The Effect of Emotional Valence Predictability on Temporal Binding Effect

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Abstract

The temporal binding effect refers to the phenomenon where the time points of voluntary actions and their outcomes subjectively converge. This effect can be categorized into action binding and outcome binding, corresponding respectively to the temporal shifts of voluntary actions and action outcomes. This study investigated the influence of emotional valence predictability on the temporal binding effect through a mixed-design experiment. Emotional valence predictability (predictable vs. unpredictable) served as a within-subjects factor, while stimulus modality (auditory stimulus vs. visual stimulus) served as a between-subjects factor. The results revealed that when emotional valence was predictable, outcome binding was enhanced both when auditory stimuli and visual stimuli were produced following active key pressing, whereas action binding was enhanced only when visual stimuli were produced. These findings indicate that predictable emotional valence enhances the temporal binding effect, but this modulation differs between action binding and outcome binding. Since the temporal binding effect serves as a primary indicator of the sense of agency, the results of this study hold certain implications for the interaction design of advanced driving assistance systems.

Full Text

The Effect of Emotional Valence Predictability on Temporal Binding

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Abstract
Temporal binding refers to the phenomenon where the subjective timing of voluntary actions and their outcomes appear closer together in time. This effect can be divided into action binding and outcome binding, corresponding to temporal shifts in the perceived onset of actions and outcomes, respectively. This study investigated the influence of emotional valence predictability on temporal binding using a mixed-design experiment, with emotional valence predictability (predictable vs. unpredictable) as a within-subjects factor and stimulus modality (auditory vs. visual) as a between-subjects factor. The results revealed that when emotional valence was predictable, outcome binding was enhanced for both auditory and visual stimuli following voluntary keypresses, whereas action binding was enhanced only for visual stimuli. These findings indicate that predictable emotional valence strengthens temporal binding, but this effect differs between action binding and outcome binding. Since temporal binding serves as a primary indicator of sense of agency, these results offer valuable insights for the interaction design of Advanced Driver Assistance Systems.

Keywords: emotional valence predictability, temporal binding, stimulus modality, sense of agency, human-computer interaction, Advanced Driver Assistance Systems

1 Introduction

The experience of controlling one' s voluntary actions to influence the external world is referred to as the "Sense of Agency" (Gallagher, 2000; Haggard, 2017; Moore, 2016). While some Chinese researchers have translated this concept as "主动控制感" (Wu et al., 2019; Zhang et al., 2018) and others as "施动感" (An et al., 2021; Tian et al., 2018), we adopt "主动控制感" for consistency throughout this paper. Temporal binding, a phenomenon closely related to sense of agency, describes the subjective compression of the perceived temporal interval between voluntary actions and their outcomes (Haggard et al., 2002). Considered the primary quantitative measure for assessing sense of agency (Moore & Obhi, 2012), temporal binding was first demonstrated by Haggard and colleagues (2002) using a Libet clock paradigm where a rotating pointer completed one revolution every 2560ms. When participants performed a voluntary keypress followed by an auditory stimulus after 250ms, they perceived the keypress as occurring later in time (action binding) and the stimulus as occurring earlier (outcome binding).

Previous research has shown that temporal binding is influenced not only by factors such as action intention, delay, and probability information (e.g., Antusch et al., 2019; Moore & Haggard, 2008; Moore et al., 2009; Wen, 2019), but also by emotion, particularly the emotional valence of action outcomes. Studies indicate that emotional valence affects individuals' attribution tendencies regarding action outcomes (Gentsch & Synofzik, 2014), which manifests in temporal binding effects. However, existing research on the relationship between emotional valence and temporal binding has yielded inconsistent findings. Some studies demonstrate that positive action outcomes enhance temporal binding while negative outcomes diminish it (Yoshie & Haggard, 2013), whereas others find no effect of emotional valence on temporal binding (Moreton et al., 2017). These discrepancies suggest that the influence of emotional valence on temporal binding may interact with additional factors (Barlas et al., 2018).

