

Voluntary action and tactile sensory feedback in the intentional binding effect

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Abstract The intentional binding effect refers to a subjective compression over a temporal interval between the start point initialized by a voluntary action and the endpoint signaled by an external sensory (visual or audio) feedback. The present study aimed to explore the influence of tactile sensory feedback on this binding effect by comparing voluntary key-press actions with voluntary key-release actions. In experiment 1, each participant was instructed to report the perceived interval (in ms) between an action and the subsequent visual sensory feedback. In this task, either the action (key-press or key-release) was voluntarily performed by the participant or a kinematically identical movement was passively applied to the left index finger of the participant. In experiment 2, we explored whether the difference in the perception of time was affected by the direction of action. In experiment 3, we developed an apparatus in which two parallel laser beams were generated by a laser emission unit and detected by a laser receiver unit; this allowed the movement of the left index finger to be detected without it touching a keyboard (i.e., without any tactile sensory feedback). Convergent results from all of the experiments showed that the temporal binding effect was only observed when the action was both voluntary

and involved physical contact with the key, suggesting that the combination of intention and tactile sensory feedback, as a form of top-down processing, likely distracted attention from temporal events and caused the different binding effects.

Keywords Intentional binding · Key-press · Key-release · Tactile sensory feedback

Introduction

Voluntary action, which involves premeditation, is the primary way in which humans interact with their environment (Elsner and Hommel 2004; Yoshie and Haggard 2013). Much of the interest in voluntary action concerns the intentional binding effect (Haggard et al. 2002; Moore and Obhi 2012; Nattkemper et al. 2010; Hughes et al. 2013), which refers to a subjective compression of time between the initiation of a voluntary action and its conclusion, which is signaled by the reception of external sensory (visual or audio) feedback.

Factors that influence this binding effect are voluntary action, visual/auditory sensory feedback, or the causal relationship between them. Some researchers assert that intention is necessary for this effect. This view emphasizes the role of prediction in intentional binding. In a study in which intention was disrupted by transcranial magnetic stimulation (TMS) over the motor cortex, the temporal binding effect was significantly weakened (Haggard et al. 2002). Moore and Haggard (2008) also found that the shift in the perceived time of action toward the “expected time” occurred even in rare “action only” trials. In addition, the properties of visual/auditory sensory feedback have also been found to influence the binding effect (Yoshie and Haggard 2013; Failing and Theeuwes 2016). Highly rewarded visual sensory feedback

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was found to expand perceived time (Failing and Theeuwes 2016). The third factor lays emphasis on the causal relationship between actions and their sensory (visual or audio) consequences (Stetson et al. 2006; Humphreys and Buehner 2009; Buehner 2012; Desantis et al. 2016). Causal inferences are more likely to be based on the properties of the action-feedback relation, such as contiguity and contingency. Contiguity refers to the temporal proximity of the actions and the visual/auditory sensory feedback, and studies have found that the binding effect is weakened when the action-feedback delays is increased (Haggard et al. 2002). Increasing the probability of outcome with action has also been shown to significantly increase the contribution of predictive and retrospective inferential processes to intentional binding (Engbert and Wohlschläger 2007; Moore et al. 2009).

The relationship between voluntary action and visual sensory feedback appears to partially explain the emergence of binding effect for voluntary key-release actions. As the temporal interval between action and visual sensory feedback was ≤ 150 ms, both voluntary key-press and key-release actions induced the same intentional binding effect (Zhao et al. 2013). These results suggested that the combination of voluntary action and visual sensory feedback determined the short-lived binding effect for voluntary key-release actions. However, when the temporal interval between action and visual sensory feedback was greater than 150 ms, the voluntary key-press induced a robust binding effect, whereas the key-release action induced no binding effect (Zhao et al. 2013, 2014b). This difference in binding effect between the voluntary key-press and key-release actions cannot be explained by any of the three factors mentioned above, because these factors were held constant across the two voluntary action conditions. The cause of this difference in binding effect between voluntary key-press and key-release actions is far from fully understood.

By comparing key-press actions, where a key-press action is defined as finger contact with the keyboard, with key-release actions, where a key-release action is defined as finger departure from the keyboard, we found that the tactile perception related to touching or contacting the keyboard might have been ignored in previous studies. This combination of voluntary action and tactile sensory feedback from the keyboard for key-press actions might influence temporal experience. A recent study suggested that tactile stimuli might influence our perception of time. When tactile stimuli were presented to the motor effector before and during movement, their perceived temporal separation was reduced. The temporal sense was found to be compressed around the hand movements only when tactile stimuli were delivered to the hand that was intended to move and not when delivered to the stationary hand (Tomassini et al. 2014). We hypothesized that the sense of

touch or tactile perception caused by these types of voluntary actions leads to the different binding effects observed for key-press and key-release actions.

