Choosing, Doing, and Controlling: Implicit Sense of Agency over Somatosensory Events

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Abstract

Sense of agency—a feeling of control over one's actions and their outcomes—might include at least two components: free choice over which outcome to pursue, and motoric control over the action causing the outcome. We orthogonally manipulated locus of outcome choice (free choice/instructed) and motoric control (active/passive), while measuring the perceived temporal attraction between actions and outcomes ("temporal binding") as an implicit marker of agency. Participants also rated stimulus intensity. Actions caused higher or lower levels of either painful heat, or mild electro-tactile stimulation. We found that both motoric control and outcome choice contributed to outcome binding. Moreover, free choice, relative to instructed action, attenuated high intensity outcomes, but only when participants made an active movement. Thus, choosing, not just doing, influences temporal binding and perceived sensory magnitudes, though in different ways. Our results show these implicit measures are sensitive both to voluntary motor command and instrumental control over action outcomes.

Keywords: action selection; temporal binding; pain; sense of agency; sensory attenuation; tactile; voluntary action

Choosing, Doing, and Controlling: Implicit Sense of Agency over Somatosensory Events

Voluntary action is accompanied by a “sense of agency”—the feeling of initiating and controlling one’s own actions and their sensory outcomes. The delay between a movement and its outcome is perceived as shorter when the movement is voluntary than when it is involuntary—an effect sometimes called “intentional binding” (Haggard & Clark, 2003; Haggard, Clark, & Kalogeras, 2002). This temporal binding effect consists of two dissociable components: a shift in the perceived time of the action forward towards the outcome (“action binding”) and a shift in the perceived time of the outcome backward towards the action that caused it (“outcome binding”; Haggard, Clark, & Kalogeras, 2002; Wolpe, Siebner, Haggard & Rowe, 2013). Temporal binding occurs even without voluntary action, for example, when judging the time of an external event with a sensory consequence (Buehner, 2012; Buehner & Humphreys, 2009). Nevertheless, comparing an agentic condition to an appropriate non-agentic control condition reveals a component of binding attributable to intentional action, over and above other factors. This intentional component of binding has been proposed as one implicit marker of agency (Haggard, 2008).

The concept of agency includes two forms of control. First, agents select which outcome to pursue. Second, they use motoric control to initiate the action that triggers the outcome. The former component, outcome selection control, has received limited attention in the temporal binding literature. Binding increases with reliability of outcome timing (Haggard et al., 2002) and probability of outcome occurrence (Moore & Haggard, 2008). Moreover, top-down (false) beliefs about control over outcome timing influence binding (Desantis, Roussel, & Waszak, 2011). On the other hand, one study found no effect of control over outcome identity (i.e., which of two tones was triggered by the action) on binding (Desantis, Hughes, & Waszak, 2012). However, that study used neutral outcomes without any particular meaning to participants, making action selection arbitrary.

In a novel design, we orthogonally manipulated choice over outcome identity (free or instructed) and motoric action initiation (active or passive) to investigate how each factor contributes to temporal binding, while keeping outcome identity entirely predictable across conditions. To make the choice of outcome meaningful, we used pain as a motivationally significant outcome. Previous studies that used valenced outcomes found less temporal binding for negative outcomes than for positive or neutral outcomes (Takahata et al., 2012; Yoshie & Haggard, 2013). Moreover, voluntary cognitive control should normally select actions that minimize pain. We therefore expected stronger temporal binding when choosing actions that cause less pain, rather than more pain.

Sensory attenuation has also been proposed as an implicit measure of agency (Blakemore, Frith, & Wolpert, 1999). Compared to passive movements, voluntary actions reduce the perceived intensity of sensory events simultaneous with (Williams, Shenasa, & Chapman, 1998) or caused by the movement itself (e.g., Blakemore et al., 1999; Wang, Wang, & Luo, 2011). Whether sensory attenuation and intentional binding reflect the same underlying processes is an important, unresolved question in agency research (Hughes et al., 2013). A previous study found no relation between inter-subject differences in temporal binding and sensory attenuation (Dewey & Knoblich, 2014). However, a relation between these two measures might be more apparent at the single-trial level.

We measured temporal binding in blocked conditions where either a voluntary action or a passive movement was followed by a higher or lower intensity heat-pain stimulus. By comparing binding in passive and active movement conditions, we could isolate the specific part of binding attributable to voluntary motor commands, while controlling for other factors that influence the perceived interval between events. Locus of outcome choice was also manipulated. In some blocks participants chose for themselves which outcome level they would receive, while in other blocks the experimenter chose for them. By comparing free choices with instructed trials, we could isolate the specific part of binding attributable to free selection of outcomes. To test whether any effects were specific to meaningful (i.e., heat-pain) outcomes, we tested higher or lower intensity non-painful electro-tactile stimuli in a separate group of participants. On each trial, participants reported the time of either their action or the outcome, and rated stimulus intensity. We considered action and outcome binding separately, because there are both theoretical reasons to expect dissociation, and experimental evidence that such dissociations occur (e.g., Desantis et al., 2011; Wolpe et al., 2013).

Considering that the pre-reflective sense of agency could reflect both choice over outcomes and motoric execution, we predicted that voluntary action and free choice would enhance temporal binding, compared to passive movement and instructed action. Furthermore, we expected that highly painful stimuli would decrease binding compared to less painful stimuli, and to non-painful tactile stimuli. We also assessed the contributions of motoric action control and outcome choice to perceived sensory magnitude. Finally, we looked for a relation between binding and sensory attenuation across trials.

