Assessing Intentional Binding with the Method of Constant Stimuli

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Abstract

Intentional binding describes the phenomenon that actions and their effects are perceived to be temporally approximated. We introduced a new method of duration estimation to the research field, the method of constant stimuli. Participants freely chose to press one of two keys or experienced passive key presses. After an interval of 250 ms or 600 ms a visual effect occurred. In Experiment 1, each key produced an effect after a specific interval. In Experiment 2, both keys produced an effect after the same interval that varied between sessions. Participants compared the duration of the action-effect interval with a tone of varying duration. To assess intentional binding, we compared the perceived duration of the action-effect interval between the active and passive condition. We showed intentional binding for 600 ms, but not for 250 ms action-effect intervals in both experiments. Thus, the method of constant stimuli is suitable to assess intentional binding.

Keywords

Intentional binding; time perception; action-effect interval; method of constant stimuli

1. Introduction

Time perception in the context of actions is biased. People perceive actions and their effects to be temporally closer to each other than they actually are. For example, Haggard, Aschersleben, Gehrke, and Prinz (2002) demonstrated that when an action causes an effect, the action is perceived to be later than an action that does not have any consequences, and the effect is perceived to be earlier in time than an equivalent stimulus that occurs independently from an action. In addition, the interval between an action and a contingently following effect is perceived to be shorter than the interval between a passive stimulation of the finger and a contingently presented stimulus (e.g. Engbert, Wohlschläger, & Haggard, 2008). This effect is called intentional binding because the action and the following effect seem to be temporally bound together and because intentional behavior seems to be important for the binding process.

Evidence suggesting that intentions play an important role for the occurrence of the binding effect comes from studies which compared active behavior, usually active key presses, to involuntary finger movements. When the participants' finger moved involuntarily due to transcranial magnetic stimulation (Haggard & Clark, 2003; Haggard, Clark, & Kalogeras, 2002) or because a machine-driven key moved the participants' finger passively (Wohlschläger, Engbert, & Haggard, 2003; see also Engbert, Wohlschläger, Thomas, & Haggard, 2007; Engbert et al., 2008), the passively induced movement and the contingently presented stimulus were perceived further apart compared to active movements and their effects. Thus, in cases without the intention to voluntarily press a key, the binding effect did not occur.

In the current study we aimed to assess intentional binding with a method that is new to this field of research, the method of constant stimuli. The method of constant stimuli is a psychophysical method that measures the perceived duration of intervals. Participants compare a standard interval with several different intervals of comparison (Lapid, Ulrich, &

Rammsayer, 2008; Gescheider, 1997). Psychophysical functions are estimated based on the probabilities that the intervals of comparison are judged to be longer than the standard interval. We investigated intentional binding in Experiment 1 with two actions that led to specific effects after specific action-effect intervals and in Experiment 2 with two actions that led to specific effects after constant intervals.

The method of constant stimuli can be applied to research on intentional binding and has some advantages over other methods that have been used in this field. Many studies that investigated intentional binding (Haggard, Aschersleben, et al., 2002, Haggard & Clark, 2002; Haggard, Clark, & Kalogeras, 2002; Haggard & Cole, 2007; Haggard, Poonian, & Walsh, 2009; Moore & Haggard, 2008; Moore, Lagnado, Deal, & Haggard, 2009; Wohlschläger, Haggard, Gesierich, & Prinz, 2003; Wohlschläger, Engbert, et al., 2003; Engbert & Wohlschläger, 2007) used the clock method (Wundt, 1887; see also Libet, Gleason, Wright, & Pearl, 1983), or other event-timing methods such as the stimulus anticipation method (Buehner & Humphreys, 2009) and simultaneity judgments (Cravo, Claessens, & Baldo, 2011). These methods do not allow direct estimation of the duration of an interval but instead measure the duration of an interval indirectly using the perceived points in time of the limiting events. On the other hand, the method of constant stimuli directly focuses on the interval between the action and the effect and therefore provides a more straightforward approach when measuring the perceived temporal relation between actions and their effects.

Other methods that have been used in research on intentional binding to assess the perceived duration of intervals are temporal magnitude estimation (Engbert et al., 2007, 2008; Humphreys & Buehner, 2009) and interval reproduction (Humphreys & Buhner, 2010). However, these methods are not always useful to investigate intentional binding because they require that the action-effect interval varies randomly from trial to trial whereas we wanted to assess intentional binding for constant and predictably varying action-effect intervals. Further, magnitude estimation has been criticized to be apt to response biases. For example, participants might change their estimation of the interval duration due to their beliefs and not their percept (see Cravo et al., 2011). Additionally, using a psychophysical method allows us to not only compare the perceived duration of action-effect intervals, but also to compare if intentional binding interacts with participants' ability to consistently estimate the time interval between key press and visual stimulus by calculating Weber fractions (see also Gibbon, 1977; Ulrich, Nitschke, & Rammsayer, 2006).

We applied the method of constant stimuli in two experiments. We used freely chosen active key presses and passive key presses, which were each followed by a key-specific effect. In Experiment 1, we used two different action-effect intervals that depended on the specific preceding key press. Thus, for example a left key press produced a red square after an action-effect interval of 250 ms while a right key press produced a blue square after an action-effect interval of 600 ms. We expected participants to perceive the duration of the action-effect intervals to be shorter in the active condition than in the passive condition, indicating intentional binding. In Experiment 2, we used the same action-effect intervals, but the action-effect intervals were held constant for both actions within one session. Again, we expected intentional binding indicated by shorter judgments for action-effect intervals in the active condition than in the passive condition.

2. Experiment 1

The goal of Experiment 1 was to demonstrate intentional binding with the method of constant stimuli. In the active condition, participants intentionally pressed one of two keys. In the passive condition, the keys popped up against the participants' fingers that rested on them. In both conditions a colored square appeared on the screen after a fixed time interval following the key press. The interval between the key press and the appearance of the square was 250 ms or 600 ms, depending on the specific key. We predicted that participants would perceive the interval between the key press and the appearance of the colored square to be shorter in the active condition than in the passive condition.