To verify this hypothesis, we needed to exclude several other possibilities: First, we needed to ascertain whether the binding effects associated with voluntary and passive touch were the same. Second, we needed to determine whether the direction of action influenced the different binding effects observed in the voluntary key-press and voluntary key-release conditions. Finally, we needed to examine whether tactile sensory feedback was sufficient to create the difference in the binding effects associated with the two actions. The present study was designed to answer these questions and was conducted to further explore the intentional binding effect through comparison between key-press and key-release actions. In experiment 1, we aimed to determine whether the different binding effects associated with key-press and key-release actions could be observed in both voluntary and involuntary conditions. A novel apparatus was employed (Zhao et al. 2014a) that enabled the participants to complete voluntary and involuntary finger movements, including both key-press and key-release actions (see Fig. 1). If the voluntary sense of touch is the cause of the different binding effects observed for the two actions, then a stronger binding effect should be observed in the voluntary key-press condition than in the other conditions. A naturalistic key-press corresponds to a *downward* action, whereas a key-release corresponds to an *upward* action. To exclude the potential factor of direction, in experiment 2, we placed the keyboard upside down, and the participants voluntarily pressed the buttons in an upward direction with tactile sensory feedback (see Fig. 3). If the direction of movement was the major cause of the difference in binding effects for the different actions, then the downward key-press and upward key-press actions should result in different binding effects. To further support our hypothesis that the combination of intention and tactile sensory feedback from keyboard was necessary, we developed another apparatus that could detect the movement of the finger by using two parallel laser beams (top and bottom laser beams; when the finger moves *downward*, the laser receiver will detect a stop signal for the top laser beam first and for the bottom laser beam second; when the finger moves *upward*, the laser receiver will detect a stop signal for the bottom laser beam first and top laser beam second). With this device, the confounding factor elicited by the tactile sensory feedback from the key-press action will be eliminated, allowing us to explore the pure relationship between action and time perception in experiment 3. We hypothesized that if both intention and tactile sensory feedback are critical, there should be no

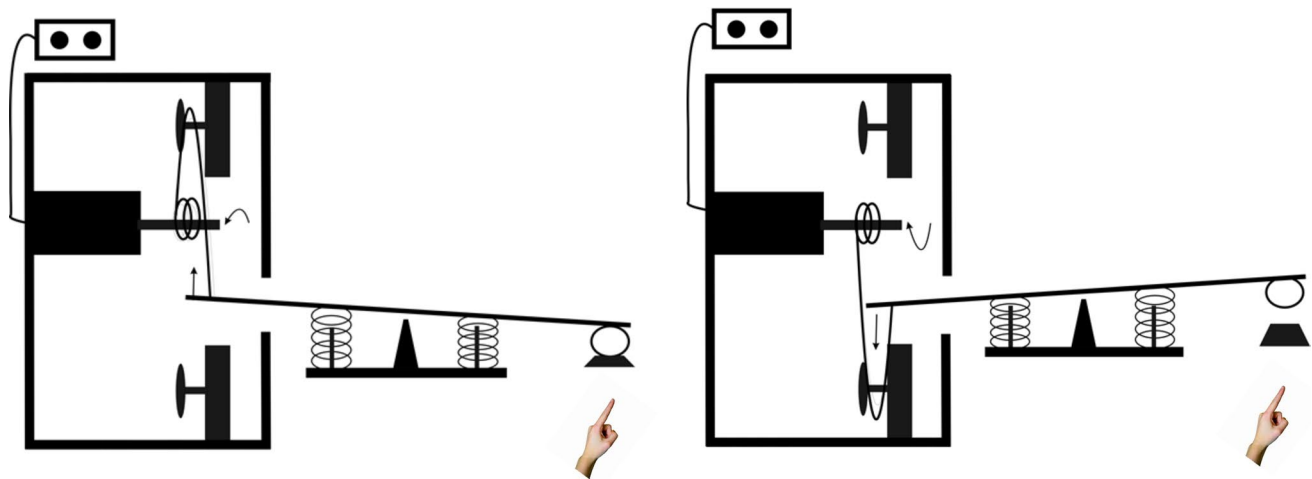


Fig. 1 Illustration of the experimental setup (MVPL). The *left panel* represents the involuntary key-press actions achieved by using this technique, whereas the *right panel* represents the involuntary key-release actions

differences between the pressing and releasing conditions when tactile feedback was removed.

Experiment 1

Materials and methods

Participants

Seventeen right-handed healthy volunteers (7 females; $M = 22.70$, $SD = 2.02$) participated in the experiment. All of the participants had normal or corrected-to-normal vision, provided written informed consent prior to the experiment and were paid for their participation.

Apparatus

A motor-driven voluntary/involuntary pressing/releasing lever (MVPL) was employed in this experiment (Zhao et al. 2014a). This apparatus consisted of a motor-driven engine system and a lever system. Each participant was asked to place his or her left index finger in the circle of the lever. To complete the involuntary key-press and key-release actions, the motor engine system, through the lever system, transferred force and caused the participant's left index finger to move up and down (Fig. 1). Voluntary key-press and key-release actions were achieved when the engine system was powered off.