Method

Participants

A power calculation in G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) indicated that 40 participants would be needed to achieve a power of 0.80, with a 2 x 2 x 2 x 2 mixed factors design and estimated effect sizes (η_p^2) of .38 to .61 for action-related manipulations of intentional binding (Haggard & Clark, 2003; Haggard et al., 2002) and .23 to .53 for valence-related manipulations of temporal binding (Takahata et al., 2012; Yoshie & Haggard, 2013). Therefore, 40 neurologically healthy adult participants (20 males, M_{age} = 25.4 years, SD_{age} = ±5.3 years) with normal or corrected-to-normal vision were recruited to participate in the study. They provided written informed consent prior to the experiment and were paid £7.50 per hour. Two participants opted not to complete the experiment during threshold determination, so they were replaced with other volunteers. The experiment was approved by the UCL Research Ethics Committee, and carried out in accordance with the provisions of the World Medical Association Declaration of Helsinki. Half of the participants received noxious radiant heat stimulation as an outcome and the other half received non-noxious electro-tactile stimulation.

Apparatus and Materials

A laptop computer running LabVIEW 2012 (National Instruments, Austin, Texas, USA) was used to run the intentional binding task, trigger the outcome stimuli, and collect participants' responses. The computer display was located 60 cm in front of the participant. Noxious radiant heat stimulation was delivered to the left hand dorsum by an infrared CO_2 laser stimulation device with a wavelength of 10.6 µm (SIFEC, Ferrières, Belgium). The laser pulse (100 ms duration) was transmitted via an optic fiber to reach a spot diameter of 6 mm. These laser pulses selectively excite Aδ- and C-fibers without co-activating lower-threshold Aβ-fibers in the dermis. Tactile stimulation with a duration of 10 ms was delivered using a Digitimer DS5 constant current stimulator (Digitimer Ltd., Welwyn Garden City, UK) connected to a pair of disposable press-stud electrodes (Biosense Medical, Chelmsford, UK) placed on the dorsum of the left hand.

Procedure

For each participant that received radiant heat stimulation, we identified the Aδ threshold for "pinprick pain" using ascending-descending-ascending staircases. The threshold was identified as the stimulus temperature that elicited reports of pinprick sensation and a reaction time (RT) less than 650 ms (Churyukanov, Plaghki, Legrain, & Mouraux, 2012; Mouraux, Guerit, & Plaghki, 2003). Starting at 38°C, the temperature was increased in steps of 4°C until the RT was less than 650 ms. Then the temperature was decreased in steps of 2°C until the RT became longer than 650 ms. Finally, the temperature was increased in steps of 1°C until the RT was less than 650 ms again, and the participant reported a pinprick sensation for 3 consecutive repetitions of the same temperature (M = 48.6°C). We then set the low stimulus intensity at 2°C above pinprick threshold, and the high stimulus intensity at 8°C above pinprick threshold. Participants were familiarized with the high and low levels of stimulation. Then they practiced rating sensory magnitude on a visual analog scale from 0 ('no pain') to 100 ('worst pain imaginable'). To help participants use the scale, they were instructed to consider the average perceived intensity of the lower stimulus as a 25 on the scale, and the average perceived intensity of the higher stimulus as a 75.

In the group that received electro-tactile stimulation, each participant's detection and pain thresholds for electrical stimulation were measured prior to the experiment. Starting at 0.5 mA, the current was increased in steps of 0.5 mA until the participant detected the stimulus. The current was then reduced in 0.5 mA steps until the stimulus was no longer detected, and then increased again until the stimulus was again perceived. This last value was taken as the detection threshold. Next, the current was increased rapidly until the participant reported that the stimulus had started to feel uncomfortable. This value was taken as the near-pain threshold. To find the pain threshold, the current was increased in steps of 0.5 mA until the participant reported that the stimulus felt painful. The current was then reduced in 0.5 mA steps until the stimulus was no longer painful, and then increased again until the stimulus was once again felt as painful. This value was taken as the pain threshold. The low and high levels of stimulation for the main experiment were then set to 45% and 55%, respectively, of the range between the detection and pain thresholds. These levels were chosen based on a pilot study in a separate group of volunteers which indicated that this difference between high and low electro-tactile intensities would match the discriminability of the high and low heat-pain stimuli. The mean difference between the high and low intensities was 1.05 mA (range = 0.55-1.15 mA). Participants were familiarized with the high and low levels of stimulation. Then they practiced rating sensory magnitude on a visual analog scale from 0 ('no sensation') to 100 ('maximum non-painful sensation'). To help participants use the scale, they were instructed to consider the average perceived intensity of the lower stimulus as a 25 on the scale, and the average perceived intensity of the higher stimulus as a 75.

At the beginning of each trial in the operant blocks, either the experimenter (in "instructed" blocks) or the participant (in "free choice" blocks) chose the stimulus level the participant would receive on that trial (high or low). Then a clock appeared on the screen, and the clock hand began to rotate. Participants fixated the clock. In "active movement" blocks, participants pressed the key corresponding to the previously chosen stimulus intensity (F4 for high intensity, or F5 for low intensity) at a time of their own choice. In "passive movement" blocks, the experimenter pressed the participant's finger instead. The outcome stimulus was delivered 250 ms after the keypress. The clock hand continued to rotate for a short time, and then stopped. Then participants used the keyboard to report either the time of the action or the time of the outcome stimulus, depending on the block. Afterwards, a visual analog scale from 0-100 appeared on the screen, and participants rated sensory magnitude as practiced earlier in the session (Fig. 1).