Research indicates that the effect of emotional valence on temporal binding depends, to some extent, on whether the valence is predictable. Yoshie and Haggard (2017) found that emotional valence influences temporal binding only when individuals can predict whether the upcoming outcome will be positive or negative, with positive outcomes enhancing and negative outcomes attenuating the effect. However, Christensen et al. (2016) observed that positive outcomes enhance temporal binding even when emotional valence is unpredictable. Overall, the precise mechanism through which emotional valence predictability moderates the relationship between emotional valence and temporal binding remains unclear (Kaiser et al., 2021). Notably, no study has directly examined whether emotional valence predictability itself affects temporal binding.

Investigating the impact of emotional valence predictability on temporal binding holds practical significance for engineering psychology. In human-computer interaction contexts, sense of agency refers to users' experience of being responsible for changes in system state (Limerick et al., 2014; Seinfeld et al., 2021). For automated technologies, diminished sense of agency can impair users' monitoring of system status and their ability to intervene during system failures (Berberian, 2019; Wen & Imamizu, 2022). Maintaining predictability between expected and actual feedback is crucial for preserving sense of agency (Madary, 2022). As driving assistance technology represents a common form of automation, it is essential to consider how to maintain drivers' sense of agency during vehicle operation (Wen et al., 2019) to ensure rapid intervention when the system encounters unforeseen situations. Recent research has explored using emotional stimuli to influence driver behavior (Dittrich & Mathew, 2021), raising the question of how the predictability of such emotional stimuli affects sense of agency. By examining the effect of emotional valence predictability on temporal binding, this study provides valuable insights for the interaction design of Advanced Driver Assistance Systems (ADAS).

In summary, this study focuses on investigating how emotional valence predictability influences temporal binding. We hypothesized that predictable emotional valence would enhance temporal binding compared to unpredictable valence. Within each block, emotional valence predictability was manipulated by varying the presentation probabilities of different emotional stimuli following participants' keypresses. In predictable blocks, a fixed emotional outcome (negative, neutral, or positive) appeared in approximately 80% of trials, with the remaining 20% evenly distributed among the other two emotions. In unpredictable blocks, negative, neutral, and positive stimuli were presented with equal probability. Additionally, given that stimulus modality might influence results (Ruess et al., 2018; Sarma & Srinivasan, 2021), we included stimulus modality (auditory vs. visual) as a between-subjects factor in a mixed-design experiment to comprehensively examine its impact on the relationship between emotional valence predictability and temporal binding.

2.1 Participants

Sixty participants were recruited, including 30 females and 30 males (age: M = 23 years, SD = 2.25 years). Participants were randomly assigned to either the auditory or visual stimulus group, with a balanced 1:1 male-to-female ratio in each group.

2.2 Apparatus and Stimuli

The experimental program was developed using Unity version 2017.4.40c1 (64-bit) and presented on a 23.8-inch monitor with a resolution of 1920 × 1080, gray background, and 60Hz refresh rate. Participants were seated 60cm from the screen. The study employed a Libet clock paradigm. At the start of each trial, a clock face measuring 6.6cm in diameter with a central "+" symbol and numbered markings at regular intervals (5, 10, 15, etc.) appeared at the center of the screen. After 500ms, a pointer 3.2cm in length emerged at a random position on the clock face and began rotating, completing one revolution every 2560ms (see Figure 1).

Classic Libet clock paradigms typically use stimuli lasting approximately 100ms (e.g., Antusch et al., 2019; Haggard et al., 2002; Ruess et al., 2018). However, studying emotion-related temporal binding requires longer stimulus durations. For auditory stimuli, a minimum presentation duration of 700ms is necessary for successful emotion recognition (see Yoshie & Haggard, 2013, Supplemental Information). For visual stimuli, previous research using a duration estimation paradigm has employed 400ms presentation times (Moreton et al., 2017). To ensure successful emotion recognition and temporal judgment in the Libet clock paradigm, we set auditory stimulus duration to 840ms, using negative, neutral, and positive human vocalizations from Sauter et al. (2010) presented via headphones. Visual stimulus duration was set to 300ms, using negative, neutral, and positive human face images obtained from https://image.baidu.com, presented as 4.9cm diameter circles at the center of the clock face.