Experimental tasks and procedure

A 17-inch cathode-ray tube (CRT) monitor that operated at a refresh rate of 85 Hz and a resolution of 1024×768

pixels was used in conjunction with the E-prime 2.0 software package for stimulus presentation and behavioral data collection. All of the participants were seated approximately 70 cm from the presentation screen in a sound-attenuated room. The experiment consisted of 8 blocks for each condition: 2 types of actions (key-press and key-release) $\times$ 2 types of agency (voluntary and involuntary) $\times$ 2 intervals (240–280 ms and 440–480 ms). Each block consisted of 50 trials (400 trials in total). The order of the eight blocks was counterbalanced across the participants. The general procedure for each trial was as follows: A black square (stimulus 1(S1); size: 1×1 cm) was first presented for at least 500 ms; then, S1 disappeared after one of the two intervals (240–280 or 440–480 ms) following participant completion of one of the different types of actions. A red square (stimulus 2(S2); 1×1 cm) was then presented for 500 ms, and the participants were asked to report the perceived interval between the two stimuli using a timescale. The dependent variable was the subjective interval duration that was estimated at the end of each trial. The different types of actions/conditions are described in greater detail below.

Voluntary key-press condition When S1 was presented in the center of the screen, the participant was asked to relax and to place his or her left index finger in the circle of the MVPL. The participant was free to press the left Ctrl key whenever he or she wished. To prevent unconscious key-presses and possible mistakes, we defined the first 500 ms of each trial as an invalid phase; during this period, pressing the Ctrl key would generate a warning that asked the participant to restart the current trial. When the Ctrl key was pressed after the invalid phase, S1 would disappear simultaneously with the pressing action, and a blank screen that lasted for

a random interval (240–280 or 440–480 ms) would follow. S2 would then appear in the center of the screen for 500 ms, and the participant was then asked to estimate the interval between S1's disappearance and S2's appearance by clicking the left mouse key on a continuous time scale (which ranged from 0 to 600 ms and had 5 markers that represented 100 ms divisions). The participant was free to click on any part of the scale to provide a precise answer. The timescale would not disappear until the estimate was entered. Finally, the trial concluded with an inter-trial interval that randomly ranged from 1800 to 2400 ms.

Voluntary key-release condition Each participant was asked to place his or her left index finger in the circle of the MVPL and to relax. A blank screen was presented until the participant pressed and held down the Ctrl key, which elicited the presentation of S1 in the center of the screen. The participant was asked to release the Ctrl key whenever he or she desired. Once the participant released the Ctrl key by voluntarily lifting the finger or wrist after the invalid phase, S1 immediately disappeared. The rest of the procedure was identical to that for the voluntary key-press condition.

Involuntary key-press condition Each participant was asked to place his or her left index finger in the circle of the MVPL, and the experimenter in the next chamber used an electronic switch to control the motor engine during each trial, leading to the participants experiencing involuntary key-press actions. In this condition, the participant was asked to put his or her left index finger in the circle of the lever system and to relax; next, the motor system, under the control of the same experimenter, would push the participant's finger down; S1 would disappear; and after a predefined interval, S2 would appear. The rest of the procedure was the same as that for the other conditions.

Involuntary key-release condition In this condition, each participant was asked to press and hold down the Ctrl key; then, his or her left index finger was lifted by the lever that was controlled by the experimenter. The rest of the procedure was the same as that of the other three conditions.

Prior to the formal experiment, to become familiar with the MVPL, the participants conducted practice trials in which they viewed 12 examples of different time intervals ranging from 100 to 600 ms and practiced estimating the duration. The participants then took part in four trials for each of the four conditions.

In addition, we asked additional 29 participants (12 females; $M = 22.35$, $SD = 1.63$) to complete a 1 to 7 point (from lowest to highest) causal ratings scale regarding the causality between action and visual sensory feedback.

Results

For the rating task, the degree of causality between action and visual sensory feedback among the voluntary key-press ($M = 6.01$, $SE = 0.27$), voluntary key-release ($M = 6.11$, $SE = 0.25$), involuntary key-press ($M = 6.00$, $SE = 0.31$), and involuntary key-release ($M = 6.09$, $SE = 0.39$) conditions showed no significant difference ($F(3, 84) = 1.21$, $p = 0.31$, $\eta_p^2 = 0.04$).

