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The influence of action-outcome delay and arousal on sense of agency and the intentional binding effect

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ABSTRACT

The sense of agency refers to the feeling of being able to initiate and control events through one's actions. The "intentional binding" effect (Haggard, Clark, & Kalogeras, 2002), refers to a subjective compression of the temporal interval between actions and their effects. The present study examined the influence of action-outcome delays and arousal on both the subjective judgment of agency and the intentional binding effect. In the experiment, participants pressed a key to trigger a central square to jump after various delays. A red central square was used in the high-arousal condition. Results showed that a longer interval between actions and their effects was associated with a lower sense of agency but a stronger intentional binding effect. Furthermore, although arousal enhanced the intentional binding effect, it did not influence the judgment of agency.

1. Introduction

The sense of agency is the feeling of being able to initiate and control events through one's self-willed actions. The sense of agency is necessary for individuals to be able to explain changes in the external world and make future predictions. Unraveling the mechanisms underlying the sense of agency is important for varied applications including engineering design, wherein the feeling of control is critical for good performance, and clinical treatment of patients with schizophrenia, who usually have an abnormal sense of agency.

Several studies have examined these underlying mechanisms. Initial research comprised investigations on the processes of comparing predicted and actual sensory information. In particular, the comparator model suggests that a predicted state is generated from an efference copy of one's motor command and is compared with an approximate actual state; a match implies the experience of the sense of agency, while a mismatch implies that the other could have potentially produced the effect (Blakemore, Frith, & Wolpert, 1999; Blakemore, Wolpert, & Frith, 1998, 2002; Frith, Blakemore, & Wolpert, 2000; Wolpert & Flanagan, 2001). The comparator model is well-supported by neurocognitive studies (Blakemore et al., 1998; Frith et al., 2000; Voss, Ingram, Haggard, & Wolpert, 2006), and can explain several phenomena related to the sense of agency. However, recent studies have suggested that internal comparison might be neither sufficient nor necessary for self-attribution or the perception of agency in some cases (Synofzik, Vosgerau, & Newen, 2008). For example, external cues or inference could also generate a "false" sense of agency (Wegner, Sparrow, & Winerman, 2004). It has been proposed that the judgment of agency may be a post-detective or reconstructive process (Haggard, 2005; Haggard & Cole, 2007; Kühn et al.,

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2011; Metcalfe & Greene, 2007; Wen, Yamashita, & Asama, 2015) generated from both, implicit perceptual processes (e.g., automatic comparison of predicted and perceived information) and explicit high-level cognitive processes (e.g., inference).

Tasks that promote a sense of agency also facilitate a well-known phenomenon, the intentional binding effect (Haggard, Clark, & Kalogeras, 2002). The intentional binding effect refers to the compression of the temporal interval between voluntary action and its external sensory effects, facilitated in conditions wherein the individual experiences a sense of agency (Haggard et al., 2002). This phenomenon indicates that action and its effect are intentionally bound together in the process of generating a sense of agency. For example, some studies have reported that individuals with schizophrenia have an excessive sense of agency (Daprati et al., 1997; Franck et al., 2001; Maeda et al., 2012; Synofzik, Thier, Leube, Schlotterbeck, & Lindner, 2010) and demonstrate a greater intentional binding effect (Haggard, Martin, Taylor-Clarke, Jeannerod, & Franck, 2003; Martin, 2013). However, a recent study that examined the influence of action-outcome consistency and delays in self-reported sense of agency and the intentional binding effect found that when the delay was longer (700 ms), consistency enhanced sense of agency but not the binding effect (Ebert & Wegner, 2010), suggesting that binding and self-reported agency reveal different aspects of the sense of agency. Furthermore, recent studies examining the binding effect have suggested that intentional binding is linked to low-level implicit aspects of the sense of agency (Moore, Middleton, Haggard, & Fletcher, 2012) and is based on both predictive and retrospective processes (Moore & Haggard, 2008).

