

## Research



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# The sense of agency is action–effect causality perception based on cross-modal grouping

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Sense of agency, the experience of controlling external events through one's actions, stems from contiguity between action- and effect-related signals. Here we show that human observers link their action- and effect-related signals using a computational principle common to cross-modal sensory grouping. We first report that the detection of a delay between tactile and visual stimuli is enhanced when both stimuli are synchronized with separate auditory stimuli (experiment 1). This occurs because the synchronized auditory stimuli hinder the potential grouping between tactile and visual stimuli. We subsequently demonstrate an analogous effect on observers' key press as an action and a sensory event. This change is associated with a modulation in sense of agency; namely, sense of agency, as evaluated by apparent compressions of action–effect intervals (intentional binding) or subjective causality ratings, is impaired when both participant's action and its putative visual effect events are synchronized with auditory tones (experiments 2 and 3). Moreover, a similar role of action–effect grouping in determining sense of agency is demonstrated when the additional signal is presented in the modality identical to an effect event (experiment 4). These results are consistent with the view that sense of agency is the result of general processes of causal perception and that cross-modal grouping plays a central role in these processes.

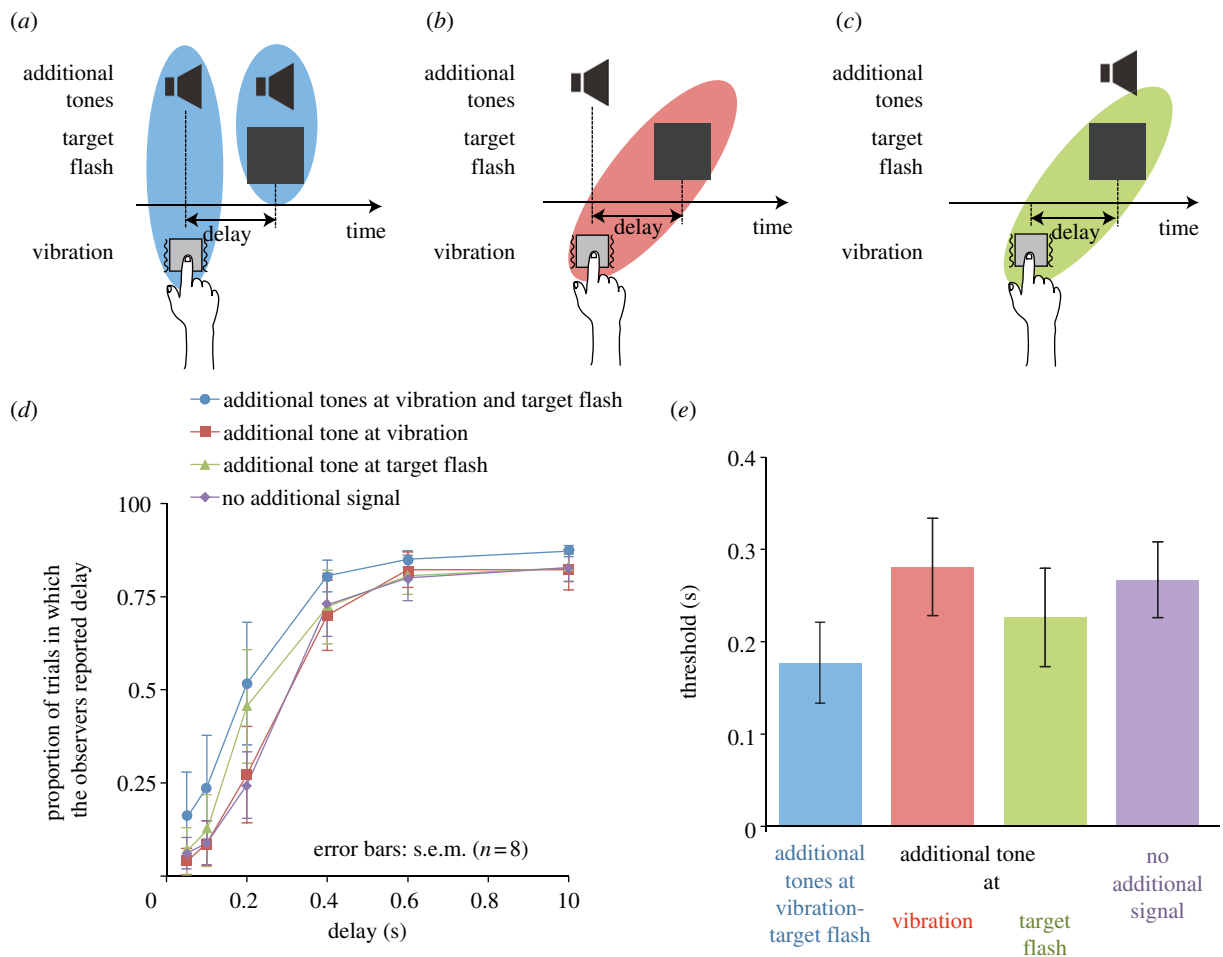
## 1. Introduction

An awareness of how our actions affect our environment is a critical aspect of human perception. Such an understanding is necessary for successful navigation of interactions with other beings and objects alike. Knowledge of our own actions often manifests as a sense of agency. Sense of agency describes the experience of controlling external events through our own actions [1]. Sense of agency arises when there is temporal contiguity and content consistency between signals related to action and those related to the putative effect [2–11].

