Explicit and implicit agency over auditory and visual action-outcomes

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1. Introduction

Sense of agency (SoA) refers to a feeling of generating one's own actions and events in the external world [1]. Action entailing sensory outcomes generates SoA when the outcomes temporally match the internal prediction [2]. As SoA comprises explicit and implicit levels [3], prior studies have employed both explicit and implicit measures. For explicit measures, subjective rating has been used [4]. For implicit measures, compression of the subjective temporal interval between action and outcome can be observed in active, but not passive, movements [5]. This intentional binding (IB) effect [5] and explicit rating [4] can be reduced by a temporal discrepancy between action and outcome, suggesting that explicit and implicit SoA are related. Indeed, studies have reported inter-individual correlations between IB and agency rating [6], postulating that one who experiences stronger or weaker IB than others also experiences stronger or weaker explicit SoA (i.e., individual difference). Nevertheless, as the inter-individual correlation is rarely the same as the *intra*-individual correlation [7], the above inter-individual correlation does not necessarily mean an intra-individual variation, which postulates that one experiences strong or weak IB when one experiences strong or weak explicit SoA.

We examined both the intra- and inter-individual correlation between explicit and implicit SoA. In the action task, participants voluntarily pressed a key that was followed by a tone (Experiment 1) or a flash (Experiment 2) with five levels of delay. Participants rated the perceived SoA and estimated the outcome delay in each trial. In the baseline task, participants were passively presented with one tone (flash) followed by another tone (flash) with the same range of delays. The estimated delays in the baseline task were used to calculate the degree of IB. We expected that longer delays would cause smaller agency rating and IB, that variability due to the outcome delay would correlate *inter*-individually between rating and IB, and that the rating and IB would correlate *intra*-individually.

2. Experiment 1

2.1. Methods

Thirty-four right-handers participated (18 females; age

19.3 ± 0.8 years). The local ethics committee approved this study and participants provided written informed consent prior to the experiment.

The stimuli were presented through headphones and comprised two pure tones with pitches of 600 (low tone) and 1,000 Hz (high tone) and duration of 100 ms. A fixation cross and instructions were coloured white and presented against a black background on a monitor.

In the action task, following the fixation cross presentation, participants voluntarily pressed the “enter” key using their right index finger. The high tone was presented 100, 300, 500, 700, or 900 ms after the keypress. The fixation cross remained for 300–500 ms after the high tone. Finally, the monitor presented a question asking participants to rate their perceived SoA over the tone (“How much did you feel that you caused the tone?”) using a Likert scale ranging from 1 (“Not at all”) to 9 (“Extremely strongly”). Next, a statement appeared on the monitor asking participants to estimate the action-outcome delay (“Estimate the delay between the keypress and the tone using 1 to 1,000 [ms]”). Participants were informed that the delay varied randomly between 1 and 1,000 ms on a trial-by-trial basis. The order of questions was counterbalanced across participants. The inter-trial interval was 700–900 ms. The baseline task was identical to the action task, except that a low tone was presented instead of voluntary keypress. The initial presentation of the fixation cross lasted for 600–800 ms. Next, the low tone was presented followed by the high tone with the five levels of delay. Participants responded to a question asking them to estimate the outcome delay (“Estimate the delay between two tones using 1 to 1,000 [ms]”). The action and baseline tasks were blocked in the order of ABAB. Participants performed either the action or baseline tasks over seven trials each with five outcome-delays per block. The block order was counterbalanced across participants. The order of the delays was randomized.

We calculated ratios by dividing the estimated delays in the baseline task by those in the action task. Larger ratios indicate stronger IB. We analysed *inter*-participant rank correlations (Spearman's rho, ρ) between the linear-regression slopes over ratings and those over estimated-delay ratios (i.e., IB). Linear regressions with five levels of outcome delay as a regressor were fitted separately to the rating and estimated-delay ratio in 70 trials of the action task for each participant

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Fig. 1 Results of Experiment 1 (left) and 2 (right). *Top*: Mean score of agency rating. *Mid*: Mean estimated outcome delay. *Bottom*: Mean ratio of estimated delay in the baseline task to that in the action task. Higher ratio indicates stronger intentional binding. Error bars denote SEM.

using the least-squares method. The estimated-delay ratio for each trial in the action task was calculated by referring to estimated delays averaged for each delay condition in the baseline task. Outcome delays as a regressor were handled in units of seconds for simplicity. We analysed *intra*-participant rank correlations between ratings and estimated-delay ratios in 70 trials for each participant.