2.1. Method

2.1.1. Participants. 34 volunteers participated in this study. As an a priori criterion to include the participants' data in the analyses, we required that the range of probabilities that the intervals of comparison were judged longer than the standard interval was at least .75. We assumed that participants with a smaller range had some difficulties with the task. The data of 10 participants had to be excluded from further analysis due to this exclusion criterion. The remaining 24 participants, 18 female, had a mean age of 24 years, *SD* = 3 years. 22 participants were right-handed and 2 were left-handed. Participants took part for course credits or received 12 €.

2.1.2. Material and apparatus. All stimuli were presented on a personal computer with a 17-inch CRT monitor equipped with the software package E-Prime 2 (Schneider, Eschman, & Zuccolotto, 2002). Acoustic stimuli were presented via VicFirth SIH1 sound-absorbing headphones to make sure that participants based their judgments of when the action-effect interval started on the haptic percepts arising from the key press and not on the sounds that the keys produced. The two keys could either be pressed by participants or pop up, thus hitting participants' fingers from below. The keys were constructed and adjusted in a way that the sensory experience of active and passive key presses was as equal as possible.

The index and middle finger of participants' left hand rested on these keys. Time judgments were given with index and middle finger of the right hand with keys 1 and 2 of the number pad of the keyboard.

Participants had to compare the duration of the action-effect interval, the standard interval, with the duration of randomly varying intervals of comparison. The standard interval started with the key press and ended with the onset of the effect, a red or a blue square (70*70 pixels), and it lasted 250 ms or 600 ms.

A 440 Hz sinus tone that lasted between 40 ms and 1104 ms indicated the interval of comparison. We applied 13 different intervals of comparison for each standard interval (see

Figure 1). Lapid et al. (2008) revealed that participants are more sensitive to discriminate differences of time intervals when the standard interval is presented in the first place than when it is presented in the second place. This is indicated by psychophysical functions with a smaller difference limen, what means that they are steeper. Relying on these findings, we decided that the standard interval should always be presented before the interval of comparison.

2.1.3. Procedure. Participants performed the active and the passive condition on two different days within one week. The order of the conditions (active first or passive first) was counterbalanced across participants, as well as the mapping of the keys (left or right) to the standard intervals (250 ms or 600 ms). For each participant, the key-interval mapping was constant throughout both experimental sessions.

Participants performed 26 practice trials first. The main part of the experiment was divided into five blocks. Each block consisted of 130 trials, thus resulting in 650 trials per experimental session without practice trials. In the passive condition, each interval of comparison was presented 25 times; in the active condition this number could slightly differ if participants pressed one of the keys more often.

In the active condition each trial started with the word “weiter” (German for “continue”) presented centrally for 400 ms, indicating that participants could press one of the keys. The standard interval started when participants pressed the key of their choice. If participants accidentally pressed the key twice an error message warned them not to press twice and the next trial started.

In the passive condition, each trial started with the word “links” or “rechts” (German for “left” or “right”) to indicate the key that was going to pop up. After a blank of 800 ms the respective passive key press followed. We informed participants which key would pop up, to maximize the similarities between the active and passive condition because in the former participants knew in advance which key they would press.

Each key press triggered a key-specific action-effect. A red square followed a left key press and a blue square followed a right key press. The square remained on the screen for 250 ms. The tone comprising the interval of comparison was presented 500 ms after the square had disappeared. The order of the intervals of comparison was randomized for each standard interval. After the tone, participants were asked to judge if the tone had been shorter or longer than the interval between the key press and the square. Participants were not informed that there were two standard intervals that always had the same duration for one key press nor about the different intervals of comparison. After a blank of 1000 ms the next trial started.

Insert Figure 1 about here

2.1.4. Data analysis and reduction. For each interval of comparison, we computed the probability that participants judged the interval of comparison to be longer than the standard interval separately for each participant and condition. The averaged probabilities per comparison interval, condition (active, passive) and action-effect interval (250 ms, 600 ms) are presented in Figure 2.

Insert Figure 2 about here

For each participant and condition, these probabilities were fitted to logistic functions using the psignifit toolbox (Wichmann & Hill, 2001) for MATLAB. From the fitted functions we extracted the .5 percentile, i.e. the point of subjective equality (PSE). The PSE is the estimated duration of the comparison at which the participant cannot discriminate between the standard and the comparison duration. Thus, the PSE serves as a measure of how long the comparison interval would have to last to be judged as equally long as the standard interval.

We further extracted the estimated .25 percentile and the estimated .75 percentile to calculate the Weber fraction. We chose to estimate the Weber fraction by dividing the difference limen by the PSE (e.g. Getty, 1975; Grondin, 2010, 2011; Grondin & Killeen, 2009). The difference limen is the difference between the estimated .75 percentile and the estimated .25 percentile divided by two. So the Weber fraction represents the discriminability of the standard duration by setting the difference limen as measure of consistency of time judgments in relation to the perceived duration of the standard.

2.2. Results and discussion

To compare the PSEs of each condition, we conducted a 2x2 ANOVA with the within-subject factors interval (250 ms, 600 ms) and key press (active, passive). The main effect interval, $F(1, 23) = 17.65$, $p < .001$, $\eta_p^2 = .43$, and the interaction between interval and key press, $F(1, 23) = 5.99$, $p = .02$, $\eta_p^2 = .21$, were significant. The main effect key press did not reach significance, $F(1, 23) = 3.55$, $p = .07$, $\eta_p^2 = .13$.

For 250 ms, participants perceived no difference between the action-effect interval in the active condition with a mean of 240 ms, *SD* = 54 ms, and the action-effect interval in the passive condition with a mean of 232 ms, *SD* = 50 ms, $t(23) = 0.85$, $p = .40$. Participants perceived the 600 ms action-effect interval to be shorter in the active condition with a mean of 299 ms, *SD* = 100 ms, than in the passive condition with a mean of 338 ms, *SD* = 112 ms, $t(23) = -2.57$, $p = .02$ (see Figure 3a).

The Weber fractions of the 250 ms interval had a mean of 0.22 (*SD* = 0.06) in the active condition and in the passive condition. The Weber fractions of the 600 ms interval had a mean of 0.23 (*SD* = 0.09) in the active condition, and of 0.22 (*SD* = 0.07) in the passive condition. A 2x2 ANOVA with the factors interval (250 ms, 600 ms) and key press (active, passive) revealed no significant effects, neither for the main effect interval, $F(1, 23) = 0.21$, $p = .65$, $\eta_p^2 = .01$, nor the main effect key press, $F(1, 23) = 0.02$, $p = .90$. $\eta_p^2 = .00$, nor the interaction between interval and key press, $F(1, 23) = 0.08$, $p = .78$, $\eta_p^2 = .00$[1].