In the present study, we focus on the influence of action-outcome delays as an external factor, and arousal as an internal factor on the sense of agency and the intentional binding effect. Several studies have used action-outcome delays as a way to manipulate sense of agency, most of which found that self-reported agency decreased with an increase in delayed intervals (Ebert & Wegner, 2010; Farrer, Valentin, & Hupé, 2013; Hon, Poh, & Soon, 2013; Kawabe, 2013; Kühn et al., 2011; Sato & Yasuda, 2005). However, few studies have investigated the influence of action-outcome delays on intentional binding (Buehner & Humphreys, 2009; Kühn, Brass, & Haggard, 2013), and to our knowledge, no study had examined the influence of delays on both agency judgment and the binding effect. On the other hand, the impact of arousal—an important aspect of attention—on sense of agency has not been previously studied. In visual perception, attention is considered to be an implicit process that contributes to the integration of separate features into an object (Treisman, 1988; Treisman & Gelade, 1980). We predict that when applying an action to an object, high arousal would enhance the implicit binding process between the action and subsequent effect. Furthermore, when manipulating arousal, external cues are not provided and the reconstructive processes involved in the sense of agency would remain unaffected.

In summary, we examine the influence of both delay and arousal on self-reported agency and the intentional binding effect. We hypothesize that delay would affect self-reported agency more than it would affect intentional binding, while arousal would influence intentional binding more than it would affect self-reported agency.

2. Experiment 1

In Experiment 1, we examined the influence of delay and arousal on self-reported sense of agency and the intentional binding effect. The interval between participants' action and the effect was varied using seven possible intervals ranging between 0 and 1000 ms. Arousal was varied based on the color of the target; red was used to increase arousal (Nakshian, 1964; Walters, Apter, & Svebak, 1982; Wilson, 1966), while black served as a baseline. The dependent variables were self-ratings of sense of agency and action-outcome interval estimations. The intentional binding effect was measured by differences in time perception between the experiment task (i.e., the estimated duration) and a baseline time-perception test (participants' perception of different time intervals).

2.1. Method

2.1.1. Participants

Participants comprised 27 students with normal or corrected visual acuity (mean age: 24.9 years; range: 22–35 years). The experiment was carried out to conform to the principles of the Declaration of Helsinki and was approved by the ethics committee of the Faculty of Engineering at the University of Tokyo. Written informed consent was obtained from all participants.

2.1.2. Tasks

Participants completed two experimental tasks, the agency-rating and interval-estimation tasks (Fig. 1), and an additional task, the time-perception task. In addition, an arousal measurement experiment was conducted with another 10 participants (see Section 2.1.4 for details).

For the agency-rating task, participants were first shown a black cross in the center of a screen with a gray background for 500 ms. Three 60-mm black or red squares appeared from the bottom of the screen and moved vertically, at a speed of 18 mm/s. The squares were placed in a row, 60 mm apart. Only the two squares on the side "jumped" upwards by 90 mm, one at a time, at random intervals, ranging 100–2000 ms, and continued to move after jumping. The purpose of presenting these jumping squares was to indicate instances of computer-induced jumping to avoid a ceiling effect for self-rated agency. Participants were instructed to press the space key with their left hand to make the central square jump vertically at a self-decided time after the presentation of all three squares. After pressing the key, the central square moved 90 mm

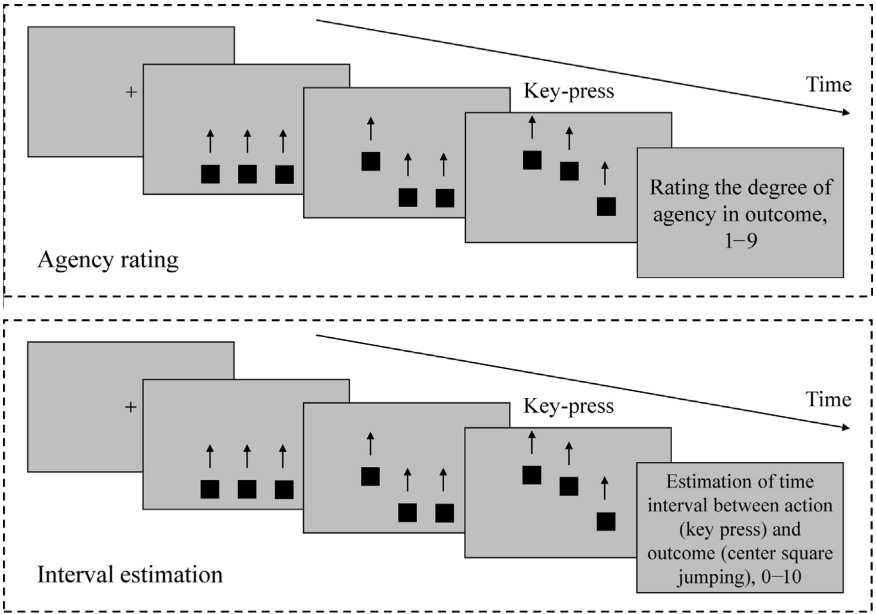

Fig. 1. The sequence of events for the agency-rating and interval-estimation tasks.