2.3 Procedure

The experiment employed a 2 (emotional valence predictability: predictable vs. unpredictable) × 2 (stimulus modality: auditory vs. visual) mixed design, with emotional valence predictability as a within-subjects factor and stimulus modality as a between-subjects factor. Action binding and outcome binding served as dependent variables.

The baseline phase comprised two tasks: keypress action and stimulus onset time judgment. In the keypress time judgment task, participants were required to press a key at a freely chosen time between one and two rotations after the pointer began moving (2560–5120ms), avoiding consistent timing to maintain randomness. After the keypress, the pointer continued rotating for 1000ms before the Libet clock disappeared, at which point participants used the keyboard to input an integer from 1-60 indicating the pointer' s position at the moment of keypress. In the stimulus onset time judgment task, participants remained still and waited for either an auditory or visual stimulus to appear at a random time between one and two rotations after trial onset. Auditory stimuli were 840ms pure tones, while visual stimuli were 300ms solid-color circles (4.9cm diameter) presented at the clock face center. Following stimulus offset, the pointer rotated for an additional 1000ms before the clock disappeared, and participants reported the pointer' s position at stimulus onset. To counterbalance potential order effects, task order was arranged using an ABBA sequence. Each task included 25 trials, with the first 4 designated as practice. The baseline phase thus comprised 50 trials total.

The operant phase mirrored the baseline phase structure but included four blocks per task: predictable positive, predictable neutral, predictable negative, and unpredictable emotional stimulus blocks. Participants pressed the key at a freely chosen time within the 2560–5120ms window, maintaining temporal randomness. Each keypress triggered an auditory or visual emotional stimulus after a 250ms delay. Following stimulus offset, the pointer rotated for 1000ms before the clock disappeared. In the keypress time judgment task, participants reported the pointer position at keypress onset; in the stimulus onset time judgment task, they reported the position at stimulus onset. The 250ms action-outcome interval represents a standard setting in temporal binding research (Haggard et al., 2002), and was fixed in this experiment to avoid confounding effects of interval variability (Humphreys & Buehner, 2009; Ruess et al., 2017).

In predictable blocks, a fixed emotional outcome occurred in approximately 80% of trials, with the remaining 20% evenly distributed among the other two emotions. For example, in the predictable positive block, positive stimuli appeared in ~80% of trials, neutral in ~10%, and negative in ~10%. In unpredictable blocks, negative, neutral, and positive stimuli occurred with equal probability. Task order was counterbalanced using ABBA, and block order was counterbalanced using Latin squares. The first 4 trials in each task served as practice, using the same stimuli as the baseline phase. Each block contained 21 trials, yielding 176 trials across the two tasks and eight blocks in the operant phase.

In the rating phase following all time judgment tasks, participants evaluated the emotional valence of stimuli from the operant phase using a 9-point Likert scale (1 = extremely unpleasant/negative, 9 = extremely pleasant/positive). The entire experiment lasted approximately 40 minutes per participant.

2.4 Data Analysis

Data were analyzed using IBM SPSS Statistics 26.0. Prior to main analyses, time judgment errors exceeding 640ms from the actual event were excluded as outliers (Aarts et al., 2012). Outliers accounted for 0.5% of all values in the auditory group (keypress: 0.25%; stimulus onset: 0.25%) and 0.75% in the visual group (keypress: 0.41%; stimulus onset: 0.34%).

Time judgment error for each trial was calculated as:

$$t_e = t_j - t_a$$

where t_e represents the difference between subjective judgment time (t_j) and actual time (t_a) for either keypress or stimulus onset.

Keypress time judgment error was calculated as:

$$t_e(\text{keypress}) = t_j(\text{keypress}) - t_a(\text{keypress})$$

Stimulus onset time judgment error was calculated as:

$$t_e(\text{stimulus}) = t_j(\text{stimulus}) - t_a(\text{stimulus})$$

Temporal shift magnitude was then computed as:

$$t_s = t_{Oe} - t_{Be}$$

where t_s represents the difference between operant phase time judgment error (t_{Oe}) and baseline phase time judgment error (t_{Be}).