Insert Figure 3 about here

In Experiment 1 we investigated intentional binding with the method of constant stimuli. As predicted, we demonstrated intentional binding with the method of constant stimuli in a setting with free choice between two actions, action-specific effects and action-specific action-effect intervals, as the action-effect interval in the 600 ms active condition was perceived to be shorter than the action-effect interval of the 600 ms passive condition. The fact that we demonstrated intentional binding for only one of the two applied intervals might be due to the applied method. Different methods to measure time perception seem to be more sensitive for intentional binding at some action-effect intervals than others. We will come back to this issue in the General Discussion section.

In addition, both action-effect intervals were underestimated compared to their physical duration. We surmise that action-effect intervals were generally underestimated because we applied an unfilled standard interval (the action-effect interval) and a filled comparison interval (the tone), and unfilled intervals are usually perceived shorter than filled ones (e.g. Craig, 1973; Wearden, Norton, Martin, & Montford-Bebb, 2007; Grondin, 2008).

There were no significant differences between any of the mean Weber fraction, indicating that the psychophysical functions had a similar steepness in all conditions. These results confirm that the participants had to deal with comparable demands in all conditions and that any observed differences in the PSEs between the active and passive condition cannot be due to a condition being more difficult than the other.

To conclude, the results of Experiment 1 indicate that intentional binding can be assessed with the method of constant stimuli. They also show that intentional binding occurs in a setting with two different action-effect intervals when the action predicts the duration of the action-effect interval. These results are in line with the recent observation that different action-effect intervals can be learned (Haering & Kiesel, in press). To investigate if the binding effect that we observed in Experiment 1 was influenced by the temporal incertitude arising from different action-effect intervals within one session, we conducted Experiment 2 in which action-effect intervals were constant.

3. Experiment 2

The method of constant stimuli can be applied to various settings. In Experiment 1, the action-effect intervals varied key-specifically. In Experiment 2, the action-effect intervals were held constant within one session. This allowed us further to investigate whether the binding effect was reduced in the setting of Experiment 1 due to increased temporal incertitude. Recent studies observed less intentional binding for unpredictable, varying action-effect intervals compared to constant action-effect intervals (Cravo et al., 2011; Haggard, Clark, et al., 2002). We assumed, however, that intentional binding effects would not be reduced for action-specific, predictable action-effect intervals compared to constant action-effect intervals because action-effect intervals were predictable in both experiments. To test this, we compared the size of the intentional binding effect for constant action-effect intervals (Experiment 2) and for action-specific action-effect intervals (Experiment 1).

3.1. Method

3.1.1. Participants. 39 volunteers participated in this study. The data of 7 participants had to be excluded from further analysis because the range of the probabilities that the interval of comparison had been judged longer than the standard interval was smaller than .75. The remaining 32 participants, 23 female, had a mean age of 26 years, *SD* = 5 years. All participants were right-handed. Participants took part for course credit or received 15 €.

3.1.2. Material and procedure. We used the same materials and procedure as in Experiment 1, except that the action-effect interval was the same for both actions within one session.

Participants performed four different sessions on different days. The sessions contained the 250 ms active condition, the 250 ms passive condition, the 600 ms active condition, and the 600 ms passive condition. One action-effect interval was always presented in two consecutive sessions so that half of the participants started with the two 250 ms conditions and finished with the two 600 ms conditions, whereas the other half of the participants started with the two 600 ms conditions and finished with the two 250 ms sessions. Within the two sessions for one interval, participants performed either the active or the passive condition first. This schema resulted in eight different orders that were counterbalanced across participants.

We reduced the number of trials per session because we presented only one action-effect interval within one session. After 13 practice trials participants performed 5 blocks of 78 trials each, thus resulting in 390 trials per session without practice trials. Each interval of comparison was presented 30 times.

3.2. Results and discussion

The averaged raw data of the participants are presented in Figure 4.To compare the PSEs of each condition, we conducted a 2x2 ANOVA with the within-subject factors interval (250 ms, 600 ms), and key press (active, passive). The main effect interval, $F(1, 31) = 187.66$, $p < .001$, $\eta_p^2 = .86$, the main effect key press, $F(1, 31) = 4.20$, $p = .049$, $\eta_p^2 = .12$, and the interaction between interval and key press, $F(1, 31) = 6.23$, $p = .02$, $\eta_p^2 = .17$, were significant.

Insert Figure 4 about here

Participants perceived no difference between the 250 ms action-effect interval of the active condition with a mean of 188 ms, *SD* = 48 ms, and the passive condition with a mean of 187 ms, *SD* = 51 ms, $t(31) = 0.09$, $p = .93$. Participants perceived the 600 ms action-effect interval to be shorter in the active condition with a mean of 377 ms, *SD* = 101 ms, than in the passive condition with a mean of 406 ms, *SD* = 114 ms, $t(31) = -2.44$, $p = .02$ (see Figure 2b).

The Weber fractions of the 250 ms interval had a mean of 0.17 (*SD* = 0.07) in the active condition and of 0.19 (*SD* = 0.07) in the passive condition. The Weber fractions of the 600 ms interval had a mean of 0.18 (*SD* = 0.06) in the active condition and in the passive condition. A 2x2 ANOVA with the factors interval (250 ms, 600 ms) and key press (active, passive) revealed that the main effect interval, $F(1, 31) = 0.20$, $p = .66$, $\eta_p^2 = .01$, the main effect key press, $F(1, 31) = 2.60$, $p = .18$. $\eta_p^2 = .08$, and the interaction between interval and key press, $F(1, 31) = 1.04$, $p = .32$, $\eta_p^2 = .03$, were not significant[2].