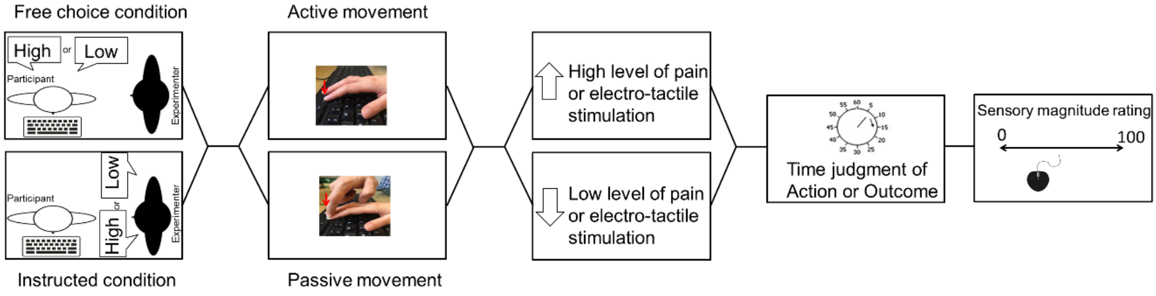

Fig. 1.

Schematic of experimental design and trial structure. Please refer to the text for further explanation.

In "instructed" blocks, the experimenter ensured that equal numbers of low and high intensity stimuli were delivered. In "free choice" blocks, participants were allowed to choose the level of stimulation they would receive on a given trial, but they were told that they had to select equal numbers of high and low intensity stimuli in each block. To help participants do this, they were given feedback about the distribution of their choices twice during each block: once after either 8 or 12 trials, and again at the end of the block. All participants complied with instructions.

In baseline action judgment blocks, the action (F4 or F5; free choice or instructed; active or passive movement) was not followed by an outcome stimulus. Participants reported the time of the action, but did not provide sensory magnitude ratings. In baseline outcome judgment blocks, no actions were made. A visual cue presented at the beginning of each trial indicated the level of heat-pain or electro-tactile stimulation to be delivered. Stimulation began 2000-4000 ms after the onset of the trial. Participants reported the time of the stimulus, and rated stimulus intensity.

Action binding and outcome binding were measured in separate sessions on different days. The threshold was taken at the beginning of each session. In total, 13 blocks (4 operant action judgment blocks, 4 operant outcome judgment blocks, 4 baseline action judgment blocks, and 1 baseline outcome judgment block) were run. Operant action judgment, operant outcome judgment, and baseline action judgment conditions each consisted of one active movement/free choice block, one active movement/instructed block, one passive movement/free choice block, and one passive movement/instructed block. Each block contained 20 trials. Block order was counterbalanced across participants along the motoric execution control and locus of outcome choice factors. Stimulus level varied within blocks. Two of the action baseline blocks were done at the beginning of the action binding session, and the other two were done at the end of that session, in a counterbalanced order. The outcome baseline block was done at either the beginning or the end of the outcome binding session (counterbalanced across participants).

Results

Intentional binding can be broken down into two separate measures: action binding and outcome binding. Action binding is the difference in the perceived time of the action when it is followed by an outcome (operant condition) compared to when it is not (baseline condition). Outcome binding is the difference in the perceived time of the outcome when it is caused by the participant's action (operant condition) compared to when it is not (baseline condition). To calculate action and outcome binding, the mean difference between the participants' time judgments and the actual time of the action/outcome in each baseline and operant condition is computed (Tables S1 and S2). Then the mean error in the baseline condition is subtracted from the mean error in the operant condition to account for any time perception biases unrelated to the operant action-outcome relationship. In particular, note that this subtraction removes baseline differences between the timing of the electro-tactile stimuli (10 ms square-wave pulses) and the radiant heat-pain stimuli (100 ms pulses with a gradual ramp-up to the target temperature). Because of these differences, participants perceived the heat-pain stimuli as occurring later in time than the electro-tactile stimuli in both baseline outcome judgment and operant outcome judgment blocks (Table S2). Importantly, differences in the perceptual latency for the two types of stimuli do not contribute to our inferences, because the perceptual latency in the baseline condition was subtracted from that in the operant condition to provide a measure of binding.

Action binding

A mixed factors analysis of variance (ANOVA) with the between-subjects factor stimulus modality (pain, tactile), and the within-subjects factors stimulus level (high, low), motoric execution control (active movement, passive movement), and locus of outcome choice (free choice, instructed) was run on action binding. There was a trend towards a main effect of motoric execution control, $F(1, 38) = 3.93$, $p = .055$, $\eta_p^2 = .09$, with more binding for active movements (M = 35.5 ms, 95% CI = [21.3, 49.6]) than for passive movements (M = 8.8 ms, 95% CI = [-16.4, 34.0]; Fig. 2). No other main effects or interactions approached significance (Table S4).