upwards with seven possible delays (0, 100, 200, 300, 500, 700, or 1000 ms). Participants rated the extent to which they felt their action caused the central square to jump on a 9-point scale (1: not at all; 9: a lot), by clicking on-screen radio buttons with a mouse using their right hand. In the interval-estimation task, participants estimated the length of the interval between the act of pressing the space key and the central square jumping event, using 11 levels from 0 to 10 with 100-ms increments (0 = no delay; 1 = 100 ms; 10 = 1000 ms). In the high-arousal condition, the central square was red while the two squares on either side were black. In the low-arousal condition, all three squares were black. Participants were informed that the colors of squares were unrelated to the tasks.

The time-perception task was conducted before and after the interval-estimation tasks. In the time-perception task, a black circle was presented for a random duration (from 100 to 1000 ms, in 100 ms increments). Participants were asked to estimate the duration by clicking one of 10 buttons labeled with a time interval. The first time-perception task was designed to allow participants to develop a sense of duration. Participants learned to differentiate between durations for as long as they needed and were then tested until they correctly estimated durations on seven consecutive trials (errors below 100 ms were permitted). The second time-perception task was conducted to establish participants' baseline time perception for the seven durations. Feedback was provided in the first task, but not in the second time-perception task.

2.1.3. Procedure

Participants were tested individually, seated on a chair positioned 50 cm away from a 27-in. LCD monitor. After explaining the first experimental task, participants performed several practice trials (3 trials for the agency-rating task and 6 trials for the interval-estimation task) and were instructed as follows: "You can send a signal to the central square by pressing the space key. After receiving the signal, the central square will jump upwards. However, the computers will sometimes disrupt your signals, either delaying them, or blocking them and making a new jump." Further, in the agency-rating task, participants were instructed to give ratings based on their intuition, while in the interval-estimation task, they were informed that the color and the squares on the sides were inconsequential. In order to maintain arousal levels, we grouped trials with the same arousal condition. Specifically, in the high-arousal trial block the central square was always red, while in the low-arousal trial block the central square was always black. The order of the two experimental tasks and the order of the two arousal conditions were counterbalanced between participants; each participant performed two blocks of each task. Each block comprised 10 trials for each delay condition, resulting in a total of 70 trials. Trial order was randomized in each block.

The time-perception task with feedback was explained and conducted before the interval-estimation task to ensure that participants' time perception of 100- to 1000-ms durations were sufficiently accurate. The time-perception task without feedback was conducted after the interval-estimation task to examine participants' baseline perception of each duration and comprised 10 trials for each interval (100, 200, 300, 500, 700 or 1000 ms) resulting in a total of 60 trials, presented in a random order. The experiment took 60 min on average. A 5-min break was allowed between the two experimental tasks.

2.1.4. Arousal measurement

Several studies have reported that the color red produces greater arousal than do other colors, such as green (Nakshian, 1964; Walters et al., 1982; Wilson, 1966). However, in this experiment, to confirm whether the red square produced greater arousal than the black one did, we conducted an additional experiment to examine the level of arousal in each condition using both subjective ratings and objective measurements (galvanic skin response; GSR). Subjective ratings have been widely used to confirm stimuli arousal (e.g., Gil & Droit-Volet, 2011; Yoshie & Haggard, 2013). On the other hand, GSR is a method of measuring sympathetic nervous system activity through sweat gland activation patterns, which are considered to be affected by psychological arousal. That is, if one experiences greater arousal, he or she would sweat more, resulting in a higher GSR. GSR has been widely used as an index of attention (e.g., Anders, Lotze, Erb, Grodd, & Birbaumer, 2004; Critchley, Mathias, & Dolan, 2001; Jacobs & Hustmyer, 1974).