To compare the PSEs of Experiment 1 and 2 (Figure 3a and 3b) we computed a 2x2x2 ANOVA with the within subject factors interval (250 ms, 600 ms), and key press (active, passive), and the between subjects factor experiment (Experiment 1, Experiment 2) on the PSEs. There were significant main effects for interval, $F(1, 54) = 140.27$, $p < .001$, $\eta_p^2 = .72$, and key press, $F(1, 54) = 7.67$, $p = .01$, $\eta_p^2 = .12$, but not for experiment, $F(1, 54) = 0.46$, $p = .50$, $\eta_p^2 = .01$. In addition, the interactions between interval and key press, $F(1, 54) = 12.66$, $p = .001$, $\eta_p^2 = .19$, and interval and experiment were significant, $F(1, 54) = 25.09$, $p < .001$, $\eta_p^2 = .32$. Importantly, the interaction between key press and experiment, $F(1, 54) = 0.01$, $p = .92$, $\eta_p^2 = .00$, and the three-way interaction were not significant, $F(1, 54) = 0.64$, $p = .43$, $\eta_p^2 = .01$. To avoid redundancy, we only describe effects including the factor experiment in the following.

The action-effect interval of 250 ms was perceived to be longer in Experiment 1 than in Experiment 2 in the active condition, $t(54) = -3.84$, $p < .001$, and in the passive condition, $t(54) = -3.29$, $p = .002$. The action-effect interval of 600 ms was perceived to be shorter in Experiment 1 than in Experiment 2 in the active condition, $t(54) = 2.85$, $p = .01$, and in the passive condition, $t(54) = 2.21$, $p = .03$.

The difference between the PSEs of the active and the passive condition that indicates intentional binding did not differ between the experiments. For the 250 ms interval, the non-significant intentional binding effect in Experiment 1, $M = - 8$ ms, $SD = 47$ ms, and in Experiment 2 did not differ from each other, $M = 1$ ms, $SD = 29$ ms, $t(54) = -0.75$, $p = .45$. For the 600 ms interval the size of the intentional binding effect in Experiment 1, $M = 39$ ms, $SD = 75$ ms, and the size of the intentional binding effect in Experiment 2, $M = 29$ ms, $SD = 68$ ms, did not differ, $t(54) = 0.51$, $p = .61$.

We also compared the results of Experiment 1 and Experiment 2 regarding the Weber fractions. We computed a 2x2x2 ANOVA on the Weber fractions with the within subject factors interval (250 ms, 600 ms), and key press (active, passive), and the between subjects factor experiment (Experiment 1, Experiment 2). Only the between factor experiment was significant $F(1, 54) = 11.33$, $p = .001$, $\eta_p^2 = .17$, indicating that the Weber fractions were smaller in Experiment 2 ($M = 0.18$, $SD = 0.07$) than in Experiment 1 ($M = 0.22$, $SD = 0.07$). The main effect interval, $F(1, 54) = 0.00$, $p = .95$, $\eta_p^2 = .00$, the main effect key press, $F(1, 54) = 0.51$, $p = .48$, $\eta_p^2 = .01$, $\eta_p^2 = .25$, the interaction between interval and key press, $F(1, 54) = 0.71$, $p = .41$, $\eta_p^2 = .01$, the interaction between interval and experiment, $F(1, 54) = 0.42$, $p = .52$, $\eta_p^2 = .01$, the interaction between key press and experiment, $F(1, 54) = 0.90$, $p = .35$, $\eta_p^2 = .02$, and the three-way interaction, $F(1, 54) = 0.12$, $p = .73$, $\eta_p^2 = .00$, were not significant.

In Experiment 2 we applied the method of constant stimuli to assess intentional binding in a setting where two actions caused specific effects after an action-effect interval that remained constant throughout one session. We found exactly the same pattern of results as in Experiment 1 regarding the perceived duration of the action-effect intervals. We found intentional binding for the 600 ms interval, as the action-effect interval was perceived to be shorter in the active condition than in the passive condition for action-effect intervals of 600 ms. Comparisons of the PSEs of Experiment 1 and Experiment 2 revealed no interaction between the factors key press and experiment and no three-way interaction between key press, experiment, and interval on the perceived duration. That is, constant action-effect intervals led to a comparable amount of intentional binding as action-specifically varying action-effect intervals did.

However, the comparison of the PSEs between experiments did reveal an interaction between the factors experiment and interval, because the perceived duration of long and short intervals drifted towards the mean when they were not constant throughout one session. We suppose that this might constitute an effect that generally occurs in time perception when comparing time perception for constant time intervals with time perception for intermixed time intervals of different length. Importantly, this effect did not contradict our hypothesis, as it was true for both the active and the passive condition.

We also found a similar pattern of results as in Experiment 1 regarding the Weber fractions. There were no significant differences between the conditions. The comparison of the experiments revealed that the Weber fractions were larger in Experiment 1 than in Experiment 2, so the duration estimations were more challenging when the participants dealt with different action-effect intervals during the same session. As we did not observe an interaction between this finding and the factor key press, we assume that it reflects the demands of the task in general in both experiments, but that it is independent of the binding effect.

4. General Discussion

The goal of the present work was to apply the psychophysical method of constant stimuli on research on intentional binding. Intentional binding describes the phenomenon that the interval between actions and their consecutive effects is perceived to be shorter than an interval of the same physical duration between passive key presses and consecutive effects, respectively. Thus, actions and their effects are perceived to occur temporally closer to each other in comparison to passive key presses and effects.

Participants pressed keys in the active condition or they were pressed by keys in the passive condition. In Experiment 1, each effect occurred after an action-specifically varying action-effect interval, while action-effect intervals were held constant in Experiment 2. Participants perceived the action-effect interval to be shorter in the active condition than in the passive condition for action-effect intervals of 600 ms in both experiments. Thus, we demonstrated that intentional binding can be assessed with the method of constant stimuli. Additionally, the method of constant stimuli allows assessing the Weber fraction as a measure of discriminability of the intervals between key press and effect. Intentional binding is often described as a bias of time perception between actions and effects. With our results we can show that this bias does not impede participants' ability to estimate the perceived duration per se.