Temporal contiguity and content consistency have also been suggested to contribute to the determination of causal inference in the mind [12], a proposal later supported by studies of phenomenal causality [13,14]. This commonality of properties is consistent with a view that the sense of agency is a product of the general determination of causality between action and effect [9,15].

Owing to the modularity of processing in the human brain, action-related signals and effect-related signals are likely to arise in different processing modules. Consequently, the sense of agency (or the causal perception between action and effect signals) could be computationally analogous to the perception of cross-modal temporal relationships in general, including perception of simultaneity and inter-stimulus delay between sensory signals originating in distinct sensory modalities. This led us to a hypothesis that the sense of agency may be produced by processes governing grouping or binding of sensory signals, similar to those governing cross-modal temporal perception.

To test this hypothesis, in the first experiment, we created a situation in which the effect of cross-modal grouping could be modulated by the presence



**Figure 1.** The stimulus conditions and results of experiment 1. (a–c) Stimulus conditions tested in experiment 1 and the results predicted from a hypothesis that the sense of agency is a perceptual grouping between action and effect. (a) ‘Additional tones at vibration and target flash’ condition. When both vibration and flash are accompanied by, respectively, synchronized tones, perceptual grouping between vibration and flash will be hampered because the vibration groups together with the first tone while the flash groups together with the second tone. This will also enhance the detection of a delay between vibration and flash. (b) ‘Additional tone at vibration’ condition. Perceptual grouping between vibration and flash will not be hampered when vibration is accompanied by an additional tone because the tone and flash are not competing to group with the vibration, hence temporal grouping between vibration and flash is also maintained. (c) ‘Additional tone at target flash’ condition. Perceptual grouping between vibration and flash will not be hampered when the flash is accompanied by an additional tone because the tone and flash are not competing to group with the vibration. (d) Proportion of trials in which a black square was perceived to be delayed from a passive vibration in tasks with and without the auditory additional signals. Group mean of threshold for detecting the delay is shown in (e). Error bars denote standard errors of mean ( $n = 8$ ).

or the absence of additional stimuli [16,17]. As all events were passively perceived, this experiment did not contain any effect of agency. Subsequent experiments examined whether similar manipulations could also affect the sense of agency, as measured by both apparent compressions of the interval between action and effect (intentional binding), and subjective causality ratings. Our results were consistent with the hypothesis that perceptual grouping processes play a similarly critical role in the production of sense of agency as that found for passive cross-modal temporal judgements.

## 2. Experiment 1

The purpose of this experiment was to create a situation in which perceptual grouping between cross-modal signals was modulated by task-irrelevant sensory signals presented in a third, task-irrelevant modality. Using a task containing no action, we estimated the baseline effect to be compared with those obtained in the subsequent experiments with tasks concerning the sense of agency. We had participants detect the delay between a tactile vibration and a visual

flash. The ease of delay detection reflects the strength of perceptual segregation (or weakness of perceptual grouping) of the two signals [18]. We synchronized the task-irrelevant tones with either the vibration (figure 1b), the flash (figure 1c) or both (figure 1a), and observed the effects of these tones on delay detection. We expected an improvement of delay detection particularly in the final condition, since it is known that the addition of synchronized task-irrelevant auditory signals enhances the temporal segmentation of the targets [16,17].

### (a) Methods

#### (i) Participants

Eight adults participated in this experiment (and all the following experiments). The participants were unaware of the specific purpose of experiments. They reported they had normal or corrected-to-normal visual acuity. They were paid for their participation. The experiments were conducted according to the principles laid down in the Helsinki Declaration. Written informed consent was obtained from all participants in this study.

## (ii) Apparatus

Visual stimuli were presented on a 15-inch CRT monitor (2236-3DN, IBM) with a resolution of  $1024 \times 768$  pixels and the refresh rate of 60 Hz. To present auditory stimuli, we used headphones (HDA 200, Sennheiser). We also used a vibrotransducer (Vp2, Acoupe Laboratories) to present vibration stimuli. A computer (Mac mini, Apple) controlled stimulus presentation and data collection with MATLAB and its extension (PSYCHTOOLBox v. 3) [19,20]. The physical onset timing among visual, auditory and tactile stimuli was confirmed using an oscilloscope connected to a phototransistor and a microphone.

