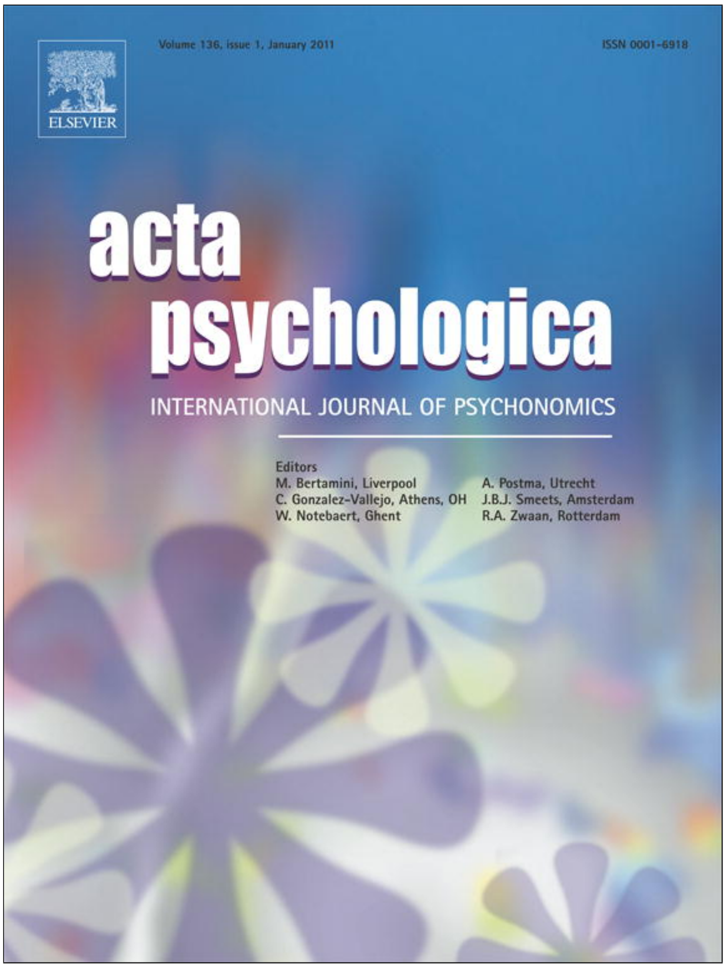

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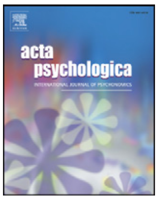

The relation between action, predictability and temporal contiguity in temporal binding

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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.

2.2. Apparatus and stimuli

The experiment took place in a dimly lit, quiet room. Stimuli were presented on a 19″ monitor (refresh rate 100 Hz). Stimulus presentation was controlled by a program for psychophysical experimentation, *E-prime software* (Schneider, Eschman & Zuccolotto, 2002). A white dot (radius 0.1° visual angle) was presented centrally as fixation point. The flash consisted of a white disk (0.15° radius, 10 ms duration, presented in the centre of the screen). The auditory stimulus was a tone of 1000 Hz, 65 dB and 10 ms duration.

2.3. Design

Each trial started with the presentation of the fixation point (Fig. 1A). In *Action* sessions, the fixation point remained on screen until the volunteer lifted the right-index finger.[1] In *Action-Fixed Interval* sessions, the beep was always presented 250 ms after the volunteer's action (Fig. 1B). The flash, on the other hand, was presented at one out of thirteen stimulus onset asynchronies relative to the beep (SOAs: 0, ±25, ±50, ±75, ±100, ±125 and ±200 ms, each SOA being presented in 12 trials). The sign of the SOA refers to the temporal order of auditory and visual stimuli. For example, an SOA of +25 ms means that the flash was presented 25 ms after the beep. An SOA of −25 ms means that the flash was presented 25 ms *before* the beep, and thus 225 ms after the volunteer's action. In trials with an SOA of 0 ms, beep and flash coincided in time, both in their onset and offset. In all fixed interval sessions, the beep was always presented 250 ms after the right-index finger lift, independent of sign and value of SOA. The main purpose of keeping the interval between action and beep constant was to make the beep more predictable.

In *Action-Random Interval* sessions, the beep sounded at a random interval between 250 and 750 ms after the voluntary action. In this session, both stimuli, flash and beep, were unpredictable, since the interval between the volunteers' action and the onset of the stimuli was random.

In *No Action* sessions, the fixation point lasted between 1000 and 2000 ms instead of until a voluntary act. In *No Action-Fixed Interval* sessions, the beep was presented 250 ms after the disappearance of the fixation point. As in the *Action-Fixed Interval* session, the objective of the beep being presented after a fixed interval relative to the disappearance of the fixation point was to examine whether this predictability might modulate the subjective latency of the beep. In *No Action-Random Interval* sessions, the beep was presented randomly between 250 and 750 ms after the disappearance of the fixation point.

In all sessions, the participants' task was to judge whether the beep and the flash were presented simultaneously or successively, without further specification of perceived order. Participants made an unspeeded response by pressing one of two designated keys on a keypad. We favoured simultaneity instead of temporal order judgment because the former is less susceptible to response bias (van Eijk, Kohlrausch, Juola & van de Par, 2008; Zampini, Guest, & Shore, 2005; Zampini, Shore, & Spence, 2005). For example, when in doubt, subjects could be biased toward answering that the beep, which was the consequence of their action, was presented before the flash, according to a subjective logic. However, a bias towards either the "simultaneous" or "non-simultaneous" response categories will not affect temporal binding magnitude estimates.

2.4. Procedure

Before each experimental session, all participants completed two blocks of 30 practice trials, in which the participants' task was to judge whether the beep and the flash were presented simultaneously or successively. To facilitate task learning, only three SOAs were used in the practice blocks (first block: −250, 0 and 250 ms; second block: −125, 0 and 125 ms).