Ten students (mean age: 25.1 years; range: 23–33 years) participated in the arousal measurement experiment. Participants completed two blocks of different arousal conditions, each containing 35 trials with five trials for each delay condition. In each trial, identical to the experimental task, participants pressed the space key to trigger the central square to jump at varied delays. Agency rating and interval estimation were not performed. After completing the first block, participants answered a questionnaire on arousal where they rated their consciousness and attention in the block on a 9-point scale for eight items (Table 1; e.g., 1 = my consciousness was vague, 9 = my consciousness was clear). Following this, they took a 1-min break and completed the second block and questionnaire. During the experiment, participants wore a grounding electrode on their left wrist and a pair of GSR electrodes attached to the bases of their index and middle fingers. They were instructed to keep their left hand relaxed and stationary. GSRs were recorded by a biological measuring system (DL-3100, S&ME Corp.) at a frequency of 500 Hz. The baseline that measured their relaxed state was corrected to 0. The block order was counterbalanced between participants and the trial order was randomized in each block. The arousal measurement lasted for about 15 min on average.

2.2. Results

2.2.1. Agency rating

The means and standard errors of agency ratings in each condition of the agency-rating task are presented in Fig. 2. We conducted a 2×7 (arousal $\times$ delay) repeated-measures ANOVA on the rating scores. The main effect of action-outcome delay was significant ($F(6,156) = 169.45$, $p < .01$, $\eta_p^2 = 0.87$), but the main effect of arousal and the interaction between arousal and delay were not significant ($F(1,26) = 0.14$, *n.s.*, $\eta_p^2 = 0.01$; $F(6,156) = 1.66$, *n.s.*, $\eta_p^2 = 0.06$, respectively). We conducted post hoc comparisons between delay conditions; when the delay increased over 200 ms, the rating significantly decreased (Tukey's HSD: difference between the 0-ms and 100-ms conditions: *n.s.*; difference between the 100-ms and 200-ms conditions: $p = .09$; difference between the 200-ms and 300-ms conditions, and the remaining conditions: $ps < .01$).

2.2.2. Intentional binding effect

The intentional binding effect was calculated by deducting each participant's estimations in the interval-estimation task from his/her estimations in the second time-perception task. Because we did not measure time perception for 0 ms, the results of intentional binding effect were calculated for the other six delay conditions (Fig. 3). We applied a 2×6 (arousal $\times$ delay) repeated-measures ANOVA on binding effect. The main effect of action-outcome delay was significant ($F(5,130) = 10.69$, $p < .01$, $\eta_p^2 = 0.29$). Post-hoc comparisons (Tukey's HSD test) between delays showed that the effect did not differ between the 100-ms, 200-ms, 300-ms, and 500-ms conditions ($ps > .10$); but the effect in the 700-ms condition was significantly larger than in the 100-ms, 200-ms, and 300-ms conditions ($ps < .01$); and the effect in the 1000-ms condition was significantly larger than in the 100-ms, 200-ms, 300-ms, and 500-ms conditions ($ps < .01$). The difference between the 700-ms and 1000-ms conditions was not significant ($p = .97$). The main effect of arousal was also significant ($F(1,26) = 8.33$, $p < .01$, $\eta_p^2 = 0.24$). Thus, the intentional binding effect was stronger in the high-arousal condition than the low-arousal condition. However, the interaction between arousal and delay was not significant ($F(5,130) = 0.90$, *n.s.*, $\eta_p^2 = 0.03$).

We also compared the intentional binding effect against 0 ms (i.e., no intentional binding) using two-tailed *t*-tests. The significance level was set at 0.0083 according to the Bonferroni correction. For both the low- and high-arousal conditions, only binding effects in the two longer delay conditions were significant (in the low-arousal condition, 700 ms: $t(26) = 3.17$, 1000 ms: $t(26) = 3.07$; in the high-arousal condition, 700 ms: $t(26) = 4.46$, 1000 ms: $t(26) = 4.60$, $ps < .0083$).

Table 1
Scale items of the arousal questionnaire.