Outcome binding

A mixed factors ANOVA with the between-subjects factor stimulus modality (pain, tactile), and the within-subjects factors stimulus level (high, low), motoric execution control (active movement, passive movement), and locus of outcome choice (free choice, instructed) was run on outcome binding. Note that more negative values indicate greater outcome binding. There was a main effect of motoric execution control, $F(1, 38) = 6.01$, $p = .019$, $\eta_p^2 = .14$, with more binding for active movements (M = -208.1 ms, 95% CI = [-251.9, -164.3]) than for passive movements (M = -172.9 ms, 95% CI = [-215.3, -130.5]). There was also a main effect of locus of outcome choice, $F(1, 38) = 6.50$, $p = .015$, $\eta_p^2 = .15$. Binding was stronger in the free choice condition (M = -207.3 ms, 95% CI = [-250.4, -164.3]) than in the instructed condition (M = -173.7 ms, 95% CI = [-216.1, -131.3]; Fig. 2).

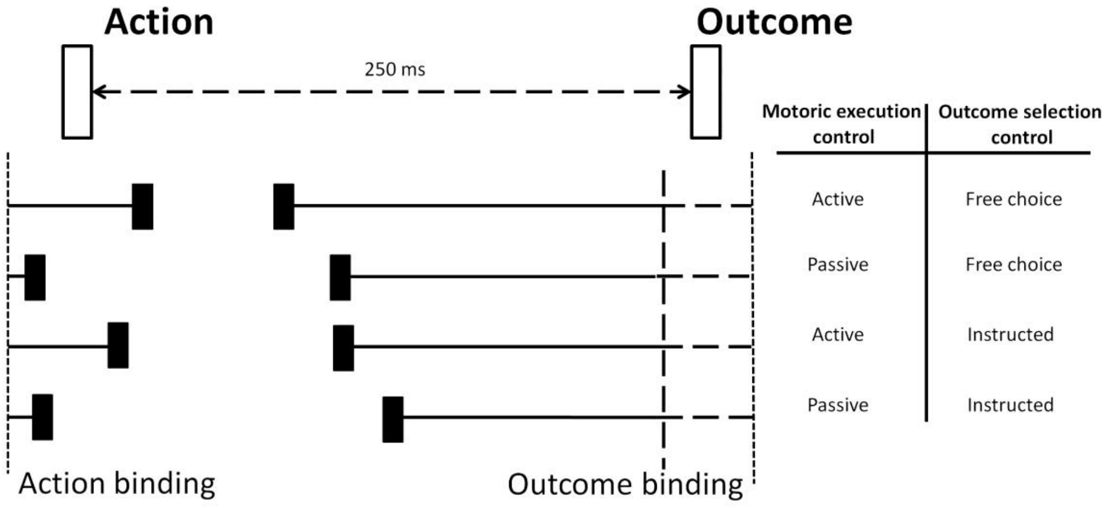

Fig. 2.

Effects of motoric execution control and locus of outcome choice on action binding (left) and outcome binding (right). The dashed lines indicate the perceived time of the action and the outcome in the corresponding baseline condition. The broken vertical line indicates a false zero for outcome binding. The solid portions of the outcome binding bars are drawn to scale from a value of -100 ms.

Moreover, there was a main effect of stimulus modality, $F(1, 38) = 5.18$, $p = .028$, $\eta_P^2 = .12$, with more binding for non-painful electro-tactile stimuli (M = -236.1 ms, 95% CI = [-293.5, -178.8]) than for painful heat stimuli (M = -144.9 ms, 95% CI = [-202.2, -87.5]). There was also an interaction between stimulus modality and stimulus level, $F(1, 38) = 5.44$, $p = .025$, $\eta_P^2 = .12$ (Fig. 3). We explored the origin of this interaction using simple effects tests. This showed less binding for high intensity heat-pain stimuli (M = -117.1 ms, 95% CI = [-172.0, -62.3]) than for low intensity heat-pain stimuli (M = -172.6 ms, 95% CI = [-244.0, -101.3]), $F(1, 38) = 4.16$, $p = .048$, $\eta_P^2 = .10$. There was no difference in binding between the high level (M = -253.3 ms, 95% CI = [-308.1, -198.4]) and the low level (M = -219.0 ms, 95% CI = [-290.3, -147.7]) of electro-tactile stimulation, $F(1, 38) = 1.58$, $p = .216$, $\eta_P^2 = .04$. No other main effects or interactions were significant (Table S5).

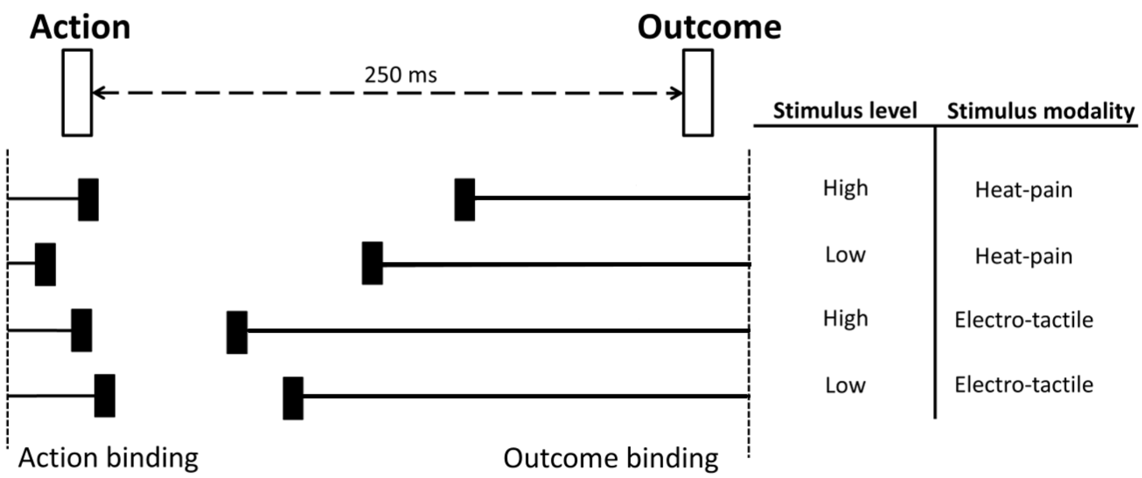

Fig. 3.