For the reported time (Fig. 2), the main effects of agency type ($F(1,16) = 5.32$, $p = 0.04$, $\eta_p^2 = 0.25$), action type ($F(1,16) = 19.26$, $p < 0.001$, $\eta_p^2 = 0.55$), and interval duration were all significant ($F(1,16) = 16.38$, $p = 0.001$, $\eta_p^2 = 0.51$). The interaction between action type and agency type was also significant ($F(1,16) = 14.54$, $p = 0.002$, $\eta_p^2 = 0.48$). A simple effect analysis of action type revealed that the reported time was shorter for the voluntary key-press condition ($M = 252.96$ ms, $SE = 12.45$ ms) than for involuntary key-press condition ($M = 302.82$ ms, $SE = 11.74$ ms; $t = -4.06$, $p = 0.001$); no significant difference was found between the voluntary key-release ($M = 294.27$ ms, $SE = 15.84$ ms) and involuntary key-release conditions ($M = 303.84$ ms, $SE = 15.78$ ms, $t = -0.09$, $p = 0.93$). With respect to agency type, the reported time was shorter for the voluntary key-press condition compared with the voluntary key-release condition ($t = -7.81$, $p < 0.001$); no significant difference was observed between the involuntary key-press and involuntary key-release conditions ($t = 0.93$, $p = 0.37$). Neither the interaction between action type and interval type ($F(1,16) = 1.02$, $p = 0.33$, $\eta_p^2 = 0.06$) nor the interaction between agency and interval type ($F(1,16) = 0.30$, $p = 0.59$, $\eta_p^2 = 0.02$) was significant. The three-way interaction between agency type, interval type, and action type was also not significant ($F(1,16) = 0.69$, $p = 0.42$, $\eta_p^2 = 0.04$). To determine whether the magnitude of binding effects remained stable across all of the trials, we compared the first half of the trials with the second half of the trials. No differences were observed between the two halves for the four action conditions across the two intervals (all $t < 0.92$, all $p > 0.05$).

Discussion

Our experiment showed that the reported time for the voluntary key-press condition was significantly shorter than that for the other three conditions across the two time intervals. Moreover, there was no difference in the reported time among the voluntary key-release, involuntary key-press, and involuntary key-release conditions.

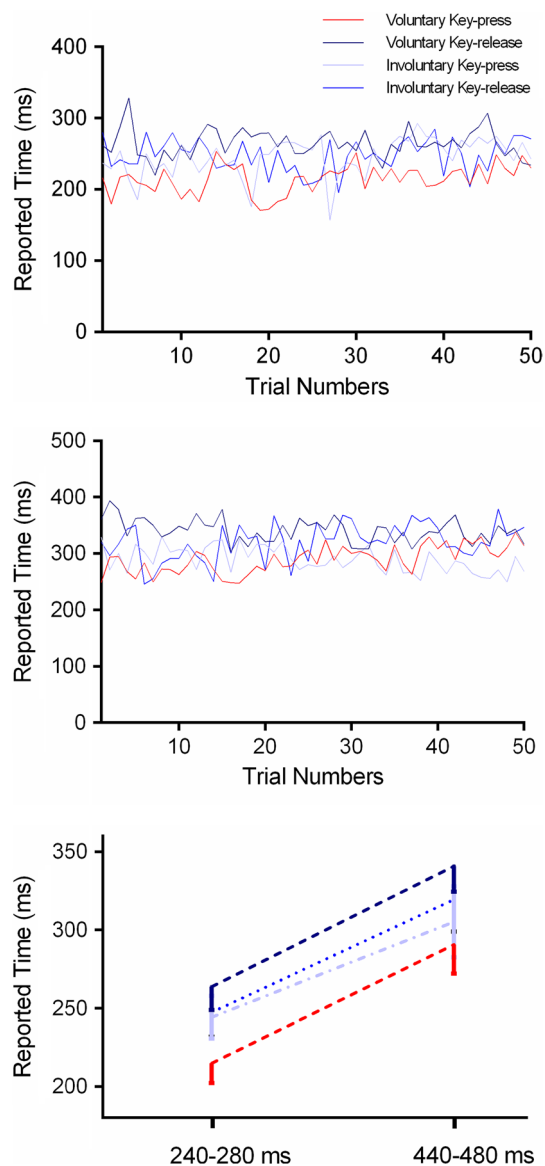


Fig. 2 The results of experiment 1. Reported times are shown for each trial for the 240–280 ms (*top*) and the 440–480 ms intervals (*middle*). The *x*-axis represents the number of trials, whereas the *y*-axis represents the reported time. The *bottom figure* depicts the reported times. The *x*-axis represents the two interval lengths (240–280 and 440–480 ms), and the *shapes* represent the reported times

The temporal binding effect for a voluntary key-press supports the results of previous studies that found this voluntary action induced a robust compression effect (Buehner 2012; Haggard et al. 2002; Engbert and Wohlschläger 2007; Engbert et al. 2008; Cravo et al. 2009; Humphreys and Buehner 2009; Moore et al. 2013, 2009; Ebert and Wegner 2010; Caspar et al. 2015). Moreover, different subjective estimations of time between key-press and key-release actions were also demonstrated here by comparing the voluntary/involuntary key-press and key-release actions

(Zhao et al. 2013, 2014b). Though the degrees of causality among the four action conditions were the same, only the voluntary key-press induced a compression of time perception. Comparison of the reported durations between voluntary key-press and voluntary key-release actions showed that intention, visual sensory feedback, and causality between them were each insufficient for the binding effect. Therefore, our experiment showed that the combination of voluntary action and somatic sensory feedback from the keyboard appeared to result in the binding effect for the voluntary key-press action. However, to exclude the potential importance of the direction of movement, we changed the direction of movement in experiment 2 to further test our hypothesis.