Positive items	Negative items
My consciousness was clear	My consciousness was vague
I was able to focus on the task	I was unable to focus on the task
I was excited	I was not excited
I was able to concentrate	I was unable to concentrate
I was not sleepy*	I was sleepy*
I was lively	I was not lively
I was not tired*	I was tired*
I was active	I was not active

Note. Items marked with an asterisk (*) were presented and scored in reverse.

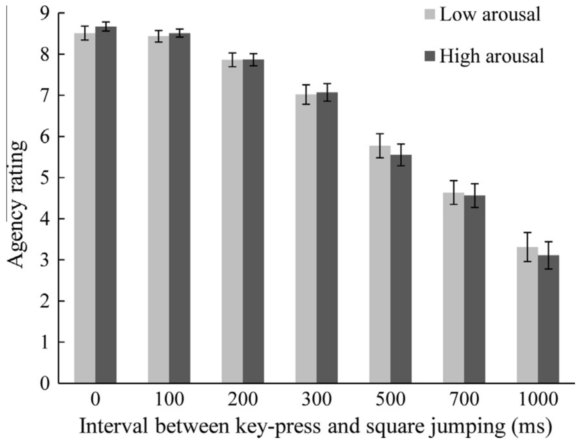

Fig. 2. Mean agency-rating scores. Error bars represent standard errors. The agency rating decreased when the action-outcome delay increased. Arousal did not influence agency rating.

Furthermore, in order to examine the way sense of agency and arousal influence time perception, we conducted regression analyses for each participant, using delay as the independent variable, and responses in the interval-estimation (low-arousal condition vs. high-arousal condition) and time-perception tasks (baseline time perception) as the dependent variables. The regression analyses help determine whether sense of agency or arousal shortened time perception for a specific duration or slowed down an internal clock (Wenke & Haggard, 2009). In the former case, intercepts would be smaller because of agency or arousal; and in the latter case, slopes would be smaller. The means and standard errors of slopes and intercepts are shown in Fig. 4. We applied repeated-measured ANOVAs (baseline, low-arousal, and high-arousal) to the slopes and intercepts, respectively. For the slopes, the main effect was significant ($F(2,52) = 13.85$, $p < .01$, $\eta_p^2 = 0.35$), and post hoc comparisons (Tukey's HSD test) showed that the slopes in the low- and high-arousal conditions were significantly smaller than that in the baseline condition (*ps* < .01). There was no significant difference between the low- and high-arousal conditions ($p = .67$). Regarding intercepts, the main effect was not significant ($F(2,52) = 0.58$, *n.s.*, $\eta_p^2 = 0.02$). The results indicated that sense of agency slowed down the internal clock rather than removed a fixed period of time.

2.2.3. Measurement of arousal

The means of arousal ratings and GSRs in each condition are presented in Fig. 5(A) and (B), respectively. The mean rating score in the high-arousal condition was significantly higher than that in the low-arousal condition ($t(9) = 2.66$, $p < .05$). The mean GSR in the high-arousal condition was also significantly higher than that in the low-arousal condition ($t(9) = 2.43$, $p < .05$). Therefore, both subjective and objective measurements confirmed that arousal was manipulated effectively.

2.3. Discussion

The purpose of the present study was to examine the influence of delay and arousal on self-reported sense of agency and the intentional binding effect. We hypothesized that the development of the subjective judgment of agency (i.e., self-reported agency) involves reconstructive processes and is substantially affected by action-outcome delays, while the

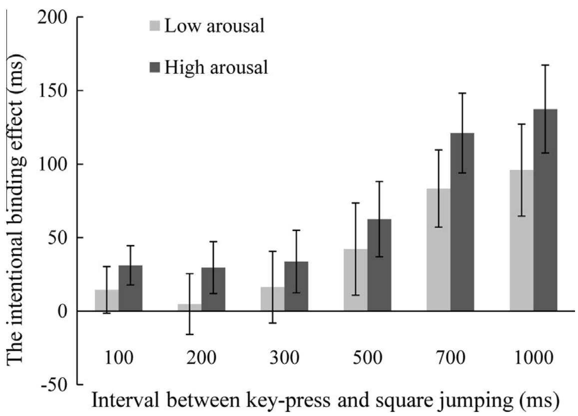

Fig. 3. The intentional binding effect in each delay condition according to arousal levels. Error bars represent standard errors. The binding effects were facilitated by high arousal and were significantly larger in the 700- and 1000-ms-delay conditions than in the shorter delay conditions.