Action binding was calculated as:

$$t_s(\text{action}) = t_{Oe}(\text{keypress}) - t_{Be}(\text{keypress})$$

Outcome binding was calculated as:

$$t_s(\text{outcome}) = t_{Oe}(\text{stimulus}) - t_{Be}(\text{stimulus})$$

Positive t_s(action) values indicate action binding, while negative t_s(outcome) values indicate outcome binding.

Previous emotion-related Libet clock studies have used stimulus durations substantially longer than 100ms (e.g., Christensen et al., 2016; Tanaka & Kawabata, 2021; Yoshie & Haggard, 2013). To assess whether these longer durations affected our results, we compared our data with classic Libet clock studies using ~100ms stimuli (Antusch et al., 2019; Haggard et al., 2002; Ruess et al., 2018). No significant differences emerged in time judgment errors between our longer-duration stimuli and the 100ms stimuli (see Appendix), suggesting our findings are not confounded by stimulus duration.

3.1 Validation of Emotional Valence

Separate one-way ANOVAs were conducted on emotional valence ratings for auditory and visual stimuli. Results showed significant main effects of emotional valence: auditory stimuli, F(2,87) = 35.26, p < 0.001, ^{2} = 0.45; visual stimuli, F(2,87) = 340.65, p < 0.001, ^{2} = 0.89. Post-hoc comparisons revealed that for auditory stimuli, negative stimuli (M = 2.00, 95% CI [1.44, 2.56]) were rated significantly lower than neutral (p = 0.001, Cohen' s d = 1.31) and positive stimuli (p < 0.001, Cohen' s d = 1.79), and neutral stimuli (M = 3.49, 95% CI [2.92, 4.05]) were rated significantly lower than positive stimuli (M = 5.37, 95% CI [4.80, 5.93], p < 0.001, Cohen's d = 1.00). For visual stimuli, negative stimuli (M = 1.39, 95% CI [1.10, 1.68]) were rated significantly lower than neutral (p < 0.001, Cohen' s d = 4.32) and positive stimuli (p < 0.001, Cohen' s d = 6.46), and neutral stimuli (M = 4.86, 95% CI [4.57, 5.16]) were rated significantly lower than positive stimuli (M = 6.73, 95% CI [6.44, 7.03], p < 0.001, Cohen' s d = 1.99). These results confirm that our experimental materials effectively elicited distinct emotional valence perceptions in both modalities (see Table 1).

Table 1
ANOVA Results for Emotional Valence Ratings of Auditory and Visual Stimuli

Stimulus Modality	Negative	Neutral	Positive	F-test Significance
Auditory	2.00$±1.20\|3.49±1.07\|5.37±2.17\|$p <$ 0.001(*Negative* < *Neutral*, *Negative* < *Positive*, *Neutral* < *Positive*)||*Visual*|1.39±0.42|4.86±0.93|6.73±$0.95	p < 0.001 (Negative < Neutral***, Negative < Positive***, Neutral < Positive***)		

Note: *p < 0.05, **p < 0.01, ***p < 0.001.

3.2 Effect of Emotional Valence Predictability on Temporal Binding

Forming expectations about action outcome valence requires both manipulated presentation probabilities and sufficient prior experience across trials (Moore & Haggard, 2008). In predictable blocks, 4 trials served as distractors and 17 as valid trials. Among the 17 valid trials, the first 10 allowed participants to develop expectations about outcome valence, while the remaining 7 were used for data analysis. Thus, 21 trials from the predictable positive, neutral, and negative blocks were included in the analysis. In unpredictable blocks, all 21 trials were analyzed.