One of the major concerns in our experimental design was to ensure that the volunteers would associate their voluntary action with the beep`s onset in *Action* conditions and the disappearance of the fixation point with the beep's onset in *No Action* conditions. In experiments involving recalibration of temporal order perception by exposure to stimulus asynchrony, the common procedure is to habituate the volunteer with pairs of non-simultaneous stimuli before each trial or experimental block (Fujisaki et al., 2004; Keetels & Vroomen, 2008; Vroomen et al., 2004). Based on that methodology, our volunteers were also exposed to a block of 20 adaptation trials at the start of each experimental block. These trials were similar to the experimental trials, but, instead of both flash and beep being presented after the voluntary action—or the disappearance of the fixation point, in *No Action* sessions—only the beep was presented (Fig. 1C). In 80% of the adaptation trials, the beep was similar to the beep used in experimental trials (1000 Hz, 65 dB). In the remaining 20% the beep had a lower frequency (500 Hz, 65 dB). The participant's task in this adaptation block was to report after each trial which tone had been presented. The objective of this task was to ensure that participants attended to the tone. In *Random Interval* the adaptation phase also had a random interval between the events. The adaptation phase was present in all conditions, to make them comparable.

Additionally, to maintain the relationship between the beep onset, and the preceding voluntary action (*Action* sessions) or fixation point disappearance (*No Action* sessions), the beep was presented without flash in "catch trials" composing approximately 30% of the experimental trials. Subjects were instructed to respond randomly in these trials. The purpose was to have the participants preserve the association between action or fixation point disappearance and beep throughout the experimental session, as is commonly done in temporal recalibration experiments, a strategy known as top-up adaptation (Keetels & Vroomen, 2008; Sugano et al., 2010; Vroomen et al., 2004).

All participants completed all four experimental sessions (*Action-Fixed Interval*, *No Action-Fixed Interval*, *Action-Random Interval*, and *No Action-Random Interval*). Each session consisted of two practice blocks and four experimental blocks. Each experimental block consisted of 20 adaptation trials followed by 55 experimental trials. Thus, each experimental session had a total of 220 experimental trials, out of which 64 were catch trials, and the other 156 (13 SOAs × 12 presentations) were actual trials.

2.5. Results

The evolution of the proportion "simultaneous" responses as a function of stimulus onset asynchrony was analyzed under a generic perceptual decision model based on common elements of signal detection theory (e.g., Green & Swets, 1966). We assumed that the measure of interest for a simultaneity judgment, the temporal interval, would be internally coded as a variable subject to normally distributed noise (variance σ^2). This noisy internal representation, say, x, is then compared against an interval bounded by a lower and an upper criterion for simultaneity (Fig. 2A). Specifically, when x falls within an interval with a given length, a critical half-interval κ, below or above simultaneity, the observer gives a "simultaneous" response. In the other case, the response is "non-simultaneous" without further qualification. The internal representation of the temporal interval is shifted relative to physical time because of experimental

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[1] To measure the finger lift we used an infrared light beam. In resting position, the finger obstructed this infrared light beam. Upon lifting the finger, the beam activated an electronic switch through an infrared sensor. We preferred finger lifts over finger presses because the former did not cause any sound when executed. The sound caused by a finger press might have influenced the effects we were interested in measuring.

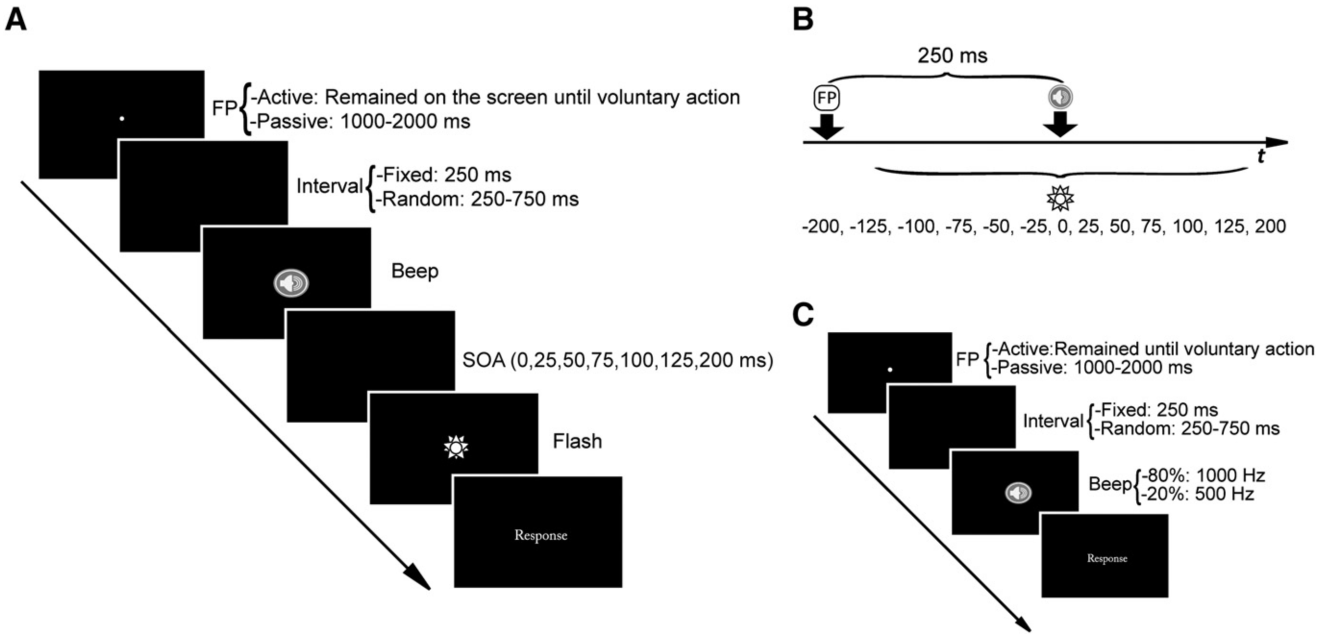

Fig. 1. A) Schematic representation of an experimental trial. The fixation point disappeared after a certain period (*No Action* sessions) or after voluntary action (*Action* sessions). After an interval that depended on the experimental session, the two stimuli were presented with different SOAs. The subjects' task was to judge if both stimuli were presented simultaneously or not. B) Temporal relation between the fixation point (FP) and the beep in *Fixed Interval* sessions. The beep was always presented 250 ms after the disappearance of the fixation point, whether the session was *Action* or *No Action*. C) Schematic representation of an adaptation trial. The fixation point disappeared after a certain period (*No Action* sessions) or after a voluntary action (*Action* sessions). After an interval that depended on the experimental session, a beep was presented. The subjects' task was to judge whether the beep presented was a high- or a low-pitch one.

manipulations and, possibly, a fixed visual/auditory latency difference. Without taking other factors into account, this would mean that the probability of a "simultaneous" response is formally equivalent to the area under a normal distribution centred on the SOA, bounded by κ below and above an internal point of subjective simultaneity.