## (iii) Stimuli

The visual stimulus (i.e. target flash) was a dark square (with the size of  $4 \times 4$  dva) at the centre of display against a neutral grey background. The duration of the dark square was randomized in a range between 0.3 and 0.8 s on each trial. The tactile stimulus (a passive vibration), presented to a participant's index finger, had a sinewave carrier frequency of 120 Hz, and a duration of 0.0167 s with rise/fall durations of 0.00835 s. Auditory stimuli (i.e. the additional tones) were pure tone auditory burst(s). The frequency of the pure tone was 0.8 kHz, and its duration was 0.0167 s with rise/fall durations each of 0.005 s. There were four experimental conditions. In the 'additional tones at vibration target flash' condition (figure 1a), two pure tones were presented; the first pure tone was presented synchronously with the vibration stimulus, and the second pure tone was presented synchronously with the dark square target flash. In the 'additional tone at vibration' condition (figure 1b), the pure tone was presented synchronously with the vibration stimulus. In the 'additional tone at target flash' condition (figure 1c), the second pure tone was presented synchronously with the dark square as the target flash. In the 'no additional signal' condition, no pure tones were presented. In each condition, there was a temporal delay (0.05, 0.1, 0.2, 0.4, 0.6 or 1 s) between the passive vibration and the appearance of the target flash (figure 1a–c).

## (iv) Procedure

Experiments were conducted in a darkroom. Observers sat at a distance of 50 cm from the CRT display and viewed the display while placing their index finger on the vibrotransducer. The task was to judge whether the onset of the target flash was delayed from the passive vibration. Each observer performed 480 trials: 4 (additional tone conditions)  $\times$  6 (levels of delay of onsets between passive vibration and target flash)  $\times$  20 repetitions. The pattern of additional tones and six levels of delay between the vibration stimulus and the target flash were tested as within-subject factors. The order of trials was pseudo-randomized. It took 30 min for each observer to complete this experiment.

## (b) Results and discussion

We computed the proportion of trials in which the observers reported a delay between the vibration stimulus and target flash for each level of physical delay in the presence/absence of the additional tones (figure 1d; see the electronic supplementary material). We individually fitted a cumulative Gaussian curve to estimate the threshold producing a 0.5 detection rate for the delay (averaged data in figure 1e). Using the thresholds,

we conducted a one-way repeated measures ANOVA with the pattern of additional tones as a within-subject factor. The main effect of the presence of additional tones was significant ( $F_{3,21} = 14.932$ ,  $p < 0.0001$ , partial  $\eta^2 = 0.681$ ). The threshold for detecting the delay of the target flash from the passive vibration was significantly lower in the 'additional tones at vibration and target flash' condition than in the other three conditions ( $p < 0.05$ ; figure 1e). Moreover, the threshold in the 'additional tone at target flash' condition was significantly lower than the threshold in the 'additional tone at vibration' condition ( $p < 0.05$ ). These results demonstrate that the detection of a delay between the onsets of tactile and visual stimuli can be enhanced by the presence of synchronized additional signals that are presented in a task-irrelevant modality. Considering that the difficulty of delay detection is a measure of the strength of grouping between the tactile and visual signals, our finding extends on those previously reported by Keetels & Vroomen [16] and Vroomen & Keetels [17]. A possible process underlying this effect is that unambiguous segmentation between two auditory signals helps temporal segmentation between signals in other modalities that are cross-modally linked with those auditory signals [21]. A reduction in the threshold for the 'additional tones at target flash' condition is consistent with the idea that shaper temporal segregation of tactile and auditory signals [22] helps segmentation of a tactile signal from a visual signal that is cross-modally linked with an auditory signal.

## 3. Experiment 2

The second experiment examined whether the sense of agency between an action (i.e. button press) and the effect (i.e. appearance of a dark square on the display) was affected by the presence of additional task-irrelevant tones in the same way as the passive perceptual judgement used in experiment 1. We measured the apparent temporal compression between action and its effect event. The sense of agency can be implicitly measured by the magnitude of apparent temporal compression between action and effect, the so-called intentional binding [23]. Strong intentional binding occurs with a strong sense of agency rating [7,24] and/or strong perception of causality [15,25,26]. We predicted that the additional-tones-induced reduction of grouping between action and its effect would result in a diminished sense of agency.