Effects of outcome stimulus level and modality on action binding (left) and outcome binding (right). The dashed lines indicate the perceived time of the action and the outcome in the corresponding baseline condition.

Non-intentional contributions to temporal binding

The main purpose of our study was to look at aspects of temporal binding related to two key components of intentional action, specifically, motoric execution control and locus of outcome choice. However, non-intentional factors such as causal relations between actions and outcomes can also contribute to temporal binding, and may indeed account for the bulk of the perceived temporal compression between events (Buehner, 2012; Buehner & Humphreys, 2009; Cravo, Claessens, & Baldo, 2009). In fact, we observed some temporal binding even in a completely non-agentic condition of our experiment, where participants controlled neither motoric execution nor outcome choice (passive, instructed condition; Fig. 2). To formally examine these non-intentional contributions to action and outcome binding, we used one-sample *t*-tests to compare action binding and outcome binding in the entirely non-agentic (passive movement, instructed action) condition to 0 (i.e., no change in time estimation error between baseline and operant conditions). We found that this non-intentional part of action binding was not statistically significant, $t(39) = 1.08$, $p = .288$, Cohen's $d = .17$ (M = 13.1 ms, 95% CI = [-11.5, 37.8]). We did, however, find significant non-intentional outcome binding, $t(39) = -6.24$, $p = .0000002$, Cohen's $d = -.99$ (M = -156.7, 95% CI = [-207.5, -105.9]).

Sensory magnitude ratings (operant blocks)

A five-way mixed factors ANOVA with the between-subjects factor stimulus modality (pain, tactile), and the within-subjects factors block type (operant action judgment block, operant outcome judgment block), stimulus level (high, low), motoric execution control (active movement, passive movement), and locus of outcome choice (free choice condition, instructed condition) was run on sensory magnitude ratings. Note that block type was included as a nuisance variable rather than a factor of interest. There was a main effect of stimulus level, $F(1, 38) = 409.81$, $p < .00001$, $\eta_P^2 = .92$, confirming that participants indeed perceived the higher intensity stimulus as more intense (M = 61.7, 95% CI = [58.3, 65.0]) than the lower intensity stimulus (M = 24.1, 95% CI = [22.3, 26.0]) in both the painful heat and innocuous electro-tactile stimulation conditions. An interaction between stimulus modality and stimulus level was found, $F(1, 38) = 9.34$, $p = .004$, $\eta_P^2 = .20$. Simple effects tests showed that the high level of heat-pain (M = 65.3, 95% CI = [60.6, 70.1]) was rated higher than the high level of electro-tactile stimulation (M = 58.0, 95% CI = [53.3, 62.7]), $F(1, 38) = 4.92$, $p = .033$, $\eta_P^2 = .11$, while the low level of heat-pain (M = 22.1, 95% CI = [19.5, 24.8]) was rated *lower* than the low level of electro-tactile stimulation (M = 26.1, 95% CI = [23.5, 28.8]), $F(1, 38) = 4.72$, $p = .036$, $\eta_P^2 = .11$. That is, participants perceived a greater difference in intensity between the high and low levels of heat-pain than between the high and low levels of electro-tactile stimulation

There was also an interaction between stimulus level and locus of outcome choice, $F(1, 38) = 7.28$, $p =.010$, $\eta_P^2 = .16$. Simple effects tests showed that the high levels of stimulation were perceived as more intense in the instructed condition (M = 62.1, 95% CI = [58.8, 65.4]), than in the free choice condition (M = 61.2, 95% CI = [57.8, 64.7]), $F(1, 38) = 6.02$, $p =.019$, $\eta_P^2 = .14$. The low level of stimulation was perceived as equally intense in the instructed condition (M = 23.8, 95% CI = [21.9, 25.8]) and the free choice condition (M = 24.4, 95% CI = [22.6, 26.3]), $F(1, 38) = 0.07$, $p = .791$, $\eta_p^2 = .002$.

In addition, there was a three-way interaction between stimulus level, locus of outcome choice, and motoric execution control, $F(1, 38) = 14.73$, $p = .0005$, $\eta_p^2 = .28$. Simple effects tests showed that the interaction between stimulus level and locus of outcome choice described above was only present when participants executed an active movement to exert their outcome choice, $F(1, 38) = 28.23$, $p < .0001$, $\eta_p^2 = .43$, and not when the experimenter passively moved their finger, $F(1, 38) = 0.94$, $p = .340$, $\eta_p^2 = .02$ (Fig. 4). High levels of stimulation were perceived as less intense when they were freely chosen by the participant *and* produced by an active movement, compared to when the participant was merely instructed to actively press the key producing a high level of stimulation, $F(1, 38) = 6.48$, $p = .015$, $\eta_p^2 = .15$. There was no difference between free choice and instructed conditions when a passive movement produced the high level of stimulation, $F(1, 38) = 0.06$, $p = .802$, $\eta_p^2 = .002$. In contrast, low levels of stimulation were perceived as *more* intense when freely chosen and produced by an active movement, compared to when the participant was instructed to press the key producing a low level of stimulation, $F(1, 38) = 20.35$, $p < .0001$, $\eta_p^2 = .35$. Again, there was no difference between free choice and instructed conditions when a passive movement produced the low level of stimulation, $F(1, 38) = 2.29$, $p = .138$, $\eta_p^2 = .06$.