In pilot experiments, it had become evident that subjects would typically not respond 100% non-simultaneous to stimuli that were very clearly separated in time. This means that, possibly because of attention lapses, subjects sometimes gave random responses. As recommended by Wichmann and Hill (2001—but here with different parameterization), this factor was accounted for in the data model by the inclusion of a lapse rate λ. In lapse trials, subjects would respond "simultaneous" at a guess rate γ, representing a pure response bias relative to this category. The model as a whole has a shape that deviates somewhat from other simultaneity models such as the scaled bell shape used by some other research groups (Fujisaki et al., 2004; van Eijk et al., 2008; Vroomen et al., 2004; Zampini, Guest, et al., 2005). The predicted proportions "simultaneous" for extremely negative or extremely positive SOAs, the left and right lower asymptotes, are the product of guess and lapse rate ($\lambda \times \gamma$). The informative parts of the model are symmetrical psychometric curves, the left of which increases as a rescaled Gaussian distribution function up to a maximum at SOA = PSS (Point of Subjective Simultaneity), and the right of which decreases at the same rate for SOA > PSS (Fig. 2B). This model is flexible and allows for a ceiling proportion $(1-\lambda)$ $(1-\gamma)$ of "simultaneous" responses over an arbitrarily wide range of the SOA scale, which would not have been possible with an unmodified bell curve. In this model, the noise variance σ^2 steers the inclination of the left and right curves: the larger the noise variance, the shallower the slopes. One can think of this parameter as the inverse of subject-dependent temporal representation accuracy. For example, lower values of σ indicate that small increases of the SOA would drastically change the proportion of simultaneous/non-simultaneous responses near the simultaneity criterion. On the other hand, high values of sigma indicate that the proportion of simultaneous/non-simultaneous responses would only change after large changes of the SOA.

The observed distributions of responses were fitted according to this framework for each participant and condition (Fig. 2B). Responses were modelled as binary outcomes with as predicted "simultaneous" probability:

$$Pr(\text{"simultaneous"}) = \lambda \times \gamma + (1-\lambda) \times \int_{\alpha-\kappa}^{\alpha+\kappa} \varphi_{norm}\left(x, \mu = SOA, \sigma^2\right) dx$$

where λ is the lapse rate, γ is the guess rate, κ is the volunteer's simultaneity criterion, *alpha* (α) refers to the PSS and *sigma* (σ) is inversely related to the slope of the curves. A single lapse (λ), guess (γ) and criterion (κ) were estimated for each participant, along with four PSS (α) and four noise standard deviations (σ), one for each experimental session.

Parameters were estimated by a maximum likelihood procedure written in R, using its implementation of a quasi-Newton optimization method, with sensible boundary values to facilitate convergence (L-BFGS, software and documentation at R-project.org).

The statistical analysis of the obtained estimates consisted of a repeated measures analysis (linear mixed model) run under SAS Procedure MIXED (SAS Institute, Cary, NC, USA). Two separate analyses were performed, one with sigma and one with PSS (α) as the dependent variable. Based on Akaike's Information Criterion, a compound symmetry covariance structure was chosen for both analyses. The Satterthwaite method was used to generate the approximate denominator degrees of freedom (Littell, Milliken, Stroup & Wolfinger, 1996). The PSS and sigma values were each submitted to two-way within-participants ANOVA with the factors Action (*Action* versus *No Action*) and Interval Type (*Fixed* versus *Random*).

The analysis of sigma estimates did not indicate significant main effects of either *Action* ($F_{(1,30)} = 0.81$; $p > 0.35$) or *Interval Type* ($F_{(1,30)} = 0.71$; $p > 0.4$). Also the interaction between the two factors was not found to be significant ($F_{(1,30)} = 0.06$; $p > 0.8$). Our results suggest that

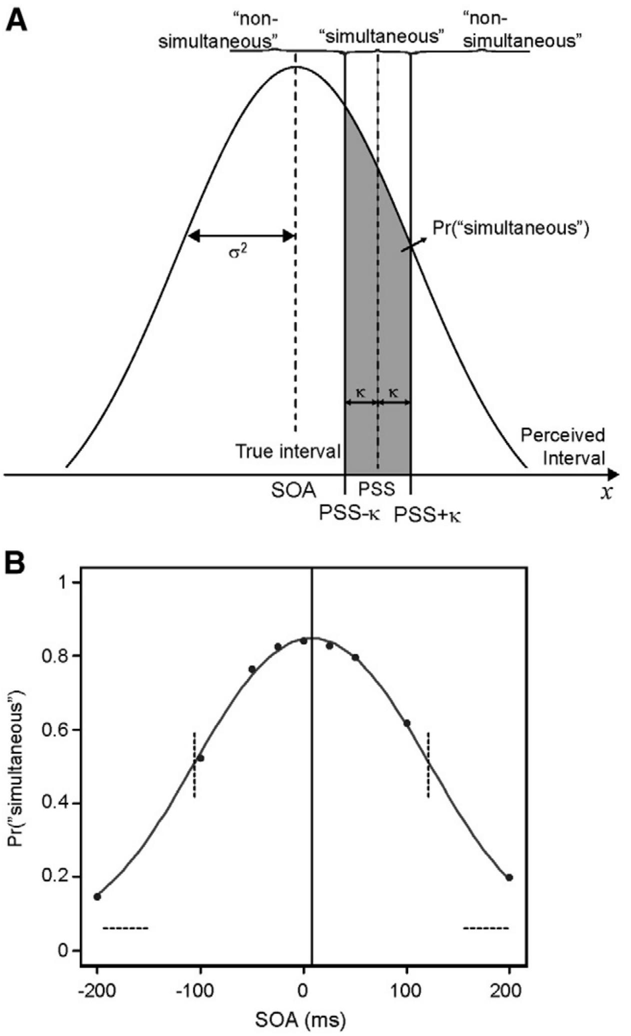

Fig. 2. A) Graphical representation of the model for simultaneity judgment. The perceived interval, X, is distributed as a normal distribution with spread σ around the true event interval, SOA. The interval percept is compared against a simultaneity point PSS; a 'simultaneous' evaluation is made when X falls within a region κ of the PSS. Note that the resulting probability of a simultaneity response (area under the density function in the PSS ± κ interval, corresponding to the ordinate in B) is symmetric around SOA = PSS, and that the probability is at maximum at this point. B) Simultaneous response proportions aggregated across conditions and observers as a function of SOA (ms). The horizontal dashed lines represent the product of guess and lapse rate. Vertical dashed lines represent the criterion κ and the vertical solid line represents the PSS.