2.2. Results and discussion

The left column of Fig. 1 summarizes the results. Analysis of variance (ANOVA) revealed an effect of outcome delay on the agency rating (Greenhouse-Geisser corrected df , $F(1.87, 61.66) = 170.02$, $p < 0.01$). Post-hoc comparisons indicate significant differences between each adjacent delay condition (Bonferroni corrected $ps < 0.01$). The explicit SoA over the auditory outcome decreased with the increasing outcome delay.

ANOVA revealed the main effects of the outcome delay ($F(1.22, 40.11) = 262.36$, $p < 0.01$) and task ($F(1, 33) = 31.81$, $p < 0.01$) on estimated delays. There was no interaction between the two factors ($F(2.74, 90.39) = 0.45$, $p =$

0.701). Post-hoc tests revealed significant differences between all adjacent delay conditions (Bonferroni corrected $ps < 0.01$), suggesting that participants were able to discriminate the levels of outcome delay. Shorter estimated-delay in the action task than in the baseline task suggested that IB emerged regardless of action-outcome temporal discrepancy. The estimated-delay ratio (i.e., IB) decreased with increasing outcome delays. Outcome delay had an effect on the estimated-delay ratio ($F(1.16, 38.37) = 20.06$, $p < 0.01$). Post-hoc tests showed differences between all adjacent delay conditions (Bonferroni corrected $ps < 0.05$) except between the 500 and 700 ms conditions ($p = 0.999$). IB can be attenuated by temporal contiguity between action and outcome.

We found positive correlations between linear regression slopes for agency rating and IB ($\rho = 0.372$, $p = 0.030$). IB and agency rating were similarly modulated by action-outcome temporal contiguity. Finally, we calculated intra-individual correlations between rating and IB on a trial-by-trial basis. Correlation coefficients (ρ) from 34 participants ranged from 0.016 to 0.912. We estimated the average coefficient as 0.577 with bootstrapped 95% confidence interval (CI) from 0.505 to 0.648 (10,000 iterations). Agency rating and IB were positively correlated *within* individuals. Explicit and implicit SoA might coincide while being modulated by action-outcome congruence.

3. Experiment 2

Experiment 2 aimed to replicate Experiment 1 and investigate modality-specificity by using visual outcomes.

3.1. Methods

Thirty-four new right-handers participated (17 females; age 19.5 ± 1.0 years). Tasks were identical to Experiment 1, except that the low and high tones were replaced with grey and blue circles, respectively. The circles subtended to 2.4° (visual angle) of the diameter to surround the fixation cross and lasted for 100 ms. In the action task, questions asking participants to rate the SoA (“How much did you feel that you had caused the blue circle?”) and estimate the delay (“Estimate the delay between the keypress and the circle using 1 to 1,000 [ms]”) were presented. In the baseline task, the question “Estimate the delay between two circles using 1 to 1,000 (ms)” was asked.

3.2. Results and discussion

Agency rating decreased with increasing outcome delays (Fig. 1, right column). ANOVA revealed an effect of outcome delay ($F(2.03, 66.87) = 269.15$, $p < 0.01$) and differences between adjacent delay conditions (Bonferroni corrected $ps < 0.01$).

As for delay estimation, ANOVA revealed the main effects of the outcome delay ($F(1.38, 45.61) = 380.76$, $p < 0.01$). However, we did not find a main effect of the task ($F(1, 33) = 0.92$, $p = 0.346$) or an interaction between the two factors ($F(2.52, 82.99) = 1.10$, $p = 0.349$), suggesting that there was no IB for visual outcomes. We performed one-sample Wilcoxon signed-rank tests comparing estimated-delay ratios with 1. A ratio of 1 indicates veridical estimation. Ratios exceeded 1 in the 100-ms ($V = 439$, $p = 0.038$) and 300-ms delay conditions ($V = 477$, $p = 0.010$), suggesting

that visual IB can occur when the outcome delay is smaller than 500 ms.

