed here led to speculations that the relationship between time and (self-)causality might be explained by principles of predictive coding theories of cognition and perception: in the presence of uncertainty, the brain uses the learned correlation between a short time interval separating two events, and their seeming causal connectedness, to inform judgments in either domain.

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