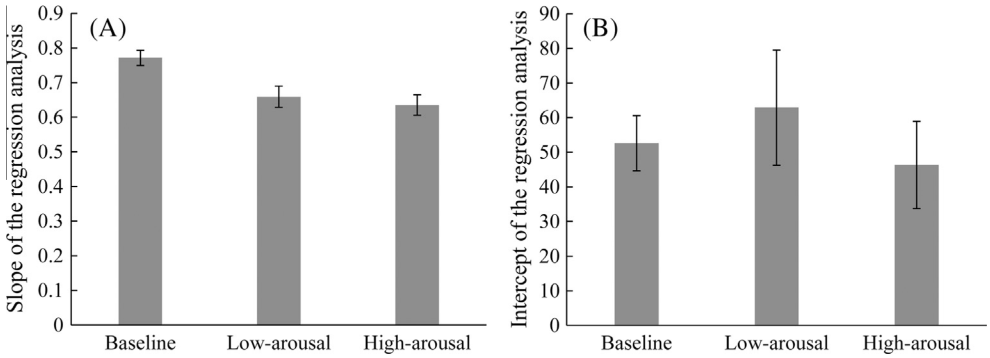

Fig. 4. The parameters of regression analyses. (A) The slope. (B) The intercept. Error bars represent standard errors. In the regression analyses, delay was the independent variable and participants' responses in the interval-estimation (low- and high-arousal conditions) and time-perception tasks (baseline) were the dependent variables. Agency (baseline and low-arousal vs. high-arousal) significantly influenced the slope but did not significantly affect the intercept.

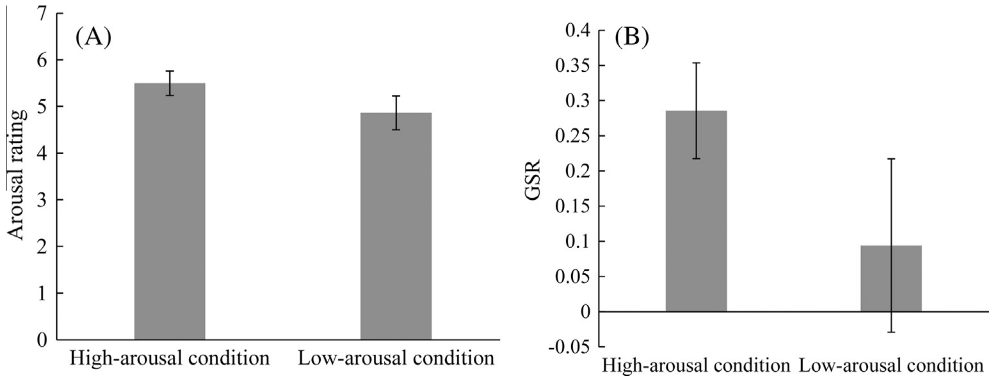

Fig. 5. The results of the subjective and objective arousal measurements. (A) The average arousal ratings in each arousal condition. (B) The average GSRs in each arousal condition. Error bars represent standard errors. Both arousal ratings and GSRs in the high-arousal condition were higher than those in the low-arousal condition.

intentional binding effect reflects a more implicit process enhanced by arousal. Our hypotheses were supported by the results. Increments in the interval between action and effect were accompanied by a decrease in agency rating, and surprisingly, by an increase in the intentional binding effect. Further, high levels of arousal enhanced the intentional binding effect, but had no influence on agency rating. The results suggest that subjective judgment of agency through self-reports and the intentional binding effect seem to reflect very different aspect of the sense of agency. In addition, the difference in arousal levels between low- and high-arousal conditions was confirmed by both subjective and objective measurements, indicating that the participants experienced greater arousal in the condition where they controlled a red square than that where they controlled a black square.

Before discussing our results in the context of theories on the sense of agency, we must address whether arousal facilitated the intentional binding effect because of a change in time perception. A number of prior studies on time perception have reported that increased attentional resources (Block & Zakay, 1997) or arousal (New & Scholl, 2009) resulted in time dilation, not compression. In Experiment 2, we examined the influence of arousal—by manipulating square color (red or black)—on the perception of temporal intervals.