## (a) Methods

### (i) Observers

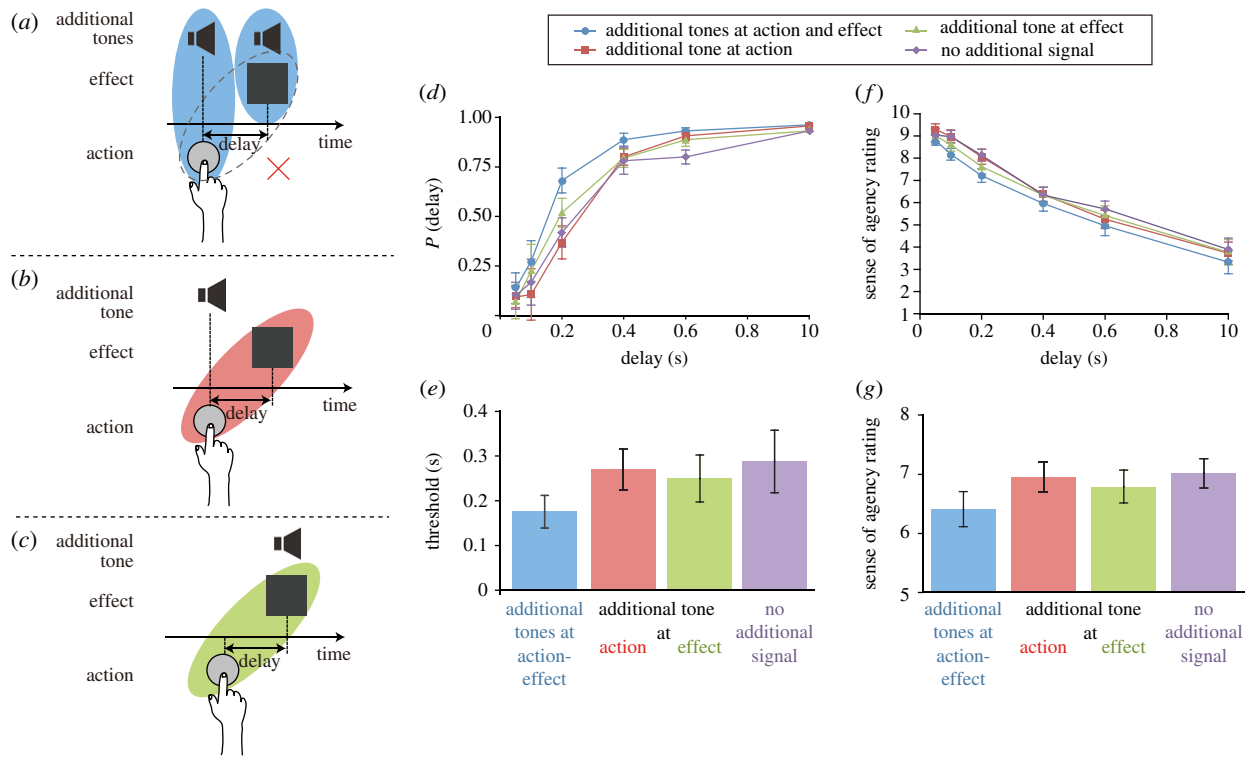
Eight observers participated in the delay judgement task. All of the observers had participated in experiment 1 but were still unaware of the specific purpose of experiments.

### (ii) Apparatus

Identical to experiment 1 except that the vibrotransducer was no longer used.

### (iii) Stimuli

The observer's key press triggered the presentation of a dark square as target flash. The stimulus properties of the flash were identical to that used in experiment 1. A temporal delay (0.05, 0.1, 0.2, 0.4, 0.6 or 1 s) was inserted between the button press and the appearance of the target flash (figure 2a–c).



**Figure 2.** (a–c) Stimulus conditions tested in experiments 2 and 3 and the results predicted from a hypothesis that the sense of agency is a perceptual grouping between action and effect. (a) ‘Additional tones at action and effect’ condition. When both action and effect are accompanied by, respectively, synchronized tones, perceptual grouping between action and effect will be hampered because action groups together with the first tone while the putative effect groups together with the second tone. This will also cause a weak sense of control for effect. (b) ‘Additional tone at action’ condition. Perceptual grouping between action and effect will not be hampered when action is accompanied by an additional tone because the tone and flash are not competing to group with the button press, hence temporal grouping between action and effect is also maintained. (c) ‘Additional tone at effect’ condition. Perceptual grouping between action and effect will not be hampered when the effect is accompanied by an additional tone because the tone and flash are not competing to group with the button press. (d) The results of the delay judgement task in experiment 2. Proportion of trials in which the effect was perceived to be delayed from the active button press in tasks with and without auditory additional signals. Group mean of threshold for detecting the delay is shown in (e). Error bars denote standard error of mean ( $n = 8$ ). (f) The results of the rating task in experiment 3. Rating values for the sense of agency with and without additional tones as a function of temporal delay. (g) Rating values of (f) collapsed across temporal delays. Error bars denote standard error of mean ( $n = 12$ ).

The duration of the dark square was randomized in a range between 0.3 and 0.8 s on each trial. We tested three patterns of additional tones (figure 2a–c for ‘additional tones at action and effect’ condition, ‘additional tone at action’ condition and ‘additional tone at effect’ condition, respectively) and ‘no additional signal’ condition. To prevent observers from hearing the sound of the vibration or their own button press, they were asked to wear headphones through which auditory white noise was presented from the initiation of each trial to the disappearance of the target flash.

#### (iv) Procedure

Identical to that used in experiment 1 except for the following. The observers were asked to press an assigned key to trigger the dark square as a target, and judged whether the onset of the target flash was delayed from their button press. Each experimental condition was repeated 20 times. Thus, each observer performed 480 trials: 4 (additional tone conditions)  $\times$  6 (levels of delay of onsets between passive vibration and target flash)  $\times$  20 repetitions. The pattern of additional tones and six levels of delay between the button press and the target flash were tested as within-subject factors. The order of trials was pseudo-randomized across observers. It took 30 min for each observer to complete this experiment.