Experiment 2

Materials and methods

Participants

Eighteen right-handed healthy volunteers (10 females; $M = 21.33$, $SD = 2.02$) participated in the experiment. All of the volunteers had normal or corrected-to-normal vision, provided their written informed consent prior to the experiment, and were paid for their participation.

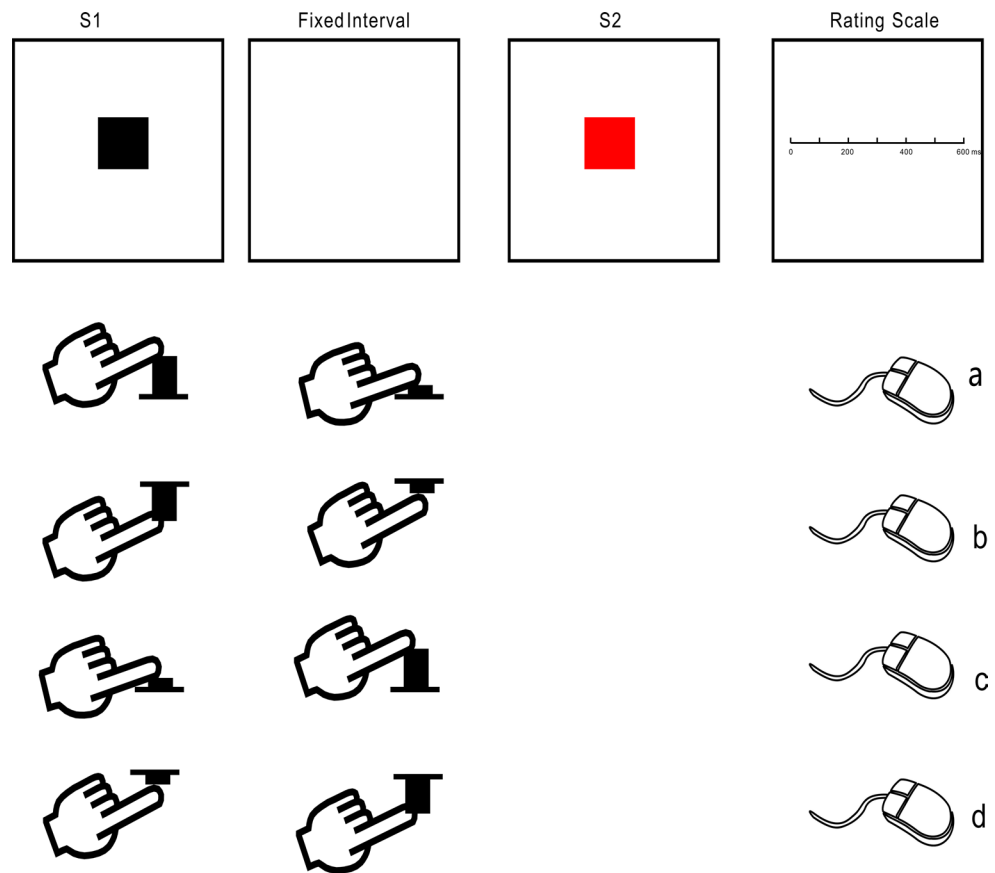
Stimuli and procedure

The experiment involved eight conditions: two types of voluntary actions (key-press and key-release), two directions (downward and upward), and two intervals (240–280 ms and 440–480 ms). Thus, for each time interval, the experiment contained four conditions, with 8 individual blocks in total. Each block consisted of 50 trials (400 trials in total). The order of the eight blocks was counterbalanced across the participants. The procedure was the same as for experiment 1 except for particular aspects of the four actions (Fig. 3).

In the downward key-press condition, the keyboard was upright. The distance between the Ctrl key and the desk screen was approximately 3 cm for each of the four types of actions. Each participant was asked to relax and to place his or her left index finger on the Ctrl key. S1 (the same stimulus as in experiment 1) appeared in the center of the screen, and the participant was asked to press the Ctrl key voluntarily.

In the upward key-press condition, the keyboard stand was upside down, and the participant was asked to place his or her left finger under the Ctrl key. When S1 first appeared in the center of the screen, the participant was asked to lift his or her finger and contact the Ctrl key voluntarily, at which point S1 would disappear.

