Causality and the perception of time

David M. Eagleman and Alex O. Holcombe

Does our perception of when an event occurs depend on whether we caused it? A recent study suggests that when we perceive our actions to cause an event, it seems to occur earlier than if we did not cause it.

If you hold out your hand and snap your fingers, you will not notice any difference in the time that you intend to move your fingers and the time that you hear the snap. This is true even though the auditory signals corresponding to the snap were being processed by the nervous system for more than 100 ms before your auditory experience occurred. Humans can easily perceive 20–30 ms differences in timing [1], so the fact that you did not notice a discrepancy suggests that the brain carried out some temporal sleight of hand. Did the brain actually adjust its temporal estimates of your action and its effect so that they seemed simultaneous?

If so, a crucial factor that would aid such adjustments would be the predictability of the relevant events. In the case of finger snapping, the brain is in a good position to predict the snap: after all, the best way to predict the future is to create it. There is a rich research tradition demonstrating that the predictability or unpredictability of an outcome changes the sensory experience that results [2–5]. For example, one cannot tickle oneself under normal circumstances – however, it becomes possible if a temporal delay is injected between your motor action and the end effect (say, via a robot arm [2]). But is predictability ever used by the brain to alter the perceived *time* of occurrence of events?

Until now, there has been only anecdotal evidence to support this idea. For example, in one study subjects played a video game in which a delay was injected between their mouse movement and the action on the screen. Not only were they able to adapt to the delay, but also they informally reported that their actions and effects came to seem simultaneous [6]. After this adaptation, a sudden switch to a shorter delay caused (again according to subjects' spontaneous reports) a negative
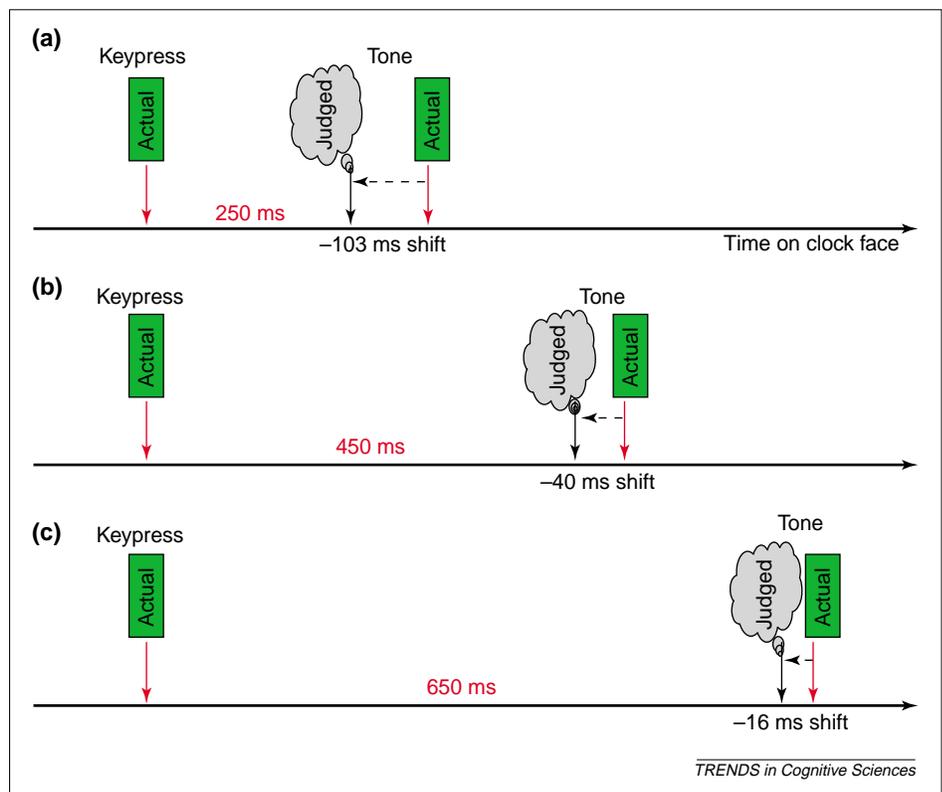
Fig. 1. Haggard *et al.* report that the judged time of a tone changes as a function of the delay between the tone and a previously executed voluntary act. As the delay is lengthened (a–c), the time mis-estimation is reduced. Mean judged time is represented by thought bubbles. In the experiment, time judgments are always retrospective, which is why they can appear to precede the actual times of occurrence on the timelines. (Representation of Haggard *et al*, Table II, fixed delay condition.)

aftereffect, wherein effects on the screen appeared to occur *before* the subjects moved the mouse. So is the brain adjusting its temporal estimates of events when they are predictably self-caused? Can actions and their results appear, retrospectively, to have non-veridical relationships in time?

Temporal judgment shifts with intentional action

A recent paper by Haggard, Clark and Kalogeras [7] provides the first direct test of this question, contributing new data in the nexus between agency and timing. They explored what happens to our subjective judgment of timing of events when an event is causally linked to a subject's intentional action.