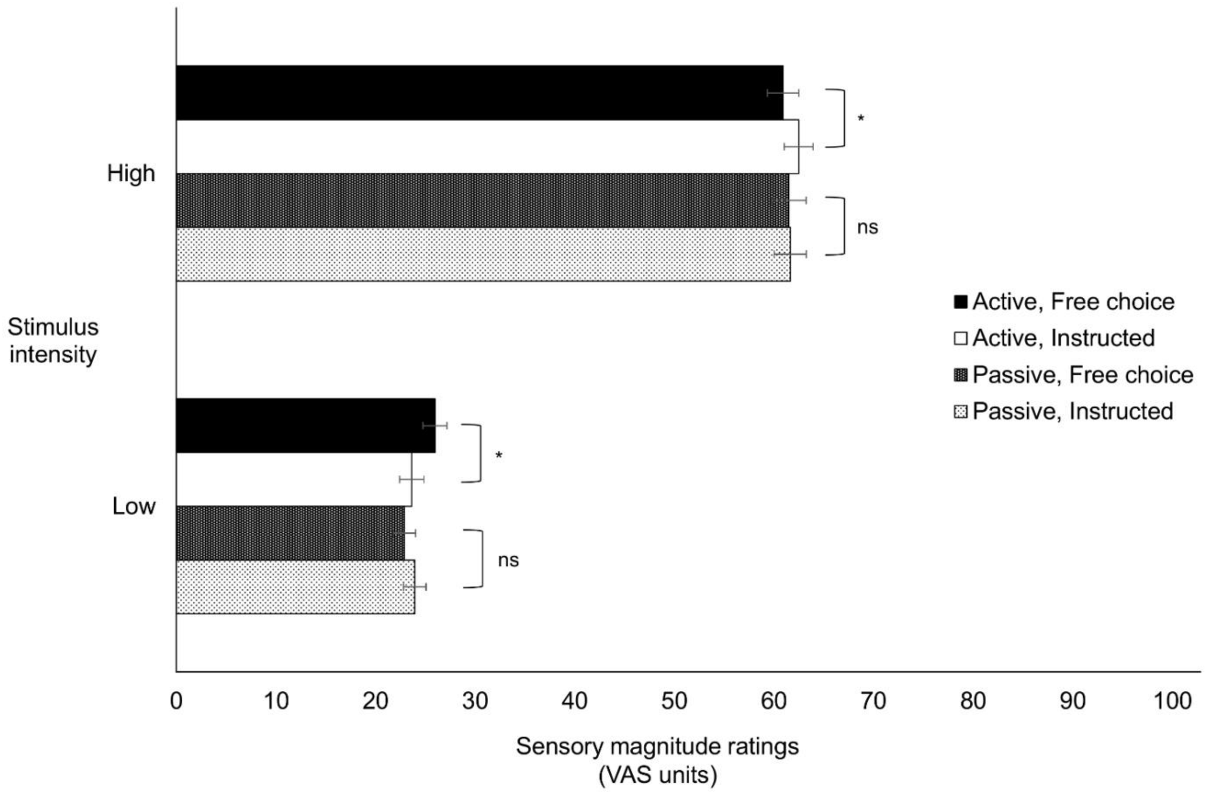

Fig. 4.

Mean sensory magnitude ratings on a visual analog scale (0-100), showing the significant interaction between stimulus level, locus of outcome choice and motoric execution control. Error bars show standard error of the mean. * = $p < .050$; ns = not significant

Finally, there was a three-way interaction between block type, stimulus modality, and motoric execution control, $F(1, 38) = 5.92$, $p = .020$, $\eta_P^2 = .14$, and a four-way interaction between block type, stimulus modality, stimulus level, and locus of outcome choice, $F(1, 38) = 8.49$, $p = .006$, $\eta_P^2 = .18$. These interactions do not represent effects of interest, and are not discussed further. No other main effects or interactions were significant (Table S6). (See Table S3 for the mean sensory magnitude ratings in all experimental conditions.)

Sensory magnitude ratings (baseline blocks)

The above analysis of sensory magnitude ratings includes only the ratings from the operant blocks, in which the outcome stimulus was caused by an action. However, participants also rated sensory magnitude in outcome baseline blocks, where no action was made, but the outcome stimulus was preceded by a visual cue indicating whether it would be high or low. To analyze sensory magnitude ratings from the outcome baseline blocks, we performed a two-way mixed factors analysis of variance (ANOVA) with the between-subjects factor stimulus modality (pain, tactile) and the within-subjects factor stimulus level (high, low). There was a main effect of stimulus level, confirming that participants rated the high-intensity stimuli (M = 60.2, 95% CI = [56.2, 64.2]) as more intense than the low-intensity stimuli (M = 23.2, 95% CI = [20.9, 25.5]), $F(1, 38) = 294.02$, $p < .00001$, $\eta_p^2 = .89$. There was also an interaction between stimulus level and stimulus modality, $F(1, 38) = 4.81$, $p = .035$, $\eta_p^2 = .11$. There was a trend toward the high level of heat-pain stimulation (M = 63.5, 95% CI = [57.8, 69.1]) being rated as more intense than the high level of electro-tactile stimulation (M = 57.0, 95% CI = [51.4, 62.7]). On the other hand, the low level of heat-pain stimulation (M = 21.7, 95% CI = [18.5, 24.9]) was rated slightly lower than the low level of electro-tactile stimulation (M = 24.8, 95% CI = [21.5, 28.0]). However, simple effects tests did not show a significant effect of stimulus modality at either the high stimulus level, $F(1, 38) = 2.63$, $p = .113$, $\eta_p^2 = .06$, or the low stimulus level, $F(1, 38) = 1.84$, $p = .183$, $\eta_p^2 = .05$.