#### (b) Results and discussion

For the data obtained in the delay judgement task (figure 2d), we calculated the delay detection threshold as in experiment 1. Using the threshold (figure 2e), we conducted a one-way repeated measures ANOVA with the pattern of the additional tones as a within-subject factor. The main effect of the presence of additional tones was significant ( $F_{3,21} = 6.025$ ,  $p < 0.005$ , partial  $\eta^2 = 0.463$ ). The threshold for detecting the delay of the target effect from the active button press was significantly lower in the ‘additional tones at action and effect’ condition than in the other three conditions ( $p < 0.04$ ). Intentional binding was diminished when the additional tones were, respectively, synchronized with the action and the target effect. The pattern of results is nearly indistinguishable from that of the cross-modal perceptual grouping (experiment 1). A Pearson’s correlation coefficient between mean thresholds in experiments 1 and 2 was 0.94. The results suggest that the sense of agency is produced by the mechanism similar to that producing cross-modal perceptual grouping.

Intentional binding was not reduced when the additional tone was synchronized with the action or the effect. These results are inconsistent with the interpretation that observers unintentionally directed their attention to the timing of the button press/additional event and therefore find the effect event less salient [27–29].



We also tested the situation wherein effect events were presented in audition while the additional signals were presented in vision (see the electronic supplementary material, experiment 1). As in experiment 2, 'additional flashes at action and effect' significantly weakened intentional binding between the observers' button press and an auditory effect event. Although the magnitude of the effect was numerically smaller (i.e. a 47 ms difference between 'additional flashes at action and effect' and 'no additional signals' conditions) than the condition of the main experiment (a 112 ms difference between the conditions), the magnitude of the effect was not significantly different between the experiments (Welch's *t*-test:  $t_8 = 1.54$ ,  $p > 0.16$ ). Taken together, the results suggest that, irrespective of modality mappings between effect events and additional signals, intentional binding follows a rule common to cross-modal grouping.

## 4. Experiment 3

One might consider that nearly perfect coincidence of the results of the first two experiments is not surprising since both used the same delay detection task. The third experiment therefore replicated the experiment though changing the task to a subjective rating of the sense of agency. Synofzik *et al.* [30] propose a two-stage model for the sense of agency. The model assumes that bottom-up and top-down driven senses of agency are represented at the first and second stages, respectively. Intentional binding (interval compression) is predominantly affected by the bottom-up driven sense of agency, while the subjective rating is significantly affected by the top-down driven sense of agency. The degradation of action–effect grouping should also reduce the sense of agency rating if perceptual grouping between action and its effect is a fundamental principle in determining the sense of agency.

### (a) Methods

#### (i) Observers

Twelve adults participated in this experiment. Eight of those 12 had previously participated in experiments 1 and 2. Considering the generally high level of individual variability in the subjective rating task, before starting data collection, we decided to recruit an additional four naive observers.

#### (ii) Apparatus

Identical to experiment 2.

#### (iii) Stimuli

Identical to experiment 2.

#### (iv) Procedure

Identical to that used in experiment 2 except for the following. The observers were asked to report the extent to which they felt they could control the presentation of the target flash by their button press with a 10 point scale (1: weak control, 10: strong control, and intermediate values: intermediate strength of the control). Before the main experiment, the observers engaged in preliminary trials (20–30 trials) to familiarize them with the rating task. The main trials started after observers reported that they were familiar with the task. Each experimental condition was repeated 10 times. Thus, each observer performed 240 trials: 4 (additional tone conditions)  $\times$  6 (levels of delay of onsets between passive

vibration and target flash)  $\times$  10 repetitions. In both tasks, the presence/absence of an additional flash and six levels of the delay between the button press and the appearance of the dark square were tested as within-subject factors. It took 15 min for each observer to complete this experiment.

### (b) Results and discussion

For the data obtained in the rating task, using the rating values for each condition (figure 2f; the data collapsed across delay conditions are shown in figure 2g), we conducted a two-way repeated measures ANOVA with temporal delay and the patterns of the additional tones as factors. The main effect of temporal delay was significant ( $F_{5,55} = 72.468$ ,  $p < 0.0001$ , partial  $\eta^2 = 0.868$ ). Importantly, we found that the addition of tones had a significant main effect ( $F_{3,33} = 7.862$ ,  $p < 0.0005$ , partial  $\eta^2 = 0.417$ ), and multiple comparison tests showed that the sense of agency was significantly weaker in the 'additional tones at action and effect' condition than the other three conditions ( $p < 0.01$ ; figure 2g).

In the electronic supplementary material, experiment 1, we also tested the situation wherein effect events were presented in audition while the additional signals were presented in vision. The effects of additional visual signals on the sense of agency rating did not reach statistical significance. Owing to the dominance of audition over vision in temporal perception [31], it was expected that the visual additional signals would weakly dictate temporal grouping between the observers' button press and auditory effect events. In support of this expectation, as described above, the difference in delay detection thresholds between with-and-without additional signals conditions was smaller in the electronic supplementary material, experiment 2 (47 ms) than in experiment 2 (110 ms). The rating process, which we assume to be noisier than the delay judgement, may not be able to reliably use the consequence of such a weak modulation of temporal grouping between action and effect, leading to non-significant effects of additional visual signals in the electronic supplementary material, experiment 2.