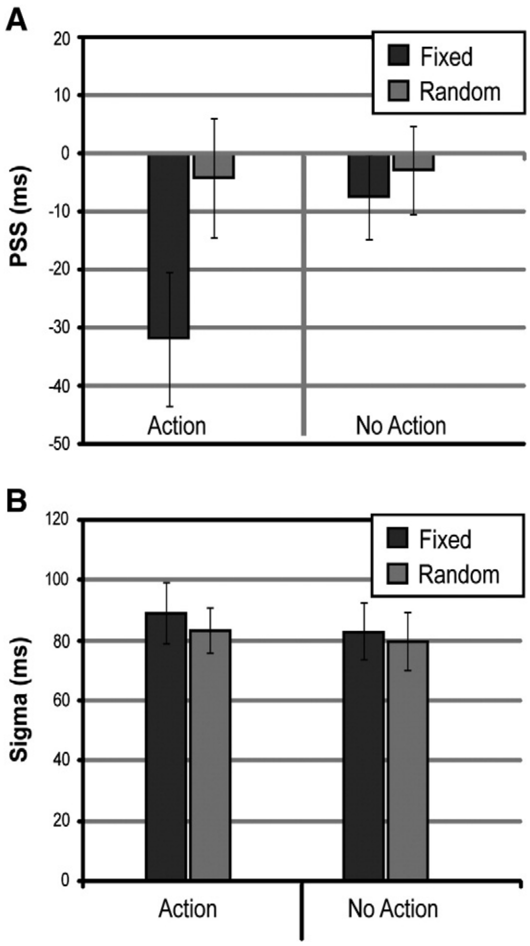

Fig. 3. A) Mean ± S.E.M. of the PSSs values obtained in Experiment 1. Negative (positive) values indicate that the beep's (flash) latency was smaller. B) Mean ± S.E.M. of the sigma values obtained in Experiment 1.

the temporal accuracy of interval judgments did not change across conditions (Fig. 3).

The PSS values indicate the SOA between beep and flash in which subjects had the highest impression of simultaneity, as estimated by the model. Fig. 3A shows that all PSS were negative, suggesting that the flash always had to be presented *before* the beep to be perceived as simultaneous. An even more negative PSS was found in the *Action-Fixed Interval* session, suggesting that in this case, the flash had to be presented even earlier than the beep. This finding is in agreement with intentional binding. If the beep is being perceived closer to the action that caused it, and therefore, earlier than in other conditions, the flash has to be presented even earlier to be perceived as simultaneous to the beep.

The analysis of the PSS revealed a significant main effect of *Action* ($F_{(1,30)} = 6.79$; $p<0.05$) and *Interval Type* ($F_{(1,30)} = 10.63$; $p<0.001$). The interaction between the two factors was significant as well ($F(1,30) = 5.49$; $p<0.05$). Fig. 3 illustrates that both main effects and interaction arose due to the difference between the *Action-Fixed Interval* and the other experimental conditions. A post-hoc pairwise comparison based on a Bonferroni procedure with Hommel correction (Shaffer, 1995) was applied to compare all four experimental conditions. The results indicate that the beep was perceived significantly earlier in *Action - Fixed Interval* conditions when compared with the other three conditions ($p<0.05$). No other significant differences were found (Fig. 3).

2.6. Discussion

Our results revealed that when subjects caused a beep that was always presented 250 ms after their action, the perceived delay between action and beep decreased. In these conditions, the flash had to be presented approximately 30 ms before the beep for both stimuli to be perceived as being simultaneous. In all other conditions, the flash had to be presented less than 10 ms before the beep for them to be perceived simultaneously. Therefore, the difference between the large negative PSS found in *Action-Fixed Interval* and the other conditions represents the magnitude of intentional binding in our experiments.

The mere presence of voluntary action in the *Action-Random Interval* was not enough to modulate the PSS. These results are in agreement with the findings of Haggard in intentional binding (Haggard, Clark, et al., 2002). We only found the effect when both factors—voluntary action and temporal predictability—were present. These main effects corroborate earlier findings regarding the existence and basic properties of intentional binding. The interaction—the fact that binding only takes place for predictable and self-provoked consequences—clarifies how these factors jointly determine the emergence of binding.

No modulation by predictability was found in *No Action* sessions,[2] in agreement with previous studies (Haggard, Aschersleben, et al., 2002; Haggard & Cole, 2007). As discussed earlier, some experiments have been designed to compare the effects of action and predictability in intentional binding. The majority of these experiments compare the temporal judgment of a beep caused by an action with the temporal judgment of a beep preceded by another beep. This type of methodology failed to find a modulation by predictability of the temporal perception of the second beep by the antecedent beep.

The lack of modulation by temporal predictability in our *No Action* conditions and in other experiments (Haggard, Aschersleben, et al., 2002; Haggard & Cole, 2007) may have been caused by a methodological issue, related to the duration of the intervals. While 250 ms between action and beep seems to be enough to cause intentional binding, it might be too short to allow for attentional modulation. Most studies in temporal attention use longer intervals, ranging from 600 to 1400 ms (Nobre, 2001). A longer interval might be necessary in *No Action* conditions due to an inherent difference with the *Action* conditions. In *Action* conditions, it is the subject himself/herself who triggers the action, so although the consequence happens 250 ms after the action, other processes (notably attentional allocation and temporal preparation for stimulus onset) can start during the motor preparation. Even if a similar mechanism should take place in *No Action* conditions, 250 ms might be too short for it to occur.

Another possible objection to Experiment 1 are the values of the Interval in *Random Interval* sessions. It can be argued that a random value range between 250 and 750 ms is too broad. Moreover, the random interval was always longer than the fixed interval. Different effects can take place in these intervals and potentially mask or confound each other. Experiment 2 compensates for both objections by using: (1) two fixed intervals (300 ms and 600 ms) between action (or disappearance of fixation point) and beep, to test if a longer interval in *No Action* sessions would result in a temporal approximation between the mentioned events; (2) in random interval conditions we used the same two intervals but presented randomly within the block.