Fig. 3 Schematic illustration of the procedure of experiment 2. Both *a* and *c* depict a voluntary key-press, but with different movement directions, and both *b* and *d* depict a voluntary key-release, but with different movement directions. When any action (*second column*) was performed, the *black square* disappeared, leaving a blank screen. After a predefined interval, the *red square* appeared (colour figure online)



In the upward key-release condition, the keyboard was upright, and the participant was asked to press and hold the Ctrl key and then release it. S1 appeared on the screen when the key was pressed down and disappeared when the key was released.

In the downward key-release condition, the keyboard stand was upside down, and the S1 did not appear on the screen. The participant was required to press and hold the Ctrl key in the upward direction. S1 then appeared in the center of the screen, and the participants were required to voluntarily release the key in a downward direction to cause the S1 to disappear.

Similar to experiment 1, all of the participants were familiar with the task before the experiment, which was accomplished using the same practice procedure. The reported times were used as the dependent variable in further analyses.

In addition, the same 29 (as in experiment 1) participants were instructed to rate the degree of familiarity of actions using a 1 to 7 point (unfamiliar to familiar) rating scale.

Results

We analyzed the mean reported time for the 8 conditions (Fig. 4). The main effect of action type was significant,

$F(1,17) = 32.00$, $p < 0.001$, $\eta_p^2 = 0.65$; with a shorter mean reported time for voluntary key-press actions ($M = 237.31$ ms, $SE = 13.25$ ms) than for voluntary key-release actions ($M = 270.00$ ms, $SE = 12.37$ ms). The main effect of direction was not significant, $F(1,17) = 0.11$, $p = 0.74$, $\eta_p^2 = 0.01$, but the main effect of interval type was significant, $F(1,17) = 37.59$, $p < 0.001$, $\eta_p^2 = 0.69$. The interactions between action type and direction, $F(1,17) = 1.63$, $p = 0.22$, $\eta_p^2 = 0.09$, action type and interval type, $F(1,17) = 1.43$, $p = 0.25$, $\eta_p^2 = 0.08$, and direction and interval type were not significant, $F(1,17) = 0.70$, $p = 0.41$, $\eta_p^2 = 0.04$. The three-way interaction between action type, direction, and interval length also was not significant, $F(1,17) = 1.28$, $p = 0.27$, $\eta_p^2 = 0.07$.

To determine whether the magnitude of binding remained stable across all trials, we split the trials into two halves and compared between them. No differences were observed between the two halves for the four action conditions across the two intervals (all $t < 1.04$, all $p > 0.05$).

Discussion

Our experiment showed that downward key-presses and upward key-presses induced an equally strong binding

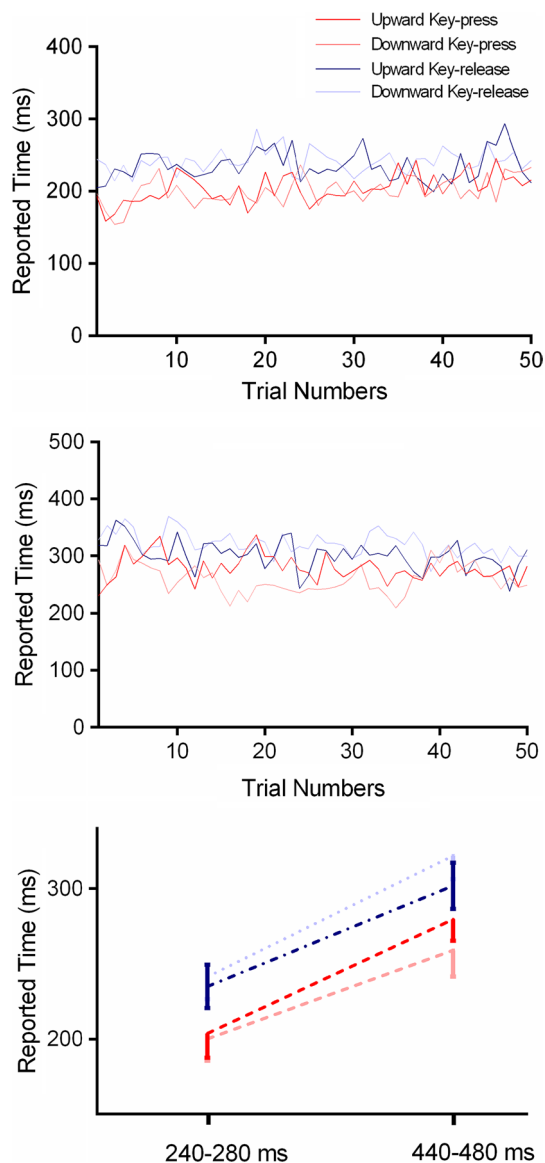


Fig. 4 The results of experiment 2. Reported times are shown for each trial for the 240–280 ms (top) and the 440–480 ms intervals (middle). The x-axis represents the number of trials, whereas the y-axis represents the reported times. The bottom figure illustrates the mean reported time for the different voluntary actions. The x-axis represents the two interval types (240–280 and 440–480 ms), and the shapes represent the reported times (pressing and releasing)