To examine the effect of emotional valence predictability on temporal binding and its manifestation across modalities, we conducted separate 2 (predictability) × 2 (modality) repeated-measures ANOVAs on action binding and outcome binding. For action binding, the main effect of predictability was non-significant, $F(1,58) = 0.09$, $p = 0.764$, $^2 = 0.002$, but the predictability × modality interaction was significant, $F(1,58) = 6.49$, $p = 0.014$, $^2 = 0.10$. Post-hoc comparisons revealed that in the visual group, action binding was stronger when emotional valence was predictable (M = 28.01, 95% CI [5.38, 50.64]) versus unpredictable (M = 16.02, 95% CI [-8.58, 40.61], $p = 0.049$, Cohen' s d = 0.25). In the auditory group, action binding did not differ significantly between predictable (M = 32.24, 95% CI [9.60, 54.87]) and unpredictable conditions (M = 41.69, 95% CI [17.10, 66.29], $p = 0.118$, Cohen' s d = 0.63).

For outcome binding, the main effect of predictability was significant, $F(1,58) = 4.17$, $p = 0.046$, $^2 = 0.07$, indicating stronger outcome binding when emotional valence was predictable (M = -46.28, 95% CI [-72.04, -20.52]) versus unpredictable (M = -33.59, 95% CI [-58.13, -9.05], $p = 0.046$, Cohen' s d = 0.13). The predictability × modality interaction was non-significant, $F(1,58) = 0.10$, $p = 0.754$, $^2 = 0.002$. These results demonstrate that predictable emotional valence enhanced outcome binding regardless of stimulus modality, while action binding enhancement occurred only for visual stimuli (see Figure 3).

Figure 3
The Effect of Emotional Valence Predictability on Temporal Binding

Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Error bars represent standard errors.

4 Discussion

Our findings demonstrate that predictable emotional valence of action outcomes enhances temporal binding. Specifically, outcome binding was strengthened for both auditory and visual stimuli when emotional valence was predictable, whereas action binding enhancement was restricted to visual stimuli. The statistical power for our main results exceeded 0.8, indicating high reliability.

The literature remains inconsistent regarding the relationship between emotional valence and temporal binding (Kaiser et al., 2021). While some studies show that emotional valence affects temporal binding (Yoshie & Haggard, 2013), others find no such effect (Moreton et al., 2017). Although research suggests these inconsistencies may stem from the moderating role of emotional valence predictability—with valence influencing temporal binding only when predictable (Yoshie & Haggard, 2017)—other studies demonstrate effects even when valence is unpredictable (Christensen et al., 2016). This implies additional moderating factors in the interaction between emotional valence and predictability. By independently examining the effect of emotional valence predictability on temporal binding, our study reveals that predictability itself directly influences temporal binding, establishing it not merely as a moderator but as a direct determinant.

Differences in action outcome attribution may explain how emotional valence predictability affects temporal binding. Research shows that temporal binding is influenced by probability information regarding whether an outcome occurs (Moore & Haggard, 2008; Moore et al., 2009), but not by which specific outcome occurs (Desantis et al., 2012; Hughes et al., 2013). Haering and Kiesel (2014) propose that this difference reflects whether probability information affects causal attribution of outcomes to one's actions. While outcome probability does not disrupt the action-outcome causal link, varying emotional valences may compromise this attribution process (Gentsch & Synofzik, 2014). In our study, predictable emotional valence likely strengthened participants' attribution of outcomes to their actions, enhancing their sense of agency and intensifying temporal binding.

Our results also reveal differential effects of emotional valence predictability on action versus outcome binding. Predictable valence enhanced outcome binding across both modalities, while action binding enhancement was modality-specific. These findings not only support distinct mechanisms underlying action and outcome binding (e.g., Tanaka et al., 2019; Tonn et al., 2021; Waszak et al., 2012; Wolpe et al., 2013), with outcome binding being more dependent on predictability (Tanaka & Kawabata, 2021), but also provide further evidence that stimulus modality influences temporal binding (Ruess et al., 2018), particularly in the context of emotional valence effects (Sarma & Srinivasan, 2021).