3. Experiment 2

3.1. Participants

Twelve volunteers took part in this experiment. Visual acuity was normal or corrected to normal, and all participants reported normal hearing. All were naive as to the purpose of the experiment.

3.2. Apparatus and stimuli

The experimental setup of Experiment 2 was identical to the setup of Experiment 1.

3.3. Design

Experiment 2 was similar in design to Experiment 1. The main difference was the existence of only nine SOAs[3] (SOAs—0, ±50, ±100, ±125 and ±200 ms, each SOA being presented in 12 trials) and the configuration of the sessions. Each volunteer participated in six experimental sessions. In *Action* sessions, as in Experiment 1, the fixation point remained on the screen until the volunteer made a right-index finger lift. In *Action-Fixed Interval* sessions, the beep was always presented 300 ms (*Action-Fixed Interval—Short*) or 600 ms (*Action-Fixed Interval—Long*) after the voluntary action. The flash was presented with one out of the nine possible SOAs relative to the beep. In *Action-Random Interval* sessions, the beep was presented randomly 300 ms or 600 ms after the voluntary action. The principal difference between *Fixed Interval* and *Random Interval* sessions was whether the intervals between action and beep were constant or intermixed. In *Fixed Interval* blocks, the interval was constant during all trials within an experimental session. In *Random Interval* blocks, the interval was 300 ms in half of the trials and 600 ms in the other half of the trials, in random permutation throughout the experimental session. It is important to stress that, differently from Experiment 1, where the interval could assume any value in between 250 and 750 ms in the *Random Interval* session, the interval in Experiment 2 was always either 300 or 600 ms.

In *No Action* sessions, the fixation point lasted for a random interval ranging from 1000 to 2000 ms. The beep could be presented 300 or 600 ms after its disappearance, either at a fixed or random interval, depending on the experimental session. In all sessions, the participants' task was to judge whether the beep and the flash were presented simultaneously or successively. Participants made an unspeeded response by pressing one of two designated keys on a keypad.

3.4. Procedure

The procedure of Experiment 2 was similar to the procedure applied in Experiment 1. However, instead of completing four experimental conditions, each participant completed six experimental conditions. Each session consisted of two practice blocks and three experimental blocks, with the exception of *Random Interval* sessions, which consisted of six experimental blocks. Each experimental block consisted of 20 adaptation trials followed by 55 experimental trials. Consequently, in *Fixed Interval* sessions, subjects completed 165 trials, out of which 47 were catch trials, and the other 108 were experimental trials (9 SOAs × 12 presentations). *Random Interval* sessions were composed of six experimental blocks instead of three, totaling 330 trials, out of which 94 were catch trials and 216 were experimental trials (9 SOAs × 12 presentations × 2 intervals).

3.5. Results

The observed distribution of responses was fitted for each participant using the same function as in Experiment 1, yielding, except for guess and lapse estimates, individual PSS and sigma values for each condition. The statistical analysis was similar to the mixed ANOVA applied in Experiment 1. The PSS and sigma values were each submitted to three-way within-participants ANOVA with the factors *Action* (*Action* versus *No Action*), *Interval Type* (*Fixed* versus *Random*) and *Interval Duration* (*Short* versus *Long*).

Analysis of sigma did not reveal any significant main effect or interaction: *Action* ($F_{(1,77)}=1.1$; $p>0.2$), *Interval Type* ($F_{(1,77)}=0.14$; $p>0.7$), *Interval Duration* ($F_{(1,77)}=0.56$; $p>0.45$); Two-way interactions: *Action × Interval Type* ($F_{(1,77)}=2.13$; $p>0.14$), *Action × Interval Duration* ($F_{(1,77)}=1.99$; $p>0.15$), *Interval Type × Interval Duration* ($F_{(1,77)}=1.25$; $p>0.26$); Three-way interaction: *Action × Interval Type × Interval Duration* ($F_{(1,77)}=0.03$; $p>0.85$). These results suggest that temporal accuracy did not change across conditions (Fig. 4B).

Analysis of the PSS did not reveal significant main effects of *Action* ($F_{(1,77)}=0$; $p>0.95$) or *Interval Duration* ($F_{(1,77)}=0.56$; $p>0.45$), but did show a significant main effect of *Interval Type* ($F_{(1,77)}=9.65$; $p<0.01$). The two-way interaction between *Action* and *Interval Duration* was not significant ($F_{(1,77)}=0.4$; $p>0.53$). The other two-way interactions had marginal significance: *Action × Interval Type* ($F_{(1,77)}=3.78$; $p=0.06$);

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[2] It could be argued that our passive condition does not involve the same sensorimotor events as the action condition, and that this might explain the lack or reduction of binding. However, the literature shows that sensorimotor pattern is not the factor that produces intentional binding: as mentioned previously, studies in which sensorimotor events were passively mimicked by mechanically imposing a movement kinematically identical to a keypress, did not induce intentional binding either (Engbert et al., 2008; Wohlschlager, Engbert, et al., 2003).

[3] In Experiment 1, we noticed that some of the 13 SOA values did not increase the amount of information we could extract from subject's performance. Therefore, we preferred to use 9 SOAs chosen strategically to gain the same amount of information in shorter experimental sessions.