In one condition, subjects judged the timing of an auditory tone by reporting the corresonding position of a rapidly moving clock hand. In a second condition, subjects voluntarily pressed a key (at a time of

their choosing) and judged the time of their keypress in the same fashion. In a third, crucial condition, subjects pressed a key that caused a tone to follow 250 ms later. In half of these trials subjects judged the time of their keypress; in the other half they judged the time of the tone. Comparing the data across conditions, the perceived times of the tone and keypress when they were causally linked were compared with the conditions in which they occurred by themselves.

Remarkably, when the tone was causally linked to the subjects' keypress, subjects judged the keypress to occur (on average) 15 ms later and the tone to occur 46 ms earlier than if these events had occurred alone. In a second experiment with different subjects, the delay between the keypress and subsequent tone was varied (to be 250, 450, or 650 ms), and subjects judged the time of the tone. Haggard *et al.* found that the further apart the keypress and tone, the more the

Box 1. The neural timing of intention

When a car suddenly pulls in front of yours, your foot is halfway to the brake before you are consciously aware of it. A baseball slugger could never make contact with a major league pitch if he tried to be conscious of the position of the ball. How often do our brains make decisions before the conscious mind is aware of it?

The first experiments to address the timing of decisions directly were conducted by Benjamin Libet and his colleagues (e.g. Ref. [a]). Their experiments asked questions about when people believed they made a decision versus when the brain began to make the decision. In one form of their experiment, they measured EEG activity while subjects voluntarily chose to lift a finger. During the task, subjects watched a rapidly moving clock hand and made a mental note of when they decided to lift their finger. This yielded three types of data: when the subject lifted her finger, when she believed she decided to lift her finger, and what her brain activity was during this time. The EEG results demonstrated that the cortex became active with a 'readiness potential' 350 ms before the reported awareness of a 'wish to move' [a]. These experiments suggested that our subjective awareness of decisions occurs measurably later than the actual events of deciding [b].

This work was later replicated and extended by Patrick Haggard and his colleagues, who suggested that the 'lateralized' readiness potential (i.e. activity in the hemisphere contralateral to a voluntary hand movement) might cause our awareness of movement initiation [c]. This work challenges folk-notions of free will, implying that the feeling of having made a decision is merely an illusion. What determines when we think the decision was made, and subsequently, when we believe our actions and their consequences occurred? Figure I relates the the timeline of the Haggard
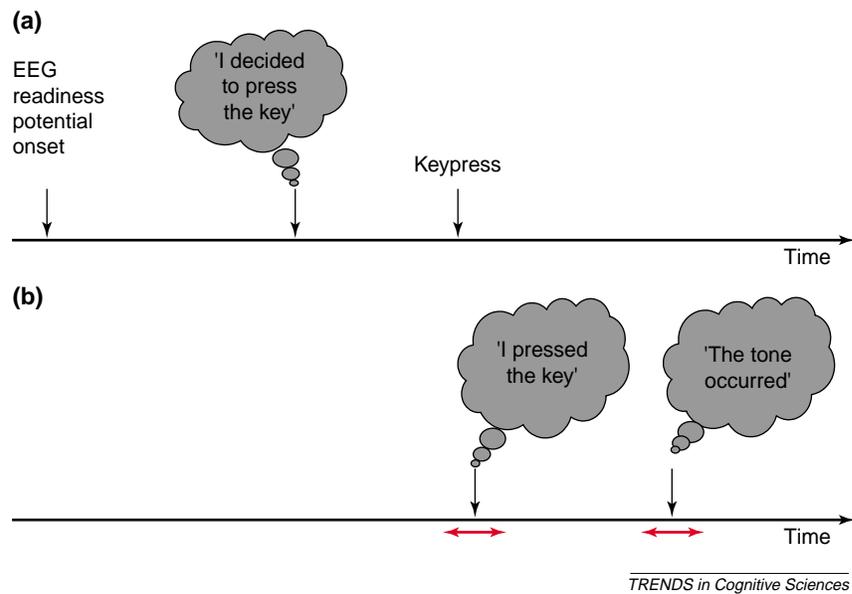
Fig I. The two timelines summarize the relationship between the Haggard *et al.* study and influential studies in its lineage. (a) summarizes the studies of Libet and his colleagues; (b) summarizes the domain of the Haggard *et al.* study. Thought bubbles represent the subjects' reports; that is, when they believed an event occurred. In the experiment, these thoughts did not occur in the same real-time sense as did the readiness potential and the keypress; instead, timing judgments are always made retrospectively. The horizontal red arrows represent the reported shift in timing judgments resulting from manipulation of causality in the Haggard *et al.* experiments.

et al. study to these earlier studies. Neural data is needed in the time window after the keypress to flesh out a general theory.