effect across the two time intervals. The reported times were significantly shorter for the voluntary key-press condition than for the voluntary key-release condition. Although the direction of movement was upward and unfamiliar for the participants, the upward key-press action also induced the same binding effect that was induced by the downward key-press action. This result is novel. We excluded the possibility that familiarity might be a factor that influenced the binding effect, for two reasons. First, although there were different degrees of familiarity between upward key-press

and downward key-press, no different binding effect was found between them. Second, the magnitude of binding was uniform across trials. However, there was insufficient evidence to suggest that both intention and tactile sensory feedback were responsible for the difference in binding effect between the key-press and key-release actions. To further investigate the role of the tactile sensory feedback in the binding effect, we removed the tactile sensory feedback from the key-press action in experiment 3.

Experiment 3

Materials and methods

Participants

Sixteen right-handed healthy volunteers (10 females; $M = 22.50$, $SD = 2.19$) participated in the experiment. All of the volunteers had normal or corrected-to-normal vision, provided their written informed consent prior to the experiment, and were paid for their participation.

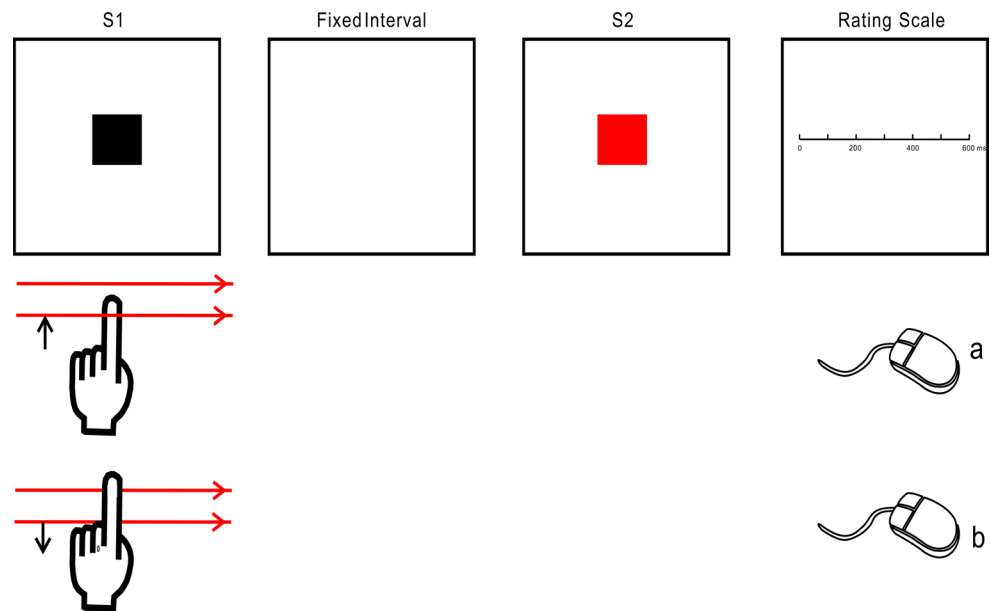
Stimuli and procedure

The experiment consisted of four blocks for each condition: two types of voluntary action (pressing and releasing) and two temporal intervals (240–280 and 440–480 ms). Each block consisted of 50 trials (200 trials in total). The order of the 4 blocks was counterbalanced across the participants. The procedure was the same as that for experiments 1 and 2, except for particular aspects of the two actions (Fig. 5).

To perform this experiment, we developed a novel apparatus that consists of laser emission/receiver units, a circuit board system, and a battery unit. During operation, two parallel laser beams are generated by the laser emission unit and received by the laser receiver unit. The distance between the two laser beams (top vs. bottom) is 1.5 cm. When the left index finger of the participant moves *downward* (i.e., pressing action), the laser receiver unit detects a stop signal for the top laser beam first and the bottom one second (Fig. 5b). In contrast, when the left index finger of the participant moves *upward* (releasing action), the laser receiver unit detects a stop signal for the bottom laser beam first and then for the top one second (Fig. 5a). Using this apparatus, neither pressing nor releasing actions are influenced by tactile sensory feedback from a keyboard.

In the pressing condition, S1 appeared in the centre of the screen, and the participant was asked to move his or her left index finger downwards to cause S1 to disappear. After a temporal interval (240–280 or 440–480 ms), S2 appeared, and the participant was asked to estimate the duration of the interval between S1 and S2. During the

Fig. 5 Illustration of the sequence of experiment 3. The illustration shows the sequence of the voluntary actions (releasing, *a*; pressing, *b*)



releasing condition, the S1 appeared in the center of screen, and the participant was asked to move his or her left index finger upwards to cause S1 to disappear. After a temporal interval (240–280 or 440–480 ms), S2 appeared, and the participant was asked to estimate the duration of the interval between S1 and S2.