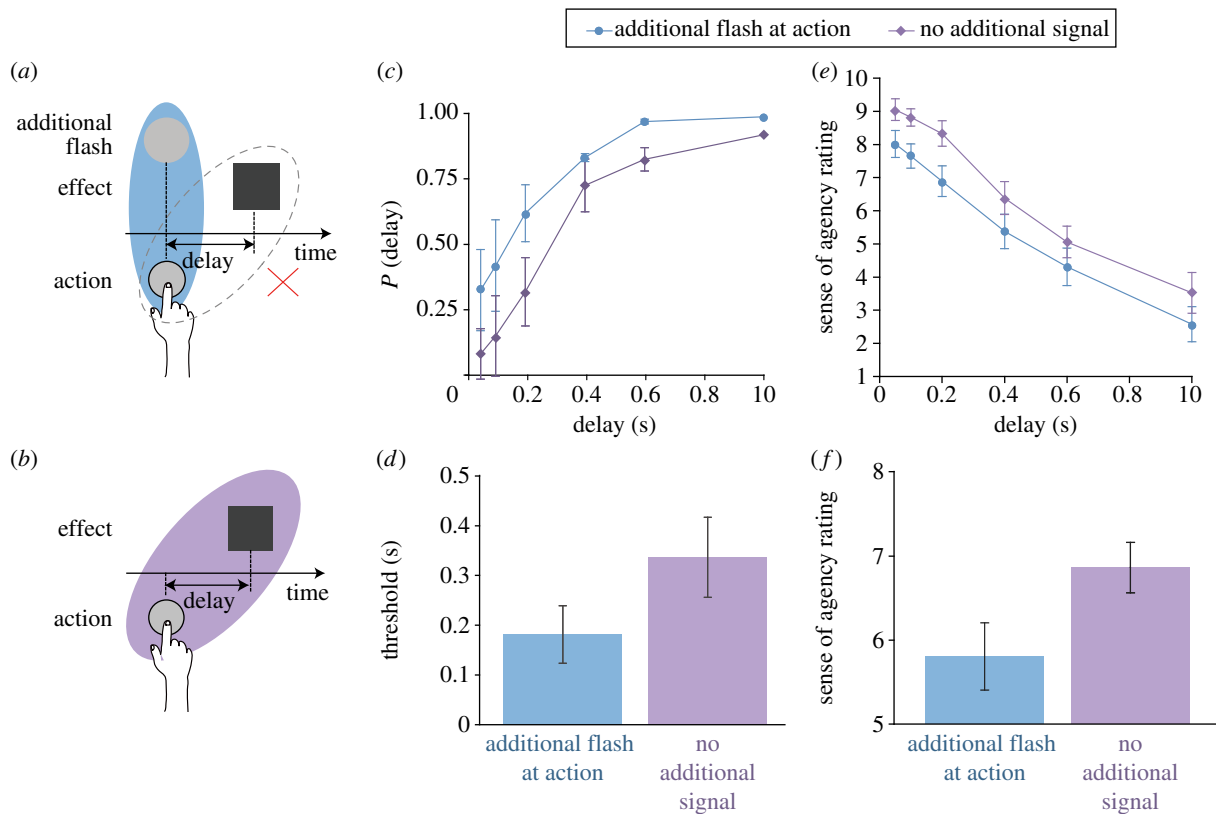
## 5. Experiment 4

In the previous experiments, the additional signals, which disrupted the action–effect grouping, were presented in the modality irrelevant to the effect events. Here, we were interested in the condition wherein the additional signals were presented in the modality identical to the effect events. Previous studies have examined the effect of perceptual grouping between signals in two sensory modalities on cross-modal temporal judgements [21,32]. If perceptual grouping underlies the determination of the sense of agency, the sense of agency will be diminished when an additional signal presented in the modality identical to effect events is synchronized with the button press, because the additional signal is more temporally proximate than the effect events, and so groups together with the button press, and reduces the strength of potential grouping between the action and the putative effect through a process that tries to find one-to-one correspondence [32,33].

### (a) Methods

#### (i) Observers

Twelve observers who had also participated in experiment 3 performed the rating task. Eight of these observers also participated in experiments 1–3.



**Figure 3.** (a,b) Stimulus conditions tested in experiment 4 and the results predicted from a hypothesis that the sense of agency is a perceptual grouping between action and effect. (a) 'Additional flash at action' condition. Perceptual grouping between action and effect will be diminished when action is accompanied by an additional flash, because the additional event competes against the target effect to group with the action. The deterioration of grouping will weaken the sense of agency. (b) 'No additional signal' condition. When an agent's action (button press) is followed by its effect (visual flash of a dark square) with a short delay, the two events temporally group together, leading to a strong sense of agency. (c) The results of the delay judgement task in experiment 4. Proportion of trials in which the effect (appearance of a black square) was perceived to be delayed from an active button press in tasks with or without the visual additional signal. Group mean of threshold for detecting the delay is shown in (d). Error bars denote standard error of mean ( $n = 8$ ). (e) The results of the rating task in experiment 4. Rating values for the sense of agency, with and without an additional flash, as a function of temporal delay of appearance of a black square from the button press of the observer. (f) Rating values of (e) collapsed across temporal delays. Error bars denote standard error of mean ( $n = 12$ ).