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b Libet, B. (1993) The neural time factor in conscious and unconscious mental events. In *Experimental and Theoretical Studies of Consciousness* (*Ciba Foundation Symposium No. 174*), pp. 123–137, John Wiley & Sons

c Haggard, P. and Eimer, M. (1999) On the relation between brain potentials and the awareness of voluntary movements. *Exp. Brain. Res.* 126, 128–133

temporal 'attraction' of the tone to the keypress was diminished (Fig. 1).

Does the 'attraction' occur because of the perception that the events were linked by the subjects' agency? To find out, the authors first had to exclude the possibility that judgments of the two events were temporally attracted simply because they occurred on the same trial rather than because they were causally related. This possibility was excluded in two ways. First, transcranial magnetic stimulation (TMS) was administered over motor cortex to create an involuntary movement. Subjects either judged the time of this involuntary movement, or the time of a tone which followed 250 ms later. Unlike the voluntary-movement condition, these events did not shift towards each other temporally. Second, in another control condition ('sham' TMS), the tone was preceded by TMS administered

over left parietal cortex, which was designed to have no noticeable effect on the subjects. In this condition, subjects judged either the time of the audible click of the TMS discharge, or the time of the tone. Again there was no significant 'attraction' of the two events. These control conditions therefore excluded the possibility that the shift was due to the presence of two events on a trial rather than being caused by the two events' intentional linkage.

Haggard *et al.* conclude that when the subjects intentionally made a movement that resulted in a tone, the perceived time of these two events shifted towards each other relative to the perceived time when they occurred alone. From the data in the involuntary (TMS-induced) movement condition, the authors report that the perceived time of the involuntary movement and the subsequent tones

shifted *away* from each other relative to when they occurred alone. Unfortunately, some of these effects are not shown to be statistically significant but, fortunately, in the authors' variable-delay experiment (Fig. 1), the authors replicated one of these effects: as in the first experiment, the tone was judged to occur earlier when it was preceded by the keypress. Taking their two experiments together, the data are persuasive that tones perceived to be a consequence of one's actions seem to occur earlier in time than solitary tones.

A Bayesian explanation?

The idea that events seem to occur earlier when one causes them is an intriguing one. But what could be the reason for this phenomenon? We offer one hypothesis.

Although the illusion might seem maladaptive, we suggest that on average it actually improves one's estimates of

the times of events. The philosopher David Hume pointed out that events that are close together in space and time are more likely than spatiotemporally distant events to be perceived as causally related [8]. With certain assumptions about the prior probabilities, it follows from Bayes' equation that events known to be causally related are more likely to be close in time and space than unrelated events. Therefore, if an organism has some uncertainty (i.e. measurement noise) associated with its estimate of the times of a cause and effect, it should shift its estimates of the times of the cause and effect toward each other. This principle would predict that events known to be causally related should seem to occur closer together in time. People are most sure that events caused by themselves are causally related, so this theory would predict that the illusion would occur in the context of the Haggard *et al.* experiment. Interestingly, this theory would also predict that events unrelated to one's own actions – but nevertheless causally linked – should show temporal attraction. However, the shift in such cases might well be smaller because organisms are typically less sure whether events not linked by their own intentional actions are causally related. As a test of whether observers of causally linked events are subject to the illusion, subjects could make temporal judgments while watching someone else perform Haggard *et al.*'s keypress/tone task.

The future of causality
Further investigation of the representation of causality, intention,

prediction and timing should be able to illuminate a number of important issues in neuroscience and psychology.

One issue is how a shift in perceived time, such as the shift in Haggard *et al.*'s experiment, is represented in the brain. Is a 50-ms shift in perceived time of a tone correlated with a similar temporal shift in the firing of some neuronal population? This notion betrays a commitment to a 'time-encodes-time' representation in the brain, which is likely to be erroneous [9,10], particularly in the light of the fact that the time judgments in the Haggard *et al.* experiments were retrospective. Instead, it seems more likely that the brain encodes time symbolically [11]. Neurophysiological experiments could yield data that would speak directly to this debate (see Box 1).

Several areas of cognitive science could benefit from investigations of timing and causality. For example, schizophrenics can suffer from the belief that some of their own thoughts are caused by someone else, as well as the delusion that unrelated events are attributable to their own agency [12]. Infants need to learn causal relations quickly in order to make sense of their world. Fast motor control is likely to require a feedback loop that continuously monitors one's intended movements and their effects. Finally, consciousness itself might be closely linked to failures of implicit prediction, arising when prediction is imperfect [13]. An exciting aspect of Haggard *et al.*'s recent paper is their demonstration that different theories about causality, intention, and prediction can now be put to experimental test.

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David M. Eagleman*
The Salk Institute For Biological Studies, 10010 N. Torrey Pines Rd, La Jolla, CA 92037, USA.
*e-mail: eagleman@salk.edu

Alex O. Holcombe
Dept of Psychology, University of California, San Diego, La Jolla, CA 92093, USA.
e-mail: holcombe@post.harvard.edu