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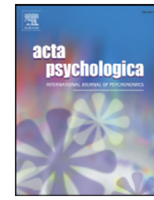

The relation between action, predictability and temporal contiguity in temporal binding

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ABSTRACT

Previous studies have documented a subjective temporal attraction between actions and their effects. This finding, named intentional binding, is thought to be the result of a cognitive function that links actions to their consequences. Although several studies have tried to outline the necessary and sufficient conditions for intentional binding, a quantitative comparison between the roles of temporal contiguity, predictability and voluntary action and the evaluation of their interactions is difficult due to the high variability of the temporal binding measurements. In the present study, we used a novel methodology to investigate the properties of intentional binding. Subjects judged whether an auditory stimulus, which could either be triggered by a voluntary finger lift or be presented after a visual temporal marker unrelated to any action, was presented synchronously with a reference stimulus. In three experiments, the predictability, the interval between action and consequence and the presence of action itself were manipulated. The results indicate that (1) action is a necessary condition for temporal binding; (2) a fixed interval between the two events is not sufficient to cause the effect and (3) *only* in the presence of voluntary action do temporal predictability and contiguity play a significant role in modulating the effect.These findings are discussed in the context of the relationship between intentional binding and temporal expectation.

1. Introduction

1.1. Conditions for intentional binding

Recent studies have demonstrated that intentional actions and their resulting effects are perceived as temporally attracted towards each other, an effect named intentional binding (Cravo, Claessens & Baldo, 2009; Engbert, Wohlschlager, Thomas & Haggard, 2007; Haggard, Aschersleben, Gehrke & Prinz, 2002; Haggard, Clark, & Kalogeras, 2002; Humphreys & Buehner, 2009). Several studies have tried to outline the necessary and sufficient conditions for this effect to occur. For example, voluntary action has been suggested to be a necessary condition, as temporal binding between elements in a sequence of tones or a sequence of actions was reduced or absent (Haggard, Aschersleben, et al., 2002; Haggard & Cole, 2007). In these studies, a condition in which an action and a beep were presented with a 250 ms interval was compared with a condition in which two beeps were presented with the same interval. The results suggest that the interval between action and beep was perceived as significantly smaller than the interval between the two beeps (Haggard, Aschersleben, et al., 2002; Haggard & Cole, 2007). In addition, studies inducing involuntary movements by transcranial magnetic stimulation (TMS) or by mechanically imposing a movement kinematically identical to a keypress did not induce intentional binding (Engbert, Wohlschlager & Haggard, 2008; Haggard & Clark, 2003; Haggard, Clark, & Kalogeras, 2002; Wohlschlager, Engbert, & Haggard, 2003). These results suggest that intentional binding is intrinsically related to voluntary action, and not to muscle activation or somatosensory feedback.

Although voluntary action seems to play a key role in intentional binding, its presence alone is not sufficient. Haggard, Clark, et al. (2002) showed that the binding effect was also modulated by temporal contiguity and temporal predictability between action and consequence. Specifically, intentional binding was stronger when the consequence of the action occurred after 250 ms than after 450 ms or 650 ms. Moreover, when the consequence was presented randomly after one of these intervals instead of after a fixed interval, the effect was reduced as well (Haggard, Clark, & Kalogeras, 2002).

A more general appraisal of intentional binding suggests that the causal relationship between action and effect is a crucial ingredient for the phenomenon to occur (Buehner, 2010; Buehner & Humphreys, 2009; Eagleman & Holcombe, 2002). However, while in a recent work Buehner and Humphreys (2009) have showed that causality is *necessary* for the effect, other findings have suggested that causality

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by itself is not *sufficient* (Cravo et al., 2009). The presence of voluntary action still seems to play a key role in modulating the effect.

Although the original explanation for intentional binding was that "events surrounding voluntary action are bound by a specific cognitive function of the central nervous system" (Haggard, Clark, et al., 2002), other possibilities have not yet been ruled out. Several results have shown that temporal approximation can occur by repeated exposure to non-simultaneous sensory events (Fujisaki, Shimojo, Kashino & Nishida, 2004; Keetels & Vroomen, 2008; Stetson, Xu, Montague & Eagleman, 2006; Vroomen, Keetels, de Gelder & Bertelson, 2004) and between actions and consequences (Stetson et al., 2006; Sugano, Keetels & Vroomen, 2010).

Some argue that the magnitude of temporal approximation between an action and its consequence is larger than between two purely sensory events (Eagleman, 2008; Haggard & Clark, 2003; Stetson et al., 2006); however, a proper quantitative comparison is difficult due to several reasons. Firstly, most studies investigating temporal approximation have an exposure phase, in which participants are presented with several stimulus pairs with a constant time lag, whereas in intentional binding studies, this exposure phase is not commonly used. Secondly, the methodologies used in both kinds of tasks are very different. While temporal approximation studies normally use temporal order or simultaneity judgments, most of the intentional binding literature is based on the rotating spot method. Thirdly, as will further be discussed, the rotating spot method results are highly variable, making a proper quantitative comparison between both effects impossible.