Predicting temporal binding from sensory magnitude ratings across trials

We used linear mixed effects models to predict action binding values from sensory magnitude ratings at the single-trial level. Mean-centered sensory magnitude ratings, stimulus modality (dummy coded: pain = 1, tactile = 0), motoric execution control (active = 1, passive = 0), and locus of outcome choice (free choice = 1, instructed = 0) were modeled as random effects. We used conditional *t*-tests (Wald tests) to test the marginal significance of each effect in the model. None of the factors were significant predictors of action binding, although the motoric execution control effect approached significance ($\beta = 25.02$, SE = ±12.98), $t(3116) = 1.93$, $p = .054$. Importantly, sensory magnitude ratings did not predict action binding, $t(3116) = 1.66$, $p = .097$ (Table 1).

Table 1. Summary of random effects in the linear mixed effects model of action binding.

Random effect	**Coefficient (ms)**[a]		**DF**	***t***	***p***
	Mean	**SE**			
(Intercept)	16.78	±14.23	3116	1.18	.238
Sensory magnitude rating (mean-centered)	0.25	±0.15	3116	1.66	.097
Stimulus modality (pain = 1, tactile = 0)	-13.75	±12.39	38	-1.11	.274
Motoric execution control (active = 1, passive = 0)	25.02	±12.98	3116	1.93	.054
Locus of outcome choice (free choice = 1, instructed = 0)	-2.01	±6.84	3116	-0.29	.769

[a]Positive coefficients indicate greater action binding.

We also modeled outcome binding values using the same linear mixed effects model design as for action binding. Stimulus modality was a significant predictor (β = 124.49, SE = ±39.04), $t(38) = 3.19$, $p = .003$, with less outcome binding for heat-pain than for electro-tactile stimuli. (Note that a more positive coefficient indicates *less* outcome binding, because a shift of the outcome towards the action corresponds to a negative value.) Motoric execution control was also a significant predictor (β = -33.87, SE = ±14.28), $t(3121) = -2.37$, $p = .018$, with more binding of outcomes produced by active movements, compared to passive movements. Finally, locus of outcome choice was a significant predictor (β = -33.70, SE = ±13.24), $t(3121) = -2.55$, $p = .011$, with more binding when the outcome stimulus level was chosen by the participant rather than by the experimenter. Sensory magnitude ratings did not predict outcome binding, $t(3121) = -0.07$, $p = .947$ (Table 2).

Table 2. Summary of random effects in the linear mixed effects model of outcome binding.

Random effect	**Coefficient (ms)**[a]		**DF**	***t***	***p***
	Mean	**SE**			
(Intercept)	-215.26	±30.04	3121	-7.17	<.0001
Sensory magnitude rating (mean-centered)	-0.03	±0.50	3121	-0.07	.947
Stimulus modality (pain = 1, tactile = 0)	124.49	±39.04	38	3.19	.003

Motoric execution control (active = 1, passive = 0)	-33.87	±14.28	3121	-2.37	.018
Locus of outcome choice (free choice = 1, instructed = 0)	-33.70	±13.24	3121	-2.55	.011

[a]Negative coefficients indicate greater outcome binding.

Discussion

We replicated previous studies showing stronger temporal binding for voluntary movements than passive movements (Haggard & Clark, 2003; Haggard et al., 2002). We also found stronger outcome binding when participants could choose the outcome level, even when the outcome was achieved by the experimenter passively moving their finger. This suggests that a process of voluntary action selection, or inverse model, contributes to temporal binding, along with other components such as the voluntary motor command (Wolpert, Ghahramani, & Jordan, 1995), and non-agentic components such as causal relations between events (Buehner, 2012; Buehner & Humphreys, 2009; Cravo, Claessens, & Baldo, 2009). A contribution of choice to temporal binding has been proposed before (Barlas & Obhi, 2013; Chambon, Wenke, Fleming, Prinz, & Haggard, 2013). However, our study provides the first evidence that the *locus* of outcome choice (free vs. instructed) affects temporal binding, irrespective of outcome identity predictability or motoric control over the action itself. In principle, our outcome choice effect could reflect top-down beliefs about one's ability to control outcomes through action selection (Desantis et al., 2011) rather than the process of action selection itself. Our study cannot distinguish these possibilities. However, one priming study found that manipulations of action selection fluency can directly alter explicit agency judgments, without top-down mediation by beliefs (Wenke, Fleming, & Haggard, 2010).

Other research has suggested that binding is not affected by outcome identity prediction (Desantis et al., 2012). Our effect of outcome control is not at odds with this finding, as stimulus intensity was completely predictable in both the free choice and the instructed conditions. Rather, our effect depended upon whether participants could choose the stimulus level for themselves, or whether the experimenter chose for them. We thus demonstrate a novel effect of the locus of outcome choice on temporal binding, even when outcome predictability was matched between free choice and instructed conditions.