## (ii) Apparatus

Identical to previous experiments.

## (iii) Stimuli

Identical to those used in previous experiments except for the following. On half of the trials (i.e. 'additional flash at action' condition), a bright disc (bright disc with diameter of  $4^\circ$ ) as an additional flash was presented for 0.0167 s immediately after the button press (figure 3a) while on the other half (i.e. 'no additional signal' condition), no bright disc was presented (figure 3b).

## (iv) Procedure

Identical to that used in experiment 3 except for the following. In the delay judgement task, the observers judged whether the onset of the target flash was delayed from their button press, while ignoring the appearance of the bright disc. Each experimental condition was repeated 20 times. Thus, each observer performed 240 trials. In the sense of agency rating task, the observers were asked to report the extent to which they felt they could control the presentation of the target flash by their button press with a 10 point scale. Each experimental condition was repeated 10 times. Thus, each observer performed 120 trials. In both tasks, the presence/absence of an additional flash and six levels of the delay between the button press and

the appearance of the dark square were tested as within-subject factors. The order of trials was pseudo-randomized. It took 20 and 10 min for each observer to complete the delay detection and rating tasks of this experiment, respectively.

## (b) Results and discussion

As in experiment 2, for the data obtained in the delay judgement task, we computed the proportion of trials in which observers reported the delay between their button press and target flash for each condition of physical delay and the presence/absence of the additional flash (figure 3c), and estimated the threshold for delay detection. The threshold was significantly lower in the 'additional flash at action' condition than in the 'no additional signal' condition ( $t_7 = 3.33$ ,  $p < 0.02$ , Cohen's  $d = 0.747$ ).

As in experiment 3, for the data obtained in the rating task, we calculated the average rating of sense of agency as a function of the temporal delay between onset of the dark square and the button press, as presented in figure 3e (average rating collapsed across temporal delay is shown in figure 3f). We conducted a two-way repeated measures ANOVA with the physical temporal delay between action and effect and the presence/absence of the additional signals as within-subject factors. The main effect of the physical temporal delay between action and effect was significant ( $F_{5,55} = 57.028$ ,  $p < 0.0001$ , partial  $\eta^2 = 0.838$ ). As predicted, the main

effect of the presence/absence of the additional flash was also significant ( $F_{1,11} = 17.287$ ,  $p < 0.002$ , partial  $\eta^2 = 0.611$ ).

These results demonstrate that perceptual grouping between the additional flash and the observer's button press weakened the grouping between button press and the target flash as the putative action effect, and consequently reduced both intentional binding and the sense of agency rating. Moreover, we observed similar suppressive effects of additional signals on the sense of agency even when the sense of agency for an auditory event was tested in the presence of the additional tone synchronized with the observers' action (see the electronic supplementary material, experiment 2). Taken together, these results again support our notion that perceptual grouping between action and effect underlies the determination of the sense of agency strongly.

## 6. General discussion

In this study, we were interested in whether cross-modal grouping processes contribute to the determination of the sense of agency. If so, this would support the premise that agency is an extension of generalized processes to determine causality. To address this issue, we first established a scenario in which cross-modal grouping affected passive temporal perception, as measured by the detection of a delay between tactile and subsequent visual stimulation. We subsequently investigated whether this same grouping effect would modulate the sense of agency as determined by both implicit (intentional binding) and explicit (subjective agency rating) measures.

In experiment 1, we found that perception of the delay between passive tactile and visual events was enhanced by the presence, relative to absence, of additional auditory events presented in synchrony with the tactile and visual events, respectively. This result is consistent with the idea that perception of unambiguous segmentation between the two auditory signals, grouped with the tactile and visual signals, respectively, assists in temporal segmentation of the tactile and visual signals, enhancing delay detection.