Results

We analyzed the mean reported time for the 4 conditions. The main effect of action type was not significant ($F(1,15) = 0.06$, $p = 0.82$, $\eta_p^2 = 0.004$), with no significant difference in the mean reported time between the voluntary pressing ($M = 262.49$ ms, $SE = 13.59$ ms) and voluntary releasing actions ($M = 260.13$ ms, $SE = 13.45$ ms). The main effect of interval type was significant ($F(1,15) = 12.58$, $p = 0.003$, $\eta_p^2 = 0.46$), whereas the interaction between action type and interval type was not ($F(1,15) = 0.01$, $p = 0.92$, $\eta_p^2 = 0.001$).

Discussion

The novel apparatus emitted two parallel laser beams that were generated by the laser emission unit and detected by the laser receiver unit, which allowed the movement of the left index finger to be detected without finger contact with a keyboard (i.e., without any tactile sensory feedback). During this experiment, we explored the relationship between action and time perception while avoiding the potential confounding factor of tactile sensory feedback.

When we removed the tactile sensory feedback from the key-press action, the intentional binding effect was the same as that induced by the release action. The results from this experiment provide the first direct evidence that both intentionality and tactile sensory feedback are necessary to induce the binding effect. We found different binding effects between key-press and key-release actions in both experiment 1 and 2. When the temporal interval was induced by the voluntary key-press action, temporal compression was observed, whereas no such compression was observed for the voluntary key-release action. However, when this tactile sensory feedback was eliminated from the voluntary key-press actions, the difference between the key-press and key-release conditions disappeared. In addition, the combination of involuntary action and tactile sensory feedback was found to not induce temporal compression in experiment 1. These results provide the first direct evidence that both intention and tactile sensory feedback are essential for different binding effects between two voluntary actions.

General discussion

The present study aimed to systematically explore the mechanism underlying the difference in the binding effect observed between key-press and key-release actions. Our results ruled out the possibility that intention, visual/auditory sensory feedback, or the causality between action and visual sensory feedback were responsible for the difference in the binding effect induced by the two actions. In addition, our results provide direct evidence that the

combination of intention and tactile sensory feedback can change our perception of time.

Consistent with our previous studies in which a temporal interval >150 ms was used (Zhao et al. 2013, 2014b), we found that only voluntary key presses induced the intentional binding effect, whereas voluntary key releases did not. Although the combination of voluntary action and visual sensory feedback was the same between the two conditions, the binding effect only emerged when the action was active and the finger had some kind of contact with the keyboard. This result is consistent with a previous study that found the intentional binding only emerged when the action was voluntary and causally connected to sensory feedback (Cravo et al. 2009). However, because this previous study did not investigate other actions, the importance of the combination of voluntary action and contact with the keyboard in the two actions could not be determined.

Our results provide evidence supporting the notion that the sense of touch can change our perception of time. Touch is by far the most interesting and necessary of the five senses. The sense of touch is an exemplary case of sensorimotor integrative processes. Tactile events uniquely occur on the surface of body and are often caused by an active movement of the body (Tomassini et al. 2014). Any movement requires acute awareness of one's own body, which is gained through proprioception, an internal form of tactile sense (O'Shaughnessy 1989). Experiments 1 and 2 demonstrated that the binding effect only emerged under the condition with the combination of intentionality and tactile sensory feedback from the keyboard. The combination of voluntary action and tactile sensory feedback from the keyboard resulted in a sense of touch, which might change the participant's temporal experience. This effect only appeared in the condition that combined voluntary action with somatic sensory feedback condition; it did not appear in the passive condition. It also suggested that conducting a motor task involving contact with the keyboard involved top-down processing, which induced changes in time perception. We hypothesize that this sense of touch was similar to a sense of agency. Familiarity with the actions was also addressed in our study. The magnitude of the binding effect did not vary across trials for experiments 1 and 2. In addition, although the two voluntary key-press actions we examined in experiment 2 differed in their degree of familiarity, they induced the same magnitude of binding. This binding effect only emerged in the voluntary condition that included tactile sensory feedback. In experiment 3, we provided robust evidence illustrating that the binding effect disappeared when the tactile sensory feedback was removed. This result suggested that both voluntary and tactile sensory feedback might have been responsible for the different binding effect between the two actions. In another study, a deafferented patient (IW) with no tactile sensory feedback revealed

tone binding in the normal range (Haggard and Cole 2007). That is, IW showed a binding effect of 53 ms for the tone, and the normal subjects' in the main experiment showed binding effects for the tone ranging from 133 to 37 ms, with mean of 85 ms. This might be explained by the combination of voluntary action and audio sensory feedback, rather than the combination of voluntary action and tactile sensory feedback. Further studies are needed to explore the consolidation of different sensory feedback modalities, such as the tactile, visual, and auditory modalities.

In conclusion, our results revealed that different experiences of time were observed between voluntary key-press and key-release actions, supporting previous studies. Moreover, our results provide evidence that a voluntary sense of touch is a critical factor influencing the intentional binding effect.

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