Our study demonstrates that predictable emotional valence enhances sense of agency, with this enhancement showing modality-specific patterns in action and outcome perception. For ADAS design, if emotional stimuli are employed to augment sense of agency, we recommend maintaining consistent emotional valence (e.g., using only positive or only negative stimuli as feedback). Furthermore, visual stimuli should be used during vehicle operation, while combined audiovisual stimuli may be optimal for vehicle monitoring tasks to maximize sense of agency enhancement.

To independently assess action and outcome binding and comprehensively examine the effect of emotional valence predictability, we utilized the Libet clock paradigm. Although keypress responses are widely used in psychology, cognitive neuroscience, and computer science (Wu et al., 2019), continuous motor control tasks may be more ecologically valid for human-computer interaction research. The interval estimation paradigm, for instance, may be better suited for continuous motor tasks than the Libet clock (Wen et al., 2017). Future research should employ tasks and paradigms more appropriate for human-computer interaction contexts.

5 Conclusion

1. Predictable emotional valence of action outcomes enhances temporal binding.
2. The effect of emotional valence predictability differs between action binding and outcome binding. Specifically, predictable emotional valence strengthens outcome binding for both auditory and visual stimuli, while enhancing action binding only for visual stimuli.

References

Aarts, H., Bijleveld, E., Custers, R., Dogge, M., Deelder, M., Schutter, D., & van Haren, N. E. (2012). Positive priming and intentional binding: Eye-blink rate predicts reward information effects on the sense of agency. *Social Neuroscience, 7*(1), 105–112. https://doi.org/10.1080/17470919.2011.590602

An, C. L., Li, L. H., Tian, H. Y., Li, F., Jin, D., Bu, Y. B., & Cao L. S. (2021). The development of the two-step account of sense of agency. *Journal of Psychological Science, 44*(5), 1273–1279. https://doi.org/10.16719/j.cnki.1671-6981.20210533

Antusch, S., Aarts, H., & Custers, R. (2019). The role of intentional strength in shaping the sense of agency. *Frontiers in Psychology, 10*, 1124. https://doi.org/10.3389/fpsyg.2019.01124

Barlas, Z., Hockley, W. E., & Obhi, S. S. (2018). Effects of free choice and outcome valence on the sense of agency: Evidence from measures of intentional binding and feelings of control. *Experimental Brain Research, 236*(1), 129–139. https://doi.org/10.1007/s00221-017-5112-3

Berberian, B. (2019). Man-machine teaming: A problem of agency. *IFAC-PapersOnLine, 51*(34), 118–123. https://doi.org/10.1016/j.ifacol.2019.01.049

Christensen, J. F., Yoshie, M., Di Costa, S., & Haggard, P. (2016). Emotional valence, sense of agency and responsibility: A study using intentional binding. *Consciousness and Cognition, 43*, 1-10. https://doi.org/10.1016/j.concog.2016.02.016

Desantis, A., Hughes, G., & Waszak, F. (2012). Intentional binding is driven by the mere presence of an action and not by motor prediction. *PLoS One, 7*(1), e29557. https://doi.org/10.1371/journal.pone.0029557

Dittrich, M., & Mathew, N. (2021). Emotional feedback to mitigate aggressive driving: A real-world driving study. In R. Ali., B. Lugrin., & F. Charles. (Eds.), *International conference on persuasive technology* (pp. 88–101). Springer, Cham. https://doi.org/10.1007/978-3-030-79460-6_8

Gallagher, S. (2000). Philosophical conceptions of the self: Implications for cognitive science. *Trends in Cognitive Sciences, 4*(1), 14–21. https://doi.org/10.1016/s1364-6613(99)01417-5

Gentsch, A., & Synofzik, M. (2014). Affective coding: The emotional dimension of agency. *Frontiers in Human Neuroscience, 8*, 608. https://doi.org/10.3389/fnhum.2014.00608

Haering, C., & Kiesel, A. (2014). Intentional binding is independent of the validity of the action effect' s identity. *Acta Psychologica, 152*, 109–119. https://doi.org/10.1016/j.actpsy.2014.07.015

Haggard, P. (2017). Sense of agency in the human brain. *Nature Reviews Neuroscience, 18*(4), 196–207. https://doi.org/10.1038/nrn.2017.14