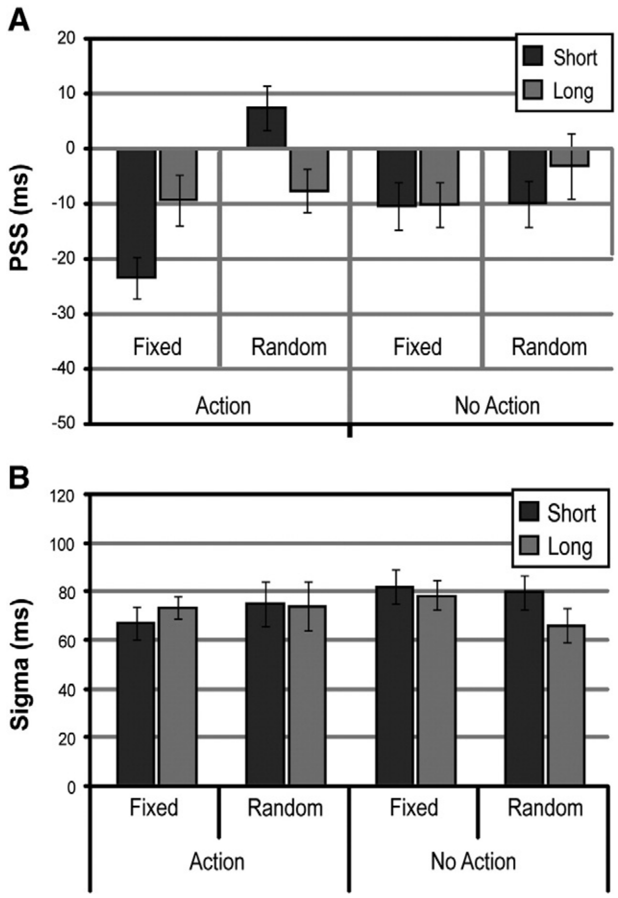

Fig. 4. A) Mean ± S.E.M. of the PSSs values obtained in Experiment 2. Negative (positive) values indicate that the beep's (flash's) latency was smaller. B) Mean ± S.E.M. of the sigma values obtained in Experiment 2.

Interval Type × *Interval Duration* ($F_{(1,77)} = 3.07$; $p = 0.08$). Importantly, the three-way interaction was significant ($F_{(1,77)} = 7.58$; $p < 0.01$).

To examine the corresponding highly significant three-way interaction, we used simple main effects analysis (Schabenberger, Gregoire & Kong, 2000). While main effects are contrasts of sums (averages) and interactions are contrasts of contrasts, simple main effects are contrasts among cell means where one factor is held fixed (Schabenberger et al., 2000). We applied simple main effects analysis to observe how the factors *Interval Type* and *Interval Duration* influenced the PSS within the *No Action* and the *Action* sessions (Littell et al., 1996). The results showed that within *No Action* sessions, the factors *Interval Type* and *Interval Duration* did not significantly modulate the PSS ($F_{(3,77)} = 0.60$, $p > 0.60$). However, within *Action* sessions, these factors *did* significantly modulate the PSS ($F_{(3,77)} = 7.64$, $p < 0.01$).

A *post-hoc* Bonferroni-based comparison with Hommel correction (Shaffer, 1995) within the *Action* session revealed a significant difference between almost all pairwise comparisons, with the exception of *Action-Fixed Interval—Long* with *Action-Random Interval—Long* ($p > 0.7$) and a nearly significant difference between *Action-Fixed Interval—Short* and *Action-Fixed Interval—Long* ($p = 0.06$).

We additionally compared the *Action-Fixed Interval—Short* condition of Experiment 2 with *Action-Fixed Interval* of Experiment 1, to see if they yielded similar values. Our results showed that there was no significant difference between the PSS as measured in these conditions ($t_{(21)} = 0.74$, $p > 0.45$).

3.6. Discussion

The results of Experiment 2 are in agreement with the main findings of Experiment 1. No effect of predictability was found in the absence of action. In *No Action-Fixed Interval* sessions, neither short nor long intervals between fixation point disappearance and beep were able to modulate the perceived latency of the beep.

In *Action* sessions, as in Experiment 1, the largest modulation occurred in the *Fixed Interval—Short* condition. The size of the intentional binding effect was similar to the magnitude obtained in Experiment 1. Additionally, the effect was shown to depend on temporal predictability and temporal contiguity, supporting results found by Haggard, Clark, et al. (2002). An unexpected finding was the increase of the beep latency in *Action - Random Interval—Short* conditions. We will return to this result in the general discussion.

Similar to Experiment 1, no significant modulation of the PSS was found in *No Action* conditions. Several studies of temporal attention have found shorter reaction times to stimuli using cue-target intervals of 600 ms, suggesting that temporal predictability can reduce perceptual latencies (Correa et al., 2006; Nobre, 2001). Even though our experiments do not use reaction times, we could still expect a similar modulation of the perceptual beep latencies in our results.[4] A possible methodological problem in our experimental procedure is that the temporal marker in the *No Action* condition is the *disappearance* of the fixation point. Most temporal attention studies use the *appearance* of a stimulus as a cue to indicate a temporal interval at which the target has a larger probability of being presented. Possibly the appearance of a stimulus is easier to use a temporal marker than its disappearance. This possibility was tested in Experiment 3.

4. Experiment 3

4.1. Participants

Ten volunteers took part in four experimental conditions. Visual acuity was normal or corrected to normal, and all the participants reported normal hearing. All participants were naive as to the purpose of the experiment. Each session lasted approximately 30 min.

4.2. Apparatus and stimuli

The apparatus and stimuli of Experiment 3 were similar to those used in Experiment 1 and Experiment 2.

4.3. Design

The design of Experiment 3 was very similar to the setup of Experiment 2. The main difference was that subjects performed only *No Action* conditions. In all sessions, the trial started with the presentation of a grey fixation point in the centre of the screen (Fig. 5). After a period of 1000–2000 ms, the fixation point turned white. In *Fixed Interval* conditions, the beep was always presented 300 ms (*Fixed Interval—Short*) or 600 ms (*Fixed Interval—Long*) after the fixation point turned white. The flash was presented at one out of the nine possible SOAs relative to the beep. In *Random Interval* conditions, the beep was randomly presented 300 ms or 600 ms after the fixation point turned white.

4.4. Procedure

The procedure of Experiment 3 was similar to the procedure of Experiment 2. However, instead of completing six experimental sessions, each participant completed two experimental sessions. Each session consisted of two practice blocks and three experimental blocks, with the exception of *Random Interval* sessions, which were composed of six experimental blocks. Therefore, in *Fixed Interval*

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[4] Another possibility is that the effect of temporal attention on reaction time is not at the level of perceptual latencies, but rather on motor process or decisional stages (Hackley, 2009; Hackley, Schankin, Wohlschlaeger & Wascher, 2007).