3. Experiment 2

3.1. Method

3.1.1. Participants

Participants comprised 20 students with normal or corrected visual acuity (mean age: 24.6 years; range: 22–31 years), 18 of whom participated in the first experiment with a gap of approximately 5 months.

3.1.2. Procedure

Participants were tested individually; all trials were performed at a computer with a mouse. On completing the first time-perception task with feedback—identical to the time-perception task with feedback in Experiment 1, aimed at developing participants' perception of short intervals below 1000 ms—participants performed a different interval-estimation task (Fig. 6). In this interval-estimation task, participants were first shown a black cross in the center of a gray background for a random duration ranging from 500 to 1500 ms. A 30-mm square was then presented 15 mm below the cross. After a specific interval (100, 200, 300, 500, 700, or 1000 ms) a second 30-mm square appeared 15 mm above the cross, presented for 500 ms. The cross and two squares were removed, and participants were instructed to estimate the temporal interval between the presentation of the two squares in 100-ms units by clicking radio buttons with a mouse. The two arousal conditions were conducted separately, in blocks. In the high-arousal condition, the cross and the two squares were red, while in the low-arousal conditions, all stimuli were black. Each block contained 10 trials for delay conditions in a random order, resulting in a total of 60 trials. The block order was counterbalanced between participants. The experiment took 15 min on average.

3.2. Results and discussion

The means of estimations are presented in Fig. 7. The 2 × 6 (arousal × delay) repeated-measures ANOVA revealed a significant main effect of action-outcome delay ($F(5,95) = 461.98$, $p < .01$, $\eta_p^2 = 0.96$), as expected. Importantly, neither the main effect of arousal nor the interaction between the two variables were significant ($F(1,19) = 0.001$, *n.s.*, $\eta_p^2 = 0.00$; $F(5,95) = 1.28$, *n.s.*, $\eta_p^2 = 0.06$, respectively). The results clearly supported our prediction that arousal—manipulated by varying colors (red and black)—would not influence time perception. Therefore, the effect of arousal on intentional binding observed in Experiment 1 was considered to be a result of changes in binding processes rather than in time perception.

4. General discussion

In the present study, we examined the influence of delay and arousal on self-reported agency ratings and the intentional binding effect. We hypothesized that the self-reported agency rating would be impaired by action-outcome delay, while the intentional binding effect would be enhanced by arousal. The results supported our hypotheses and yielded some unpredicted, novel findings.

First, action-outcome delay influenced both the agency ratings and intentional binding, surprisingly in opposite directions. Previous research suggests that intentional binding and the sense of agency share certain common processes (see Moore & Obhi, 2012). However, in the present study, agency rating gradually decreased with increases in action-outcome delay (Fig. 2), while the binding effect increased in the longer delay (700 and 1000 ms) conditions (Fig. 3). An increased binding effect in longer delay conditions may have occurred because the size of the binding effect may rely on the interval duration. Specifically, for short delays below 500 ms, the intervals between actions and outcomes may be too small to observe its compression (i.e., the floor effect). Therefore, it may be inappropriate to compare binding effects between different intervals. Nonetheless, although participants presented very low agency ratings in the two longest delay conditions (mean agency ratings were 4.6 and 3.2 out of 9, respectively), the binding effects were relatively large (mean binding effects were 102 and 117 ms, respectively; see Haggard et al., 2002 with binding effects ranging 11–97 ms). This indicates that although the participants gave a lower agency rating, they may have still implicitly bound their action to the effect.

To investigate the intentional binding effect further, we conducted regression analyses on participants' time estimation responses. The results showed that sense of agency reduced the slope but not the intercept (Fig. 4). Therefore, sense of agency may have slowed down the internal clock, as suggested in a previous study (Wenke & Haggard, 2009), rather than eliminated a fixed period of time for perception. Kühn et al. (2013) examined changes in the binding effect for short action-outcome intervals (200, 300, and 400 ms), observing that differences in the binding effect between agency conditions (passive or active action) increased with increasing action-outcome intervals. However, since their post hoc comparison results were not reported, it was unclear whether the increment in the binding effect was a result of slowing down the internal clock. Similarly, another study found that the intentional binding effect increased, corresponding to longer