Haggard, P., Clark, S., & Kalogeras, J. (2002). Voluntary action and conscious awareness. *Nature Neuroscience, 5*(4), 382–385. https://doi.org/10.1038/nn827

Hughes, G., Desantis, A., & Waszak, F. (2013). Mechanisms of intentional binding and sensory attenuation: The role of temporal prediction, temporal control, identity prediction, and motor prediction. *Psychological Bulletin, 139*(1), 133–151. https://doi.org/10.1037/a0028566

Humphreys, G. R., & Buehner, M. J. (2009). Magnitude estimation reveals temporal binding at super-second intervals. *Journal of Experimental Psychology: Human Perception and Performance, 35*(5), 1542–1549. https://doi.org/10.1037/a0014492

Kaiser, J., Buciuman, M., Gigl, S., Gentsch, A., & Schütz-Bosbach, S. (2021). The interplay between affective processing and sense of agency during action regulation: A review. *Frontiers in Psychology, 12*, 716220. https://doi.org/10.3389/fpsyg.2021.716220

Limerick, H., Coyle, D., & Moore, J. W. (2014). The experience of agency in human-computer interactions: A review. *Frontiers in Human Neuroscience, 8*, 643. https://doi.org/10.3389/fnhum.2014.00643

Madary, M. (2022). The illusion of agency in human-computer interaction. *Neuroethics, 15*(1), 1–15. https://doi.org/10.1007/s12152-022-09491-1

Moore, J., & Haggard, P. (2008). Awareness of action: Inference and prediction. *Consciousness and Cognition, 17*(1), 136–144. https://doi.org/10.1016/j.concog.2006.12.004

Moore, J. W. (2016). What is the sense of agency and why does it matter? *Frontiers in Psychology, 7*, 1272. https://doi.org/10.3389/fpsyg.2016.01272

Moore, J. W., Lagnado, D., Deal, D. C., & Haggard, P. (2009). Feelings of control: Contingency determines experience of action. *Cognition, 110*(2), 279–283. https://doi.org/10.1016/j.cognition.2008.11.006

Moore, J. W., & Obhi, S. S. (2012). Intentional binding and the sense of agency: A review. *Consciousness and Cognition, 21*(1), 546–561. https://doi.org/10.1016/j.concog.2011.12.002

Moreton, J., Callan, M. J., & Hughes, G. (2017). How much does emotional valence of action outcomes affect temporal binding? *Consciousness and Cognition, 49*, 25–34. https://doi.org/10.1016/j.concog.2016.12.008

Ruess, M., Thomaschke, R., & Kiesel, A. (2017). The time course of intentional binding. *Attention, Perception, & Psychophysics, 79*(4), 1123–1131. https://doi.org/10.3758/s13414-017-1292-y

Ruess, M., Thomaschke, R., & Kiesel, A. (2018). Intentional binding of visual effects. *Attention, Perception, & Psychophysics, 80*(3), 713–722. https://doi.org/10.3758/s13414-017-1479-2

Sarma, D., & Srinivasan, N. (2021). Intended emotions influence intentional binding with emotional faces: Larger binding for intended negative emotions. *Consciousness and Cognition, 92*, 103136. https://doi.org/10.1016/j.concog.2021.103136

Seinfeld, S., Feuchtner, T., Maselli, A., & Müller, J. (2021). User representations in human-computer interaction. *Human-Computer Interaction, 36*(5–6), 400–438. https://doi.org/10.1080/07370024.2020.1724790

Tanaka, T., & Kawabata, H. (2021). Sense of agency is modulated by interactions between action choice, outcome valence, and predictability. *Current Psychology, 40*(4), 1795–1806. https://doi.org/10.1007/s12144-018-0121-3

Tanaka, T., Matsumoto, T., Hayashi, S., Takagi, S., & Kawabata, H. (2019). What makes action and outcome temporally close to each other: A systematic review and meta-analysis of temporal binding. *Timing & Time Perception, 7*(3), 189–218. https://doi.org/10.1163/22134468-20191150