We conjecture that the method of constant stimuli is somewhat more straightforward than applying the clock method (Wundt, 1887; see also Libet et al., 1983), the stimulus anticipation method (Buehner & Humphreys, 2009) or simultaneity judgments (Cravo et al., 2011) because it directly estimates the duration of the action-effect interval instead of assessing the point in time of action and its effect separately. Further, other methods to assess the duration of the action-effect interval like temporal magnitude estimation (Engbert et al., 2007, 2008; Humphreys & Buehner, 2009) or interval reproduction (Humphreys & Buhner, 2010) require that the interval varies (at least slightly) randomly trial by trial. In contrast, the method of constant stimuli has the advantage that it can be used with varying as well as with constant action-effect intervals. Furthermore, as it does not require that the participants judge the absolute interval duration via a verbal estimation or a reproduction, it may facilitate the task for the participants and be less prone to response biases (Poulton, 1979).The method of constant stimuli may gain further importance in research on intentional binding because it allows to measure directly the perceived duration of the action-effect interval, and because it can be used flexibly in very many different settings, for example for constant and varying action-effect intervals

Interestingly, we found intentional binding for an action-effect interval of 600 ms, but not for an action-effect interval of 250 ms. The present literature is inconsistent about the question whether intentional binding increases or decreases with increasing interval duration. Interestingly, the method that is used to assess intentional binding seems to influence the sensitivity for intentional binding at different action-effect intervals. For example, Haggard, Aschersleben, et al. (2002) used action-effect intervals that were smaller than 1000 ms to investigate intentional binding with the clock method. They found that intentional binding decreased with increasing action-effect intervals. Similarly, Cravo et al. (2011, Experiment 2) found intentional binding for action-effect intervals of 300 ms, but not for 600 ms, when participants compared the time of action effects to other irrelevant stimuli.

On the other hand, Humphreys and Buehner (2009) found intentional binding for action-effect intervals up to 4000 ms using temporal magnitude estimation. Importantly, they found that intentional binding increased with increasing action-effect intervals. This is consistent with our results, in that we did not find intentional binding for action-effect intervals of 250 ms, but we did for action-effect intervals of 600 ms. Overall, it seems that methods differ regarding their sensitivity to assess intentional binding at different intervals.

We conjecture that the method of constant stimuli that we used might have more in common with temporal magnitude estimation as used by Humphreys and Buehner (2009) than with the clock method (Haggard, Aschersleben, et al., 2002; Haggard, Clark, et al., 2002) and the temporal order judgment regarding the time of the effect stimulus (Cravo et al., 2011). In studies that use the clock method or temporal order judgments, participants judge the point in time of the event in question, either action or effect, to a synchronously presented reference. In contrast, for temporal magnitude estimation and the method of constant stimuli participants have to remember the interval and compare it to either internally generated representations of time durations or to an externally presented comparison stimulus. Thus, in terms of Moore and Haggard (2008), the clock method and temporal order judgments may rely more on “predictive” comparison processes, while temporal magnitude estimation and the method of constant stimuli rely more on “postdictive” comparison processes. Thus, the differing sensitivity for intentional binding with increasing action-effect intervals may rely on the different components which are more or less pronounced due to the method used, as argued by Humphreys and Buehner (2009).

Our results regarding the comparison of Experiment 1 and Experiment 2 revealed that intentional binding occurs for predictably varying action-effect intervals without any loss of its effect size compared to a setting with constant action-effect intervals. In other studies intentional binding was decreased or disappeared when the action-effect interval varied within blocks (Cravo et al., 2011; Haggard, Clark, et al., 2002). In contrast, our results suggest that participants learned the key-specific action effect intervals. Consequently intentional binding was found for the varying action-effect interval that was predictable due to the preceding key press.

This is consistent with recent attempts to explain intentional binding based on principles of the ideomotor theory (Haggard, 2005). The ideomotor theory claims that participants acquire bidirectional associations of actions and contingently following effects (e.g. Herbart, 1825; see also Greenwald, 1970; Shin, Proctor, & Capaldi, 2010; Hoffmann, Butz, Kiesel, Herbort, & Lenhard, 2007; Pfister, Kiesel, & Hoffmann, 2011). In the current study, we applied effects that were predictable in terms of identity and point in time. Comparing our study with others (Cravo et al., 2011; Haggard, Clark, et al., 2002) suggests that predictability of the point in time plays an important role for the binding effect. Yet, the finding that intentional binding may rely on the predictability *when* an action effect will occur is remarkable, as recent research has shown that the binding effect is independent from the predictability *which* action effect will occur (Desantis, Hughes and Waszak, 2012). Future research is required to elaborate on the exact mechanisms underlying the intentional binding effect and we hope to foster such research by introducing the method of constant stimuli to this field.

The goal of this work was to introduce the method of constant stimuli as a new method in this field. The straightforwardness and flexibility of this method might inspire further research on the underlying processes of the binding process.

Acknowledgments

This research was supported by a grant of the German Science Foundation (DFG, Grant Ki 1388/3-1).

We would like to thank Svenja Scholtyssyk and Carolin Hohnecker for data acquisition, Georg Schüssler for the construction of the keys, Brandi Drisdelle and Richmond Kinney for proof-reading, and Johannes Rodrigues for his help with the figures.

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Footnotes

1 We excluded the data of 10 participants for a priori reasons. Given that we had to exclude the data of a high number of participants, we considered that our criterion might be quite severe. We repeated our analyses without excluding the data of any participant and found the same pattern of results. Regarding the PSEs, all effects were significant, main effect key press: $F(1, 33) = 4.57$, $p = .04$, main effect interval: $F(1, 33) = 13.22$, $p < .001$; interaction between interval and key press: $F(1, 33) = 10.51$, $p < .001$. These effects were due to a smaller PSE in the active condition, $M = 282$ ms, $SD = 108$ ms, than in the passive condition, $M = 322$ ms, $SD = 109$ ms; $t(33) = -3.20$, $p < .001$, for 600 ms, whereas the PSE in active condition, $M = 248$, $SD = 76$ ms, and in the passive condition, $M = 242$ ms, $SD = 66$ ms, did not differ for 250 ms, $t(33) = 0.81$, $p = .42$. Regarding the Weber fractions (250 ms active condition: $M = 0.25$, $SD = 0.09$; 250 ms passive condition, $M = 0.21$, $SD = 0.13$; 600 ms active condition, $M = 26$, $SD = 13$; 600 ms passive condition: $M = 0.23$, $SD = 0.16$), no effect reached significance, main effect key press: $F(1, 33) = 2.45$, $p = .13$, main effect interval: $F(1, 33) = 2.04$, $p = .16$; interaction between interval and key press: $F(1, 33) = 0.02$, $p = .90$.