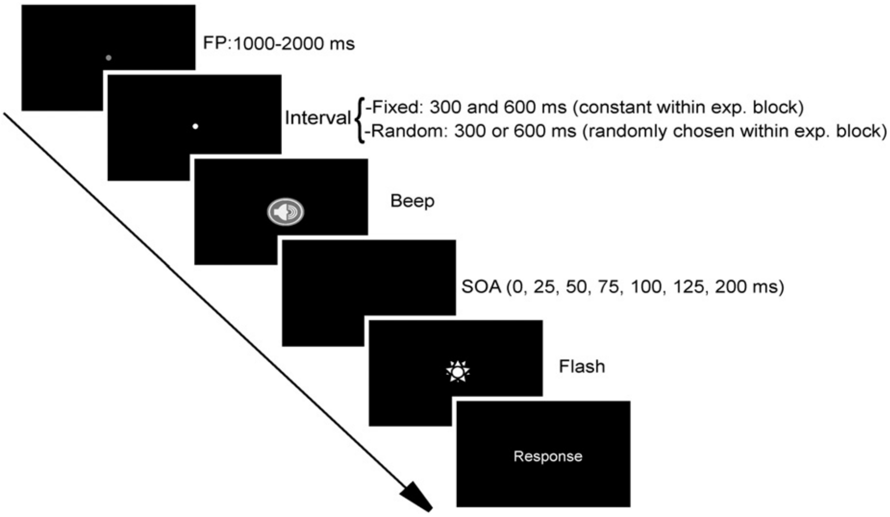

Fig. 5. Schematic representation of an experimental trial. The fixation point turned from grey to white after a certain period. After an interval that depended on the experimental session, the two stimuli were presented with different SOAs. The subjects' task was to judge if both stimuli were presented simultaneously or not.

sessions, subjects completed 165 trials, out of which 47 were catch trials, and the other 108 (9 SOAs × 12 presentations) were experimental trials. *Random Interval* sessions were composed of six experimental blocks instead of three, with a total of 330 trials, out of which 94 were catch trials and 216 were experimental trials (9 SOAs × 12 presentations × 2 intervals).

4.5. Results

The observed distribution of responses was fitted for each participant using the same function as in Experiment 1 and Experiment 2. The PSS and sigma values were each submitted to two-way within-participants ANOVA with the factors *Interval Type* (*Fixed* versus *Random*) and *Interval Duration* (*Short* versus *Long*). Analysis of sigma data did not reveal a significant main effect of either *Interval Duration* ($F_{(1,27)} = 1$, $p > 0.3$) or *Interval Type* ($F_{(1,27)} = 2.0$, $p > 0.16$), neither a significant interaction ($F_{(1,27)} = 0.02$, $p > 0.87$). Neither did the analysis of the PSS also reveal a significant effect of *Interval Duration* ($F_{(1,27)} = 0.37$, $p > 0.54$), *Interval Type* ($F_{(1,27)} = 0.18$, $p > 0.67$) or the interaction between them ($F_{(1,27)} = 0.13$, $p > 0.72$). These results suggest that neither temporal resolution nor PSS changed across conditions (Fig. 6).

4.6. Discussion

Experiment 3 replicated the basic findings of *No Action* sessions in Experiment 2. There was no effect of temporal predictability, nor of temporal contiguity on the PSS. Therefore, the absence of modulation in *No Action* sessions in Experiment 2 cannot be attributed to a weak temporal marker. One could argue that a change in appearance (or in our experiment, the change of colour of the fixation point) might also be a weak temporal marker. However, several temporal attention studies have used similar stimuli as cues. These studies found shorter reaction times to targets presented in the cued temporal interval (Correa et al., 2006; Nobre, 2001). It seems that subjects *are* able to use this kind of stimuli as efficient temporal markers.

Although we did not find a modulation of the beep by temporal predictability in our experiments, other studies have shown that repeated exposure to non-simultaneous sensory events can induce temporal approximation (Fujisaki et al., 2004; Keetels & Vroomen, 2008; Vroomen et al., 2004). One difference between most temporal recalibration experiments and our procedure is the presence of a re-exposure trial before each experimental stimulus. Possibly, because our experiments did not have this re-exposure trial, temporal

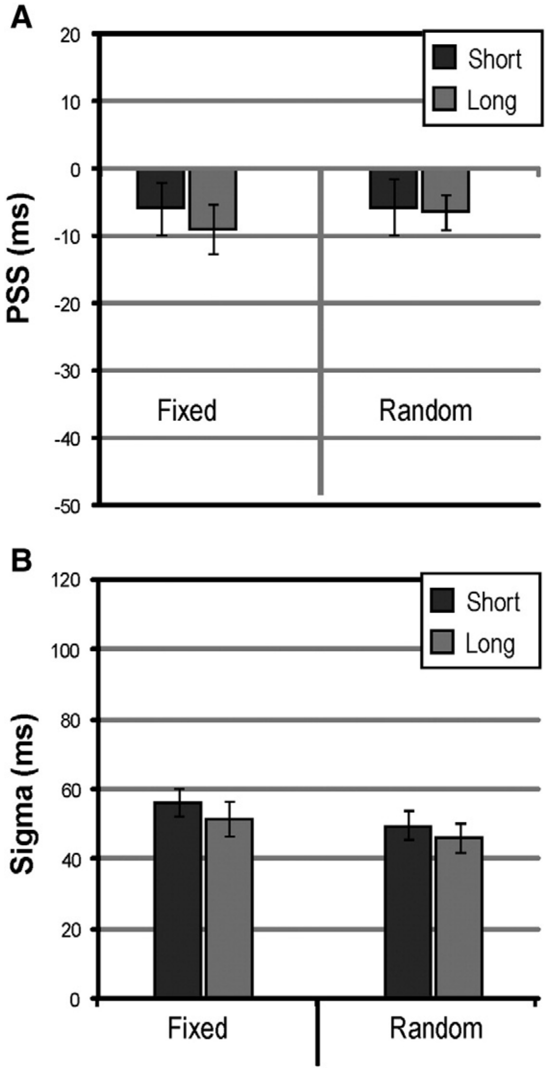

Fig. 6. A) Mean ± S.E.M. of the PSSs values obtained in Experiment 3. Negative (positive) values indicate that the beep's (flash's) perceived latency was smaller. B) Mean ± S.E.M. of the sigma values obtained in Experiment 3.

recalibration occurred to a lesser extent. Moreover, temporal recalibration is usually optimal at 100 ms intervals and significantly decreases with longer intervals (Fujisaki et al., 2004; Vroomen et al., 2004), while in our experiments the interval between flash and sound might have been too large. However, this does not invalidate the present methodology, since it is compatible with intentional binding being significantly larger than other types of temporal binding, a view also defended in other studies (Eagleman, 2008; Stetson et al., 2006).