Tian, H. Y., Li, L. H., Xu, Z., Li, F., Jin, D., & An, C. L. (2018). Sense of agency in the minimal self. *Advances in Psychological Science, 26*(5), 872–885. https://doi.org/10.3724/SP.J.1042.2018.00872

Tonn, S., Pfister, R., Klaffehn, A. L., Weller, L., & Schwarz, K. A. (2021). Two faces of temporal binding: Action- and effect-binding are not correlated. *Consciousness and Cognition, 96*, 103219. https://doi.org/10.1016/j.concog.2021.103219

Waszak, F., Cardoso-Leite, P., & Hughes, G. (2012). Action effect anticipation: Neurophysiological basis and functional consequences. *Neuroscience and Biobehavioral Reviews, 36*(2), 943–959. https://doi.org/10.1016/j.neubiorev.2011.11.004

Wen, W. (2019). Does delay feedback diminish sense of agency? A review. *Consciousness and Cognition, 73*, 102759. https://doi.org/10.1016/j.concog.2019.05.007

Wen, W., & Imamizu, H. (2022). The sense of agency in perception, behaviour and human-machine interactions. *Nature Reviews Psychology, 1*, 211–222. https://doi.org/10.1038/s44159-022-00030-6

Wen, W., Kuroki, Y., & Asama, H. (2019). The sense of agency in driving automation. *Frontiers in Psychology, 10*, 2691. https://doi.org/10.3389/fpsyg.2019.02691

Wen, W., Yamashita, A., & Asama, H. (2017). The influence of performance on action-effect integration in sense of agency. *Consciousness and Cognition, 53*, 89–98. https://doi.org/10.1016/j.concog.2017.06.008

Wolpe, N., Haggard, P., Siebner, H. R., & Rowe, J. B. (2013). Cue integration and the perception of action in intentional binding. *Experimental Brain Research, 229*(3), 467-474. https://doi.org/10.1007/s00221-013-3419-2

Wu, D., Gu, J. J., Li, M., Zhang, M., Zhang, M., Zhao, K., & Fu, X. L. (2019). Sense of agency based on action and causation: The mechanism of intentional binding effect for voluntary action. *Advances in Psychological Science, 27*(5), 804-810. https://doi.org/10.3724/sp.J.1042.2019.00804

Yoshie, M., & Haggard, P. (2013). Negative emotional outcomes attenuate sense of agency over voluntary actions. *Current Biology, 23*(20), 2028-2032. https://doi.org/10.1016/j.cub.2013.08.034

Yoshie, M., & Haggard, P. (2017). Effects of emotional valence on sense of agency require a predictive model. *Scientific Reports, 7*(1), 8733. https://doi.org/10.1038/s41598-017-08803-3

Zhang, M., Wu, D., Li, M., Ling, Y. B., Zhang, M., & Zhao, K. (2018). The measurement and neural mechanism of sense of agency. *Advances in Psychological Science, 26*(10), 1787-1793. https://doi.org/10.3724/sp.J.1042.2018.01787

Appendix

Independent samples t-tests comparing time judgment errors for auditory stimuli presented alone in our study with those from Haggard et al. (2002) and Antusch et al. (2019) revealed no significant differences: vs. Haggard et al., t(37) = -0.72, p = 0.479, Cohen' s d = 0.29; vs. Antusch et al., t(64) = -1.07, p = 0.287, Cohen' s d = 0.26. Similarly, time judgment errors for visual stimuli presented alone did not differ significantly from those reported by Ruess et al. (2018), t(76) = -0.81, p = 0.422, Cohen' s d = 0.18. These results indicate that time judgment accuracy was unaffected by stimulus duration (see Appendix Table 1).

Appendix Table 1
Time Judgment Errors (ms) Across Different Stimulus Durations

Stimulus Duration	Time Judgment Error (ms)
100ms, Haggard et al. (2002)	–
100ms, Antusch et al. (2019)	–
840ms, Present study	–
150ms, Ruess et al. (2018)	–
300ms, Present study	–

Note: Detailed values are available upon request.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.