2 As in Experiment 1, we repeated our analyses with all participants. Again, the pattern of results did not change, thus making sure that our a priori criterion did not bias the results in any direction. Regarding the PSEs, all effects were significant, main effect key press: $F(1, 38) = 5.22$, $p = .03$, main effect interval: $F(1, 38) = 125.16$, $p < .001$; interaction between interval and key press: $F(1, 38) = 8.01$, $p = .01$. These effects were due to a smaller PSE in the active condition, $M = 349$ ms, $SD = 149$ ms, than in the passive condition, $M = 389$ ms, $SD = 144$ ms; $t(38) = -2.69$, $p = .01$, for 600 ms, whereas the PSE in active condition, $M = 184$, $SD = 62$ ms, and in the passive condition, $M = 182$ ms, $SD = 65$ ms, did not differ for 250 ms, $t(38) = 0.38$, $p = .71$. Regarding the Weber fractions (250 ms active condition: $M =$

0.24, *SD* = 0.23; 250 ms passive condition, *M* = 0.24, *SD* = 0.17; 600 ms active condition, *M* = 16, *SD* = 15; 600 ms passive condition: *M* = 0.21, *SD* = 0.11), no effect reached significance, main effect key press: $F(1, 38) = 2.99$, $p = .09$, main effect interval: $F(1, 38) = 2.86$, $p = .10$; interaction between interval and key press: $F(1, 38) = 0.68$, $p = .41$.

Figure Captions

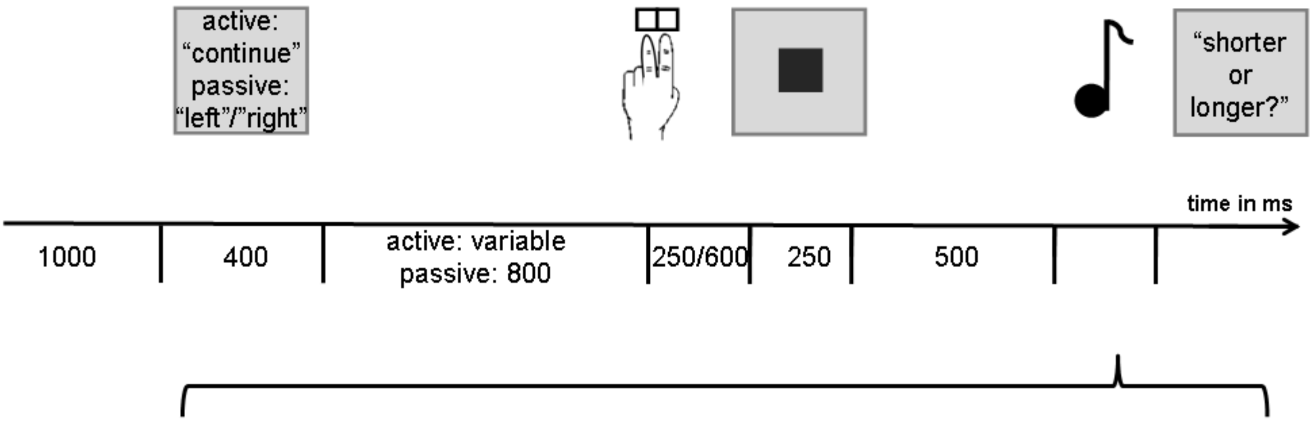
Figure 1. Trial procedure. In the active condition, the word “continue” informs the participants that they can now press one of two keys. In the passive condition, the word “left” or “right” indicates the key that will pop up against the participants’ finger. Active or passive key presses mark the onset of the action-effect interval (standard interval), and the onset of a colored square marks the offset of the action-effect interval. The duration of the action-effect interval (250 ms or 600 ms) and the color of the square (red or blue) are matched to the keys. Participants must compare the action-effect interval to a tone (interval of comparison) that varies randomly from trial to trial. The different sets of tone durations for each action-effect intervals are listed below the time course.

Figure 2a and 2b. Mean and standard error of the probability that participants judged an interval of comparison to be longer than the standard interval in Experiment 1. Figure 2a shows the data for the 250 ms action-effect interval and Figure 2b shows the data for the 600 ms action-effect interval. The figures are based on included data only.

Figure 3a and 3b. Mean and standard error of the PSEs of the active and of the passive condition, for the 250 ms and the 600 ms action-effect interval. Figure 3a shows the results of Experiment 1 and Figure 3b shows the results of Experiment 2. The action-effect interval of 600 ms is perceived shorter in the active than in the passive condition in both experiments. The figures are based on included data only.

Figure 4a and 4b. Mean and standard error of the probability that participants judged an interval of comparison to be longer than the standard interval in Experiment 2. Figure 4a shows the data for the 250 ms action-effect interval and Figure 4b shows the data for the 600 ms action-effect interval. The figures are based on included data only.

Figure 1



standard interval (ms)	intervals of comparison (ms)												
250	40	57	110	145	180	215	250	285	320	355	390	425	460
600	96	180	264	348	432	516	600	684	768	852	936	1020	1104