Buehner and colleagues (Buehner, 2012; Buehner & Humphreys, 2009) have suggested that temporal binding results from causality, and is not specific to the experience of agency. Another study found that both voluntary action and causality were necessary for temporal binding (Cravo et al., 2009). Our data further support the idea that causality contributes to temporal binding. We found substantial outcome binding (but not action binding) in a purely causal but non-agentic condition, when the experimenter chose the outcome level, and caused the outcome by pressing the participant's passive finger. The presence of outcome binding in an entirely non-agentic condition stresses the importance of using careful control conditions that isolate intentional components of temporal binding when using binding as an implicit agency measure.

We also found that more intense stimuli reduced outcome binding, but only when outcomes were painful. High pain levels have a more negative valence than lower pain levels. Intentional binding is often reduced for negatively-valenced outcomes (Takahata et al., 2012; Yoshie & Haggard, 2013), providing an implicit analog to the self-serving attribution bias (e.g., Bradley, 1978; Greenberg, Pyszczynski, & Solomon, 1982; Mezulis, Abramson, Hyde, & Hankin, 2004). The tactile stimulation, on the other hand, was less valenced. Alternatively, the reduction in outcome binding for high intensity heat-pain stimuli could be a direct consequence of stimulus intensity. Participants rated the high heat-pain stimuli as more intense than any of the other outcomes. Intense stimuli are highly salient, and act as anchors for timing judgments. The perceived time of such anchors is relatively uninfluenced by other events, such as preceding actions (Wolpe et al., 2013). Our high heat-pain stimuli may have shown relatively little binding either because of their high perceived intensity, or because of their negative valence.

Finally, we found that free choice over outcomes attenuated perceived sensory magnitudes, relative to an instructed condition, but only for high intensity stimuli. A further three-way interaction with motoric control showed that this effect was present for active but not passive movements.

Therefore, it could reflect a specific variant of sensory attenuation previously reported following voluntary actions (Blakemore et al., 1999; Wang et al., 2011; Williams et al., 1998). Interestingly, another recent study showed that sensory attenuation effects are intensity-dependent (Reznik, Henkin, Levy, & Mukamel, 2015). Previous studies of sensory attenuation did not manipulate locus of outcome choice and motoric control independently, as we have done here. Our study suggests that sensory attenuation of outcomes reflects, at least in part, the ability to choose the outcome through voluntary action. However, we found no main effect of motoric control on sensory magnitude ratings (i.e., no sensory attenuation effect, as classically defined). Therefore, our results may reflect a different form of "sensory attenuation" that primarily depends upon instrumental control over action outcomes through free choices, rather than the mere presence of a voluntary motor command. Future research should investigate whether these effects are distinct or overlapping.

Several studies have reported that painful stimuli feel less intense when they are cued than when they are unexpected (e.g., Carlsson, Andersson, Petrovic, Petersson, Öhman, & Ingvar, 2006; Crombez, Baeyens, & Eelen, 1994). Thus, agentic control over noxious stimuli might reduce pain levels by enhancing stimulus predictability. However, our participants always knew in advance which stimulus level they would receive. Further, the attenuation of self-chosen stimuli was only found when participants themselves initiated the action, and not when they were passively moved. This suggests that our "sensory attenuation" effect resulted from free choice over outcome intensity, rather than mere predictability.

Across trials, we found no association between sensory magnitude ratings and either action or outcome binding. This extends Dewey and Knoblich's (2014) finding of no relation between binding and sensory attenuation across participants. Though caution is required in interpreting null results, both findings appear to challenge the idea that sensory attenuation and temporal binding reflect a single underlying cognitive process. However, we found that both temporal binding and perceived sensory magnitude were sensitive not only to voluntary motoric control over an action, but also to instrumental control over action outcomes through free choice. To recap, we found main effects of motoric control and outcome choice on outcome binding, and an interaction effect between these factors on sensory magnitude ratings. Thus, both measures reflect key components of agency, based on a theoretical definition of agency as involving both choosing what to do, and actually doing it. However, the absence of strong trial-by-trial association suggests that binding and sensory magnitudes may not reflect a common cognitive process.

One limitation of our study was the constrained nature of “free” choices. Participants were asked to choose equal numbers of high and low intensity stimuli in each block. If we had allowed participants to make entirely free choices, they presumably would always have chosen lower intensity stimuli when those stimuli were painful. Locus of outcome choice and stimulus level would then be confounded in the heat-pain condition. We instead allowed participants to control the *distribution* of high and low intensity outcomes in each block. This arrangement constrains endogenous choice in the long run, but allows endogenous processes to contribute to the generation of individual actions.

Together, our findings show that temporal binding and perceived sensory magnitudes are influenced by motoric execution control *and* by the ability to select between alternative action outcomes. This supports the idea that binding and sensory attenuation, with appropriate non-agentic controls in place, may be implicit markers of the sense of agency, as they are sensitive to two key agency components, namely, the voluntary motor command and instrumental control over the action outcome. However, we found no relation between action or outcome binding and sensory magnitude ratings across trials, suggesting that they are not entirely consistent measures of the implicit sense of agency.

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Author Contributions

All authors contributed to the study concept and design. KB performed the data collection. KB and BB analyzed the data. All authors contributed to data interpretation. KB and BB drafted the manuscript. PH and BB provided critical revisions. All authors approved the final version of the manuscript for submission.

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