Another possibility for the effect is that the temporal interval between action and consequence is perceived as shorter because the consequence of the action is anticipated and therefore processed faster (Baldo, Cravo & Haddad, 2007). Several studies have indeed shown that when subjects can orient their attention to the instant an event of interest will happen, the event is perceived earlier (Correa, Lupiáñez, Madrid & Tudela, 2006; Nobre, 2001).

In sum, although previous studies have addressed the influence of temporal contiguity, predictability and motor action on intentional binding, they were not able to dissociate the role of each of these factors. For example, when investigating the effect of temporal predictability and contiguity, Haggard, Clark, et al. (2002) only tested conditions in which voluntary action took place, which prevents the important comparison of the influence of these factors on binding in the presence and absence of motor action. Similarly, when Humphreys and Buehner (2009) showed, contrary to Haggard's results, that the intentional binding increased for longer intervals, they also confounded temporal predictability and contiguity. As they always used mixed intervals in their experimental blocks, a possible interaction between these two factors may have been overlooked.

1.2. Current methodologies for the investigation of intentional binding

The majority of studies (Engbert & Wohlschlaeger, 2007; Haggard, Aschersleben, et al., 2002; Haggard & Clark, 2003; Haggard & Cole, 2007; Moore & Haggard, 2008; Wohlschlager, Engbert, et al., 2003; Wohlschlager, Haggard, Gesierich & Prinz, 2003 on intentional binding have used the rotating spot method originally implemented by Libet and colleagues (1983). The basic procedure in this methodology is to ask participants to report the position of a clock hand at the time an event occurred. Which events are measured depends on the experiment, but include the time of an external stimulus (tone and somatic stimulation) and the time of a voluntary action. These subjective temporal judgments can then be compared with the actual instant when the judged event occurred. Although the rotating spot method has been used in a large number of studies, it can be criticized in several aspects (Gomes, 2002; Pockett & Miller, 2007). Monitoring the clock demands a lot of attention and may distract from the normal cognitive processes underlying action control (Engbert et al., 2007). Also, several studies have shown that comparison between a moving (clock hand) and an abrupt event (a tone) can lead to spatiotemporal illusions, such as the flash-lag effect, in which a moving object is perceived as being ahead of its original position when the abrupt event happens (Baldo & Klein, 1995; Cravo & Baldo, 2008; Nijhawan, 1994).

Another criticism of this methodology is the high variability in temporal estimates. For example, Haggard, Clark, et al. (2002) found effects of 46 ms and of 96 ms, using identical stimulation. Although this variability does not speak against intentional binding as a qualitative phenomenon, it does hinder any kind of quantitative comparison between different conditions.

Because the rotating spot method was heavily criticized, direct numerical judgments of the time interval between action and effect are gaining increasing acceptance (Cravo et al., 2009; Engbert et al., 2008, 2007; Humphreys & Buehner, 2009). In this kind of task, subjects are asked to give direct numerical estimates of the interval between the events to be judged. This method has reproduced the basic properties of intentional binding, such as its dependence on intentional action (Engbert et al., 2008, 2007). However, it can argued that this method is subject to cognitive or response biases. When asked to judge the interval between an action and its consequence, subjects can give shorter estimates based on the belief that these events should happen close in time, and not because they actually experienced them together.

Moreover, recent findings using this method suggested that intentional binding occurs over intervals far greater than those previously explored, up to 4 seconds between action and consequence (Humphreys & Buehner, 2009). This result is contrary to the findings using the rotating spot method, in which the intentional binding decreased for intervals of 450 and 650 ms (Haggard, Clark, et al., 2002).

1.3. Objectives

In the present manuscript we present three fully factorial experiments designed to dissociate the influence of each one of these factors on temporal binding and to evaluate their interactions. We propose a new methodology based on simultaneity judgments to measure temporal binding. In our experiments, subjects observed a tone after executing an action (a finger lift) and a temporally independent flash, and judged whether the two stimuli, tone and flash, were simultaneous or not. We compared these results with conditions: (1) where no action was necessary; (2) under different levels of predictability; and (3) with different intervals between the events.

While our methodology is still an event-timing method, we believe that it is not susceptible to the criticisms against the rotating spot method. Although one might argue that the task is still attentional demanding, the fact the only two abrupt events are used means that subjects no longer have to continuously keep track of a moving stimulus. Moreover, no flash-lag exists in our task. Therefore, our task allows a better measurement and interpretation of the interrelation between voluntary action, temporal predictability and contiguity in provoking temporal binding.

2. Experiment 1

2.1. Participants

Eleven volunteers took part in four experimental sessions administered on different days. Visual acuity was normal or corrected to normal, and all participants reported normal hearing. They were naive as to the purpose of the experiment. They varied in their previous experience with psychophysical testing procedures. Each session took approximately 30 min to complete.