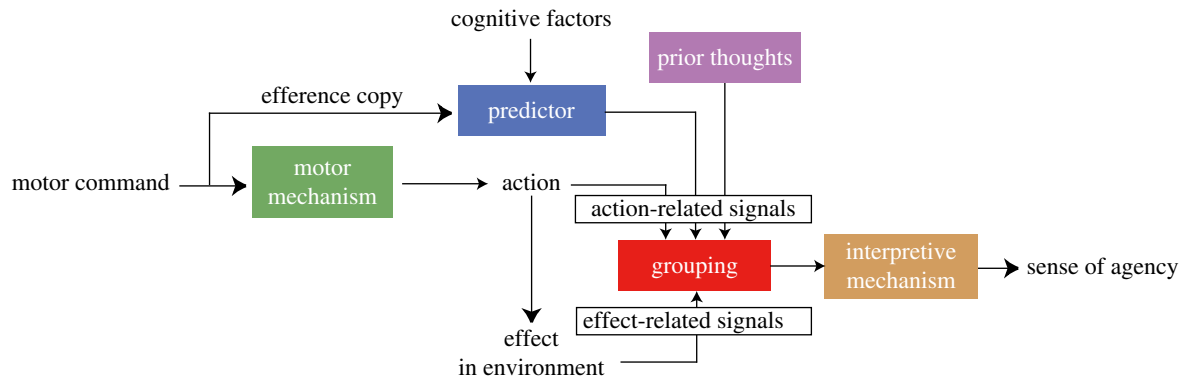
In experiment 2, we investigated whether the same manipulation, the presence or the absence of auditory events, would have an equivalent effect on sense of agency as measured by a similar delay detection task. Replacing passive tactile stimulation with an observers' button press, this task is equivalent to that typically used to reveal the intentional binding effect, often taken as an implicit measure of agency. A similar pattern of results to those obtained in experiment 1 was revealed, with the presence of the additional auditory tones enhancing detection of the delay between observers' button press and a subsequent visual effect. This outcome indicates that the same cross-modal grouping processes contribute to the perception of temporal relationships between sensory only (experiment 1) and observer generated motor-sensory (experiment 2) event pairs. Experiment 3 revealed a similar modulation of sense of agency as measured by subjective agency ratings, suggesting that cross-modal grouping processes are critical in the determination of both implicit and explicit sense of agency.

Finally, in experiment 4, we examined whether a different cross-modal grouping scenario would also lead to changes in the sense of agency. We found that the presence of an additional sensory event, presented in the same sensory modality as the putative effect of an observers' action, could modulate both implicit and explicit measures of sense of

agency. This is consistent with the previously demonstrated grouping rule of one-to-one correspondence for cross-modal pairs [32,33]. This result further supports the hypothesis that cross-modal grouping processes contribute critically to the determination of the sense of agency.

Throughout the experiments described in this study, we use several different configurations of audio, tactile, visual and motor events with different conditions sometimes containing a different number of total events. As such, it is possible that the revealed modulations of sense of agency may not be due to grouping processes, as proposed, but rather based only on these simple stimulus differences. One possible explanation based on these simple factors may be that agency is modulated only by the number of signals presented. However, in experiments 2 and 3, we found that two task-irrelevant stimuli did, while a single stimulus did not, reduce the sense of agency. While in the additional flash condition of experiment 4, we observed a strong modulation of sense of agency, despite the number of additional signals being only one. Consequently, it is clear that the number of task-irrelevant stimuli itself is not a reliable predictor of the observed modulation of sense of agency. An alternative explanation may be that the presence of an additional signal simply distracts an observer's attention away from the sensory modality of effect events. Under this hypothesis, an additional signal should have played a stronger role in experiment 3 than in experiment 4, as in the former the additional signal was presented in a different modality from effect events, while in the latter, it was presented in the identical modality to effect events; here the opposite was true. Thus, neither the number of additional signals itself nor a distraction from effect events modulates sense of agency. Rather, as we have proposed, the influence of additional signals is in disrupting perceptual grouping between action and effect.

A final point of interest is how we can incorporate this new understanding of the role of grouping between action and effect into the models for the sense of agency. Although some excellent models for the sense of agency have been proposed [30], none of the models assume the involvement of action-effect grouping in determining the sense of agency. We propose a conceptual schematic model (figure 4) describing a feasible representation of how action-effect grouping might contribute to the production of the sense of agency. Although many factors have been proposed as determinants of the sense of agency, we believe that all possibilities may be consistently comprehended in a framework of grouping between action- and effect-related signals. Action-related signals may be comprised any of three different types of signals. The first candidate (green component in figure 4) is a signal that relates to action as executed by an agent, consisting of sensory feedback or proprioceptive signal components [34,35]. The second candidate is a signal related to by prediction for action (blue component in figure 4). The prediction can be based on efference copy [2-4,36] or cognitive factors [37]. Previous studies have also suggested the importance of spatio-temporal congruity between predicted and actual sensory feedbacks [2-4], consistent with the idea that grouping based on spatio-temporal proximity between predicted and actual feedback may be a critical determinant of sense of agency. The third candidate signal relates to prior thought (magenta component in figure 4). Previous studies [9-11,38,39] have advocated several principles, such as priority,



**Figure 4.** A putative model for the sense of agency based on grouping among action- and effect-related signals. See §6 for a detailed explanation of the model.

consistency and exclusivity as those probably govern the inference of causality between prior thoughts and action/effect. In particular, the principle of exclusivity is compatible with the one-to-one mapping rule observed in experiment 4. As is often the case in studies of cross-modal cue combination, the grouping of these action- and effect-related signals is likely to be based on the relative reliability of each signal (red component in figure 4; [40,41]. Future studies are required to adequately consider the computational aspect of such a

model. Regardless of the precise nature of the computational processes underlying cross-modal grouping, it is clear from the presented results that the sense of agency is inferred by an interpretative mechanism (brown component in figure 4) for apparent causal relation between action and effect [9–11] on the basis of the action–effect grouping.

Ethical approval for this study was obtained from the ethical committee at Nippon Telegraph and Telephone Corporation (NTT Communication Science Laboratories Ethical Committee).

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