Figure2

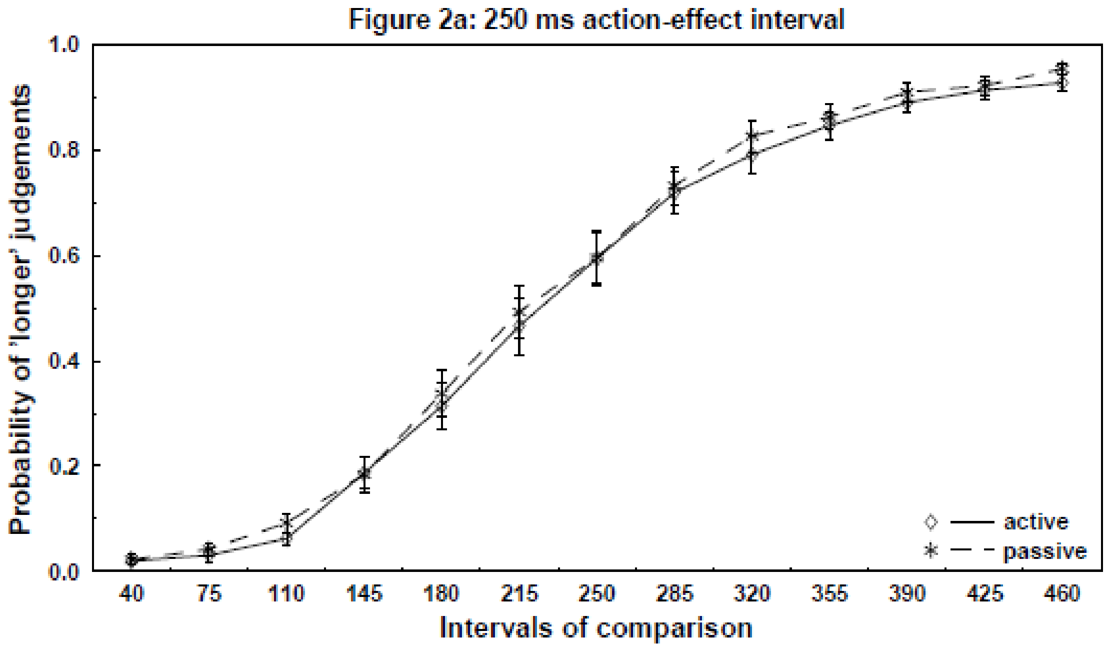


Figure 2a: 250 ms action-effect interval
Probability of 'longer' judgements
0.0
0.2
0.4
0.6
0.8
1.0
40
75
110
145
180
215
250
285
320
355
390
425
460
Intervals of comparison
active
passive

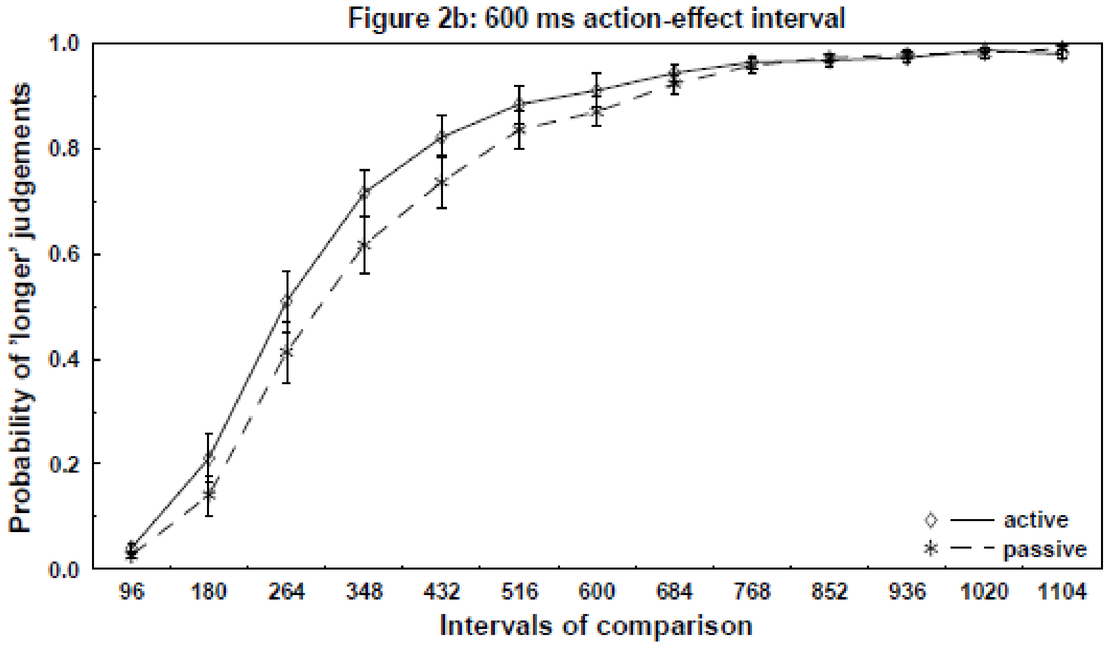


Figure 2b: 600 ms action-effect interval
Probability of 'longer' judgements
0.0
0.2
0.4
0.6
0.8
1.0
96
180
264
348
432
516
600
684
768
852
936
1020
1104
Intervals of comparison
active
passive