5. General discussion

We used a new methodology based on simultaneity judgments to measure intentional binding and to investigate its relation with voluntary action, temporal predictability and contiguity. The experimental results indicate that voluntary action is a necessary condition for temporal binding to occur and that a fixed interval (short or long) between two stimuli is not sufficient to cause the effect. The largest effect of Experiment 2 was found when the interval between action and outcome was short and predictable. No significant modulation of temporal binding by temporal predictability or contiguity was found in the absence of actions.

The new methodology reproduces the basic findings of intentional binding. Additionally, it allows for a better quantitative measure of the effect itself. In the experiments reported here, the PSS in conditions that yielded significant intentional binding varied between 20 and 30 ms. Conditions with no significant intentional binding resulted in PSS values smaller than 10 ms in all experiments. The variability in these values is smaller than typical results from the rotating spot method. In a recent study, Buehner and Humphreys also employed a simultaneity task to investigate temporal binding. In their study, subjects had to perform an action so that it appeared simultaneous with the target event (Buehner & Humphreys, 2009). However, in our experiment the judged simultaneity was between an event caused by the subject (beep in *Action* conditions) and a reference stimulus (flash). We measured whether the action selectively modulated the consequence of one's action in time.

A possible objection against our methodology is that reference event (the flash) might be bound in the same way as the action effect (the beep). Because both stimuli were triggered by the subjects' action (in Action conditions) they might both be subject to intentional binding. However, our results suggest that a voluntary action does not indiscriminately affect temporal processing of all subsequent events, but only of those that are thought to result from that action. This finding is consistent with previous results, which showed a significant binding between action and effect only in conditions in which the subject reported a strong impression of causality between their action and its consequences (Cravo et al., 2009; Ebert & Wegner, 2010).

The experimental results replicated some of the basic properties of intentional binding: a stimulus presented with a predictable and contiguous interval after a voluntary action is perceived to occur earlier in time. Additionally, the results complement previous studies by comparing the effects of temporal predictability and contiguity on temporal binding in the presence or absence of voluntary action in a fully factorial design (Haggard, Aschersleben, et al., 2002; Haggard, Clark, et al., 2002; Humphreys & Buehner, 2009). We show that no significant modulation by interval or predictability occurs without action, independent of the interval between temporal marker and target. The absence of interaction with interval duration in *No Action* conditions is important for the interpretation of the results. As discussed earlier, one could argue that a main difference between *Action* and *No Action* conditions is the time the subject has to prepare itself for the upcoming event. In *Action* conditions this preparation could start in the first moments of the motor preparation, whereas in *No Action* conditions the whole process had to take place in the 300 ms after the offset of the fixation. However, our results failed to show any significant binding between the events (disappearance of fixation point and beep) in *No Action* sessions even for longer intervals.

The presence of voluntary action, on the other hand, resulted in a significant modulation in temporal perception of the beep by both temporal predictability and contiguity. When the beep was predictable and presented shortly after the action, it was consistently perceived as occurring earlier. The effect decreased for longer intervals between action and beep, even if the outcome was predictable, as in Action-Fixed—Long conditions. This result is in agreement with Haggard's original study (Haggard, Clark, et al., 2002), although it contrasts with the findings in a more recent study (Humphreys & Buehner, 2009). As mentioned in the Introduction, Humphreys and Buehner used a temporal estimation task to test the magnitude of temporal binding in longer intervals. They found that the effect existed for intervals as long as 4 s. Moreover, they found an increase of the effect for longer intervals. A possible explanation for the difference between the results is the methodologies used. While our new methodology and Haggard's original study are event-timing methods, Humphreys and Buehner used an interval-timing task. It is well known that magnitude estimation is susceptible to a range of cognitive biases (Poulton, 1979) avoided in event-timing methods.

In *Action-Random—Short conditions*, the beep was perceived as occurring significantly later than in the other conditions. A possible reason for this result is the low temporal predictability that applies in this condition. In *Random* conditions, the beep was either presented after 300 or 600 ms. Consequently, if the beep was not presented after the short interval in a given trial, it would surely be presented after the long interval, thus raising predictability of occurrence (Coull, 2009; Nobre, Correa & Coull, 2007). Therefore, low temporal predictability of the beep only applies in *Action-Random—Short* conditions, and might be responsible for the inversion of the effect. However, similar low predictability existed in *No Action-Random Interval—Short* conditions, where no significant modulation was found, suggesting a possible interaction between temporal attention and motor process.

Another possibility for this result is that the nature of the experimental protocol implied that the flash was most likely to occur between 400 and 500 ms into the trial: if the interval was short (300 ms), the flash would occur between 100 ms and 500 ms into the trial; if the interval was long (600 ms) the flash could occur between 400 and 800 ms into the trial. Thus, participants were more likely to experience flashes in the 400–500 ms bracket than in any other interval. The higher frequency of flashes in this range might be biasing perception towards this interval. However, why this finding would be confined to active conditions, is still not clear.

Lastly, we did not find a modulation of the temporal resolution between beep and flash in any of our experiments. A recent study has presented evidence suggesting that the internal clock slows down during intentional episodes, and that it is this slowing down that leads to subjective shortenings of action-outcome intervals (Wenke & Haggard, 2009). Our results do not support this view. If the internal clock slowed down during intentional episodes, then subjects should have had an impaired discrimination between simultaneous/non-simultaneous judgments. In our task, this should have been reflected in the modulation of the sigma parameter, which did not occur.

In conclusion, we have studied the basic properties of temporal binding by developing a new methodology based on simultaneity judgments. This methodology is subject to smaller variability in temporal binding estimates, allowing for a more precise comparison between the effects in different experimental conditions. Synchronicity judgments are therefore a valid alternative and, for many purposes, a more accurate way to measure temporal binding when an event-timing method is used. The results suggest that high temporal predictability between two events is not sufficient to cause the effect, and that voluntary action, temporal predictability and short intervals between action and consequence are jointly necessary for temporal binding. Moreover, the estimates of the effect show that binding occurs mainly between the action and its specific consequence and not between action and all subsequent events.

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