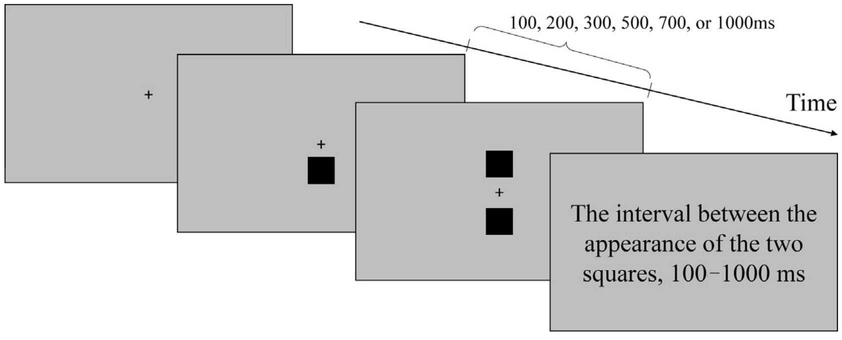

Fig. 6. The sequence of events for the time-perception task in Experiment 2.

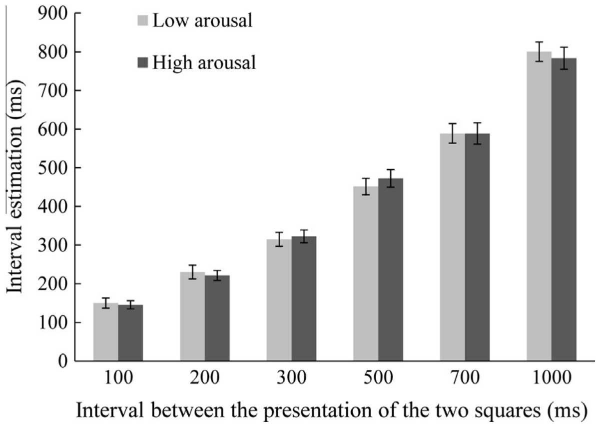

Fig. 7. Interval estimations in Experiment 2 for each delay condition according to arousal. Error bars represent standard errors. The participants' time perception for different intervals was not influenced by arousal.

action-outcome intervals (500, 900, and 1300 ms; Buehner & Humphreys, 2009). In their study, agency did not interact with delay; therefore, sense of agency appeared to eliminate a fixed amount of time for perception. However, since they did not examine the binding effect with shorter intervals, time-perception tendencies that operate during binding were unclear. Nonetheless, our results are consistent with previous studies that found that the intentional binding effect increased with increases in action-outcome delay. Moreover, from the regressions, we concluded that sense of agency slowed down the internal clock rather than eliminated a fixed amount of time, resulting in the intentional binding effect.

More importantly, we also examined the influence of an internal factor—arousal—on the sense of agency; arousal significantly enhanced intentional binding but did not affect the subjective judgment of agency. Although this manipulation was simple, both the subjective rating and objective GSR measurement confirmed that the participants experienced greater arousal when they controlled a red square than when they controlled a black square. Furthermore, Experiment 2 results confirmed that this enhancement was not induced by changes in time perception. Haggard and Cole (2007) examined the influence of attention on the intentional binding effect, finding that the intentional binding effect was stronger in the condition where participants were unable to direct their attention to action or effect, than in the condition where they knew what to attend to. This study suggests that the binding effect could also involve a reconstruction of the percept of action and effect (Haggard & Cole, 2007). We agree that the intentional binding effect probably involves both prospective and retrospective processes, and arousal enhances the former. However, since delay impaired retrospective processes but did not diminish the binding effect, this indicates that prospective rather than retrospective processes may be dominant in the intentional binding effect. Detailed research on the interaction of the two types of processes needs to be conducted.

In conclusion, the present study examined the influence of delay and arousal on the self-reported sense of agency and the intentional binding effect. We found that longer delays—external cues—greatly impaired self-reports but not the intentional binding effect; rather, the binding effect was even stronger with longer delays. On the other hand, arousal—an internal factor—enhanced the intentional binding effect, but not self-report. We concluded that the subjective judgment of agency and the intentional binding might reflect very different aspects of the sense of agency.

Acknowledgments

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