Figure 3

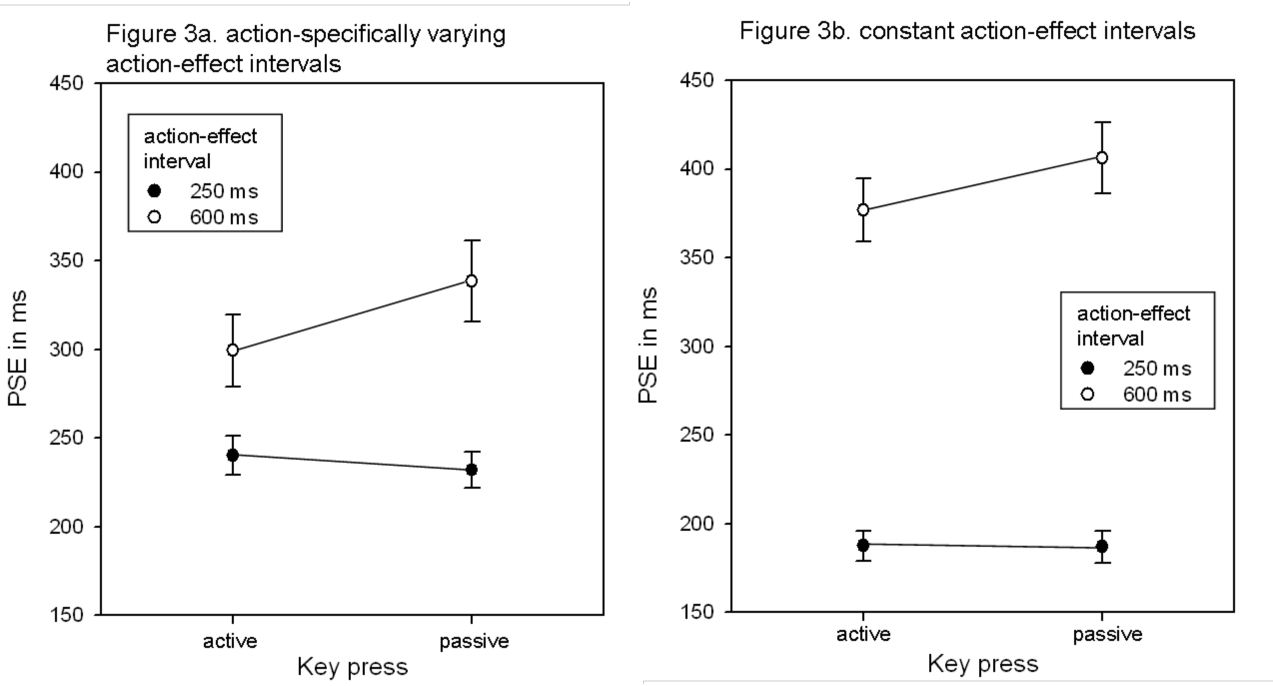


Figure 3a. action-specifically varying action-effect intervals
450
400
350
300
250
200
150
PSE in ms
action-effect interval
250 ms
600 ms
active
passive
Key press
Figure 3b. constant action-effect intervals
450
400
350
300
250
200
150
PSE in ms
action-effect interval
250 ms
600 ms
active
passive
Key press

Figure 4

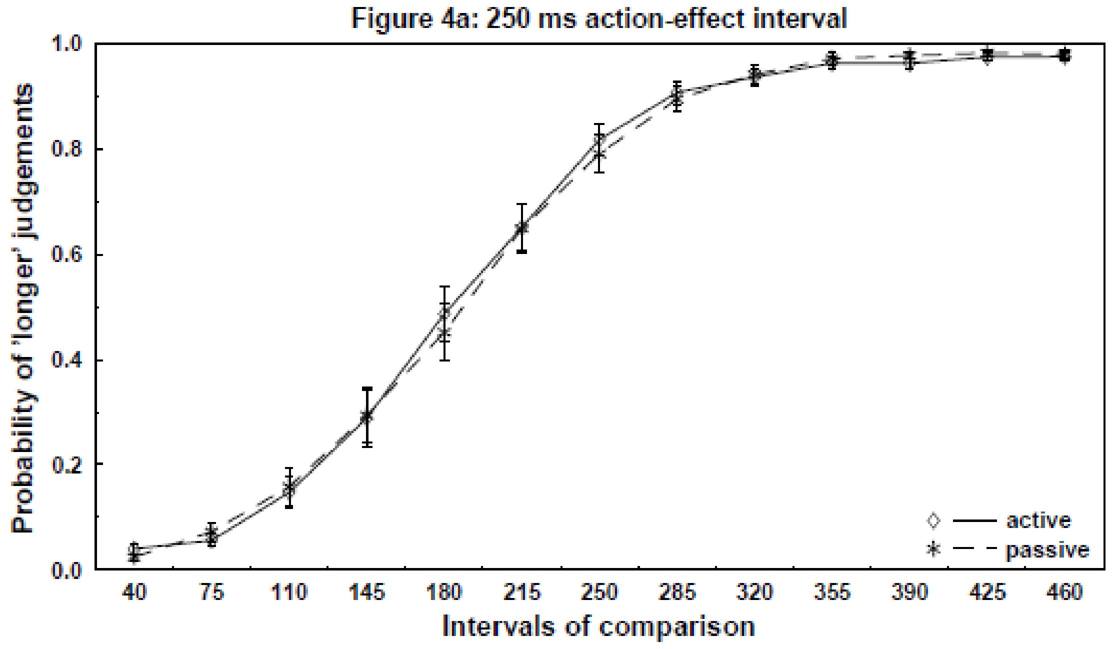


Figure 4a: 250 ms action-effect interval
Probability of 'longer' judgements
1.0
0.8
0.6
0.4
0.2
0.0
40
75
110
145
180
215
250
285
320
355
390
425
460
Intervals of comparison
active
passive

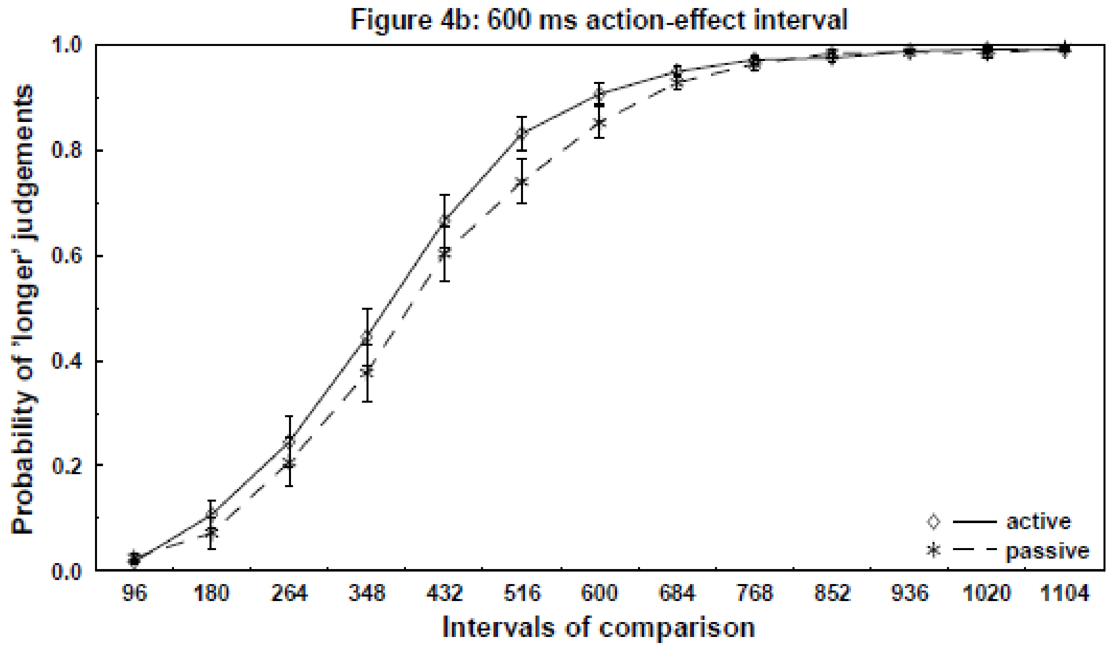


Figure 4b: 600 ms action-effect interval
Probability of 'longer' judgements
1.0
0.8
0.6
0.4
0.2
0.0
96
180
264
348
432
516
600
684
768
852
936
1020
1104
Intervals of comparison
active
passive