There was no correlation between the regression slopes for agency rating and IB ($\rho = -0.049, p = 0.783$). This might be because the slopes for IB crowded around zero (i.e., insensitive to delays). Indeed, the median slope was -1.17 (interquartile range: -3.18 to 0.15), compared with -2.89 (-6.64 to -0.60) in Experiment 1.

Finally, we analysed the intra-individual correlation between rating and IB. The mean correlation coefficient (ρ) was 0.479 (range: -0.162 to 0.820 ; bootstrapped 95% CI 0.398 to 0.562), suggesting that IB and agency rating are positively correlated within individuals. Even though there was no inter-individual correlation in the regression slope, explicit and implicit SoA over visual outcomes may correlate intra-individually.

4. General discussion

We examined inter- and intra-individual relationships between the explicit and implicit SoA. Action-outcome delays decreased the explicitly rated SoA due to temporal incongruence with internal prediction. IB for auditory outcomes were robustly observed, regardless of the outcome delays, and increasing outcome delays decreased the IB. Indeed, we found inter-individual correlations between regression slopes with outcome delay as a predictor for agency rating and IB for auditory outcome. However, the IB for visual outcome was observed only in the small delay conditions and did not show the abovementioned correlation between slopes. Importantly, *intra*-individual correlations between agency rating and IB were found in both modalities, suggesting that explicit and implicit SoA over sensory outcomes may coincide within an individual.

Subjective ratings of SoA and IB have been employed as established measures of SoA [1]. We suggested that these measures can correlate intra- and inter-individually. Although one might assume that the correlation between these two measures implies that they relate to the same underlying construct, the evidence is mixed with both dissociation [8] and association reported [6]. To account for dissociations, theoretically, different mechanisms may underlie agency judgment and IB, which might be generated at different levels [3,9]: while agency judgment relies on conceptual and evaluative processes, IB relies on perception of time. However, biases in the perception of temporal intervals and timing of action and its outcome due to IB may themselves serve as a cue for agency judgment [9]. Compressed action-outcome intervals might promote agency judgment based on temporal contiguity between an action and its outcome. Given this, it is plausible that the degree of IB is (in)directly associated with the degree of perceived SoA. This possibility finds support in psychiatric research: people with schizophrenia, who may have abnormal SoA, also show abnormally enhanced IB relative to healthy controls (e.g., [10]).

Voluntary action and/or SoA may modulate time perception. When individuals voluntarily move their body (parts), potentially entailing SoA, their subjective time is flexibly modulated based on the phases of movement [11]. Indeed, such time distortion induced by bodily movements is limited

to self-related sensory events [12]. These findings suggest a link between SoA, time perception, and IB; this notion may be supported by the present findings suggesting that SoA is associated with IB even on a trial-by-trial basis. Fluctuation of subjective time might be an adaptive function driven by SoA for optimal selection of one's own actions and online processing of sensory consequences.

Visual IB was weaker, limited to smaller outcome-delay and was insensitive to changes in outcome delay, relative to auditory IB. Weaker visual IB is consistent with a previous study [13], although that study showed that visual IB was *sensitive* to outcome delays. This might be due to the use of a different task and a different range of outcome delays. Visual inferiority in self-specific processing has also been found in the sensory attenuation induced by the match between predicted and actual sensory feedback [14], with this effect robustly observed in tactile and auditory domains (e.g., [15]). One plausible reason for this is the likelihood of pairing between the motor effector and modality of the action's outcome. Specifically, manual action and vocalization are likely to cause auditory events, while eye movement causes visual events. This idea has been supported by psychophysiological evidence [16]. To speculate, intentional binding could rely on the effector-modality coupling such that specific modalities of action outcome are predicted by an action, and, subsequently, temporally bound to the action.

We should note that two participants in Experiment 1 and one in Experiment 2 showed substantially low intra-individual correlation coefficients (-0.162 to 0.139) out of the mean ± 2 standard deviation range, although we still observed positive intra-individual correlations in Experiments 1 and 2 (0.608 and 0.498 , respectively) from a dataset without these outliers. Future studies should reveal the factors of *inter*-individual variability in *intra*-individual correlation between explicit and implicit agency.

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