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Original Articles

Temporal distortion in the perception of actions and events

Yoshiko Yabe [a,b,c,*], Hemangi Dave [d], Melvyn A. Goodale [a]

[a] The Brain and Mind Institute and the Department of Psychology, The University of Western Ontario, London, Ontario N6A 5B7, Canada
[b] Research Institute, Kochi University of Technology, 185 Miyanokuchi, Tosayamada-cho, Kami, Kochi 782 8502, Japan
[c] Japan Society for the Promotion of Science (JSPS), Kojimachi Business Center Bldg., 5-3-1 Kojimachi, Chiyoda-ku, Tokyo 102-0083, Japan
[d] The Department of Physiology and Pharmacology, Schulich School of Medicine & Dentistry, The University of Western Ontario, London, Ontario N6A 5C1, Canada

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ABSTRACT

In everyday life, actions and sensory events occur in complex sequences, with events triggering actions that in turn give rise to additional events and so on. Earlier work has shown that a sensory event that is triggered by a voluntary action is perceived to have occurred earlier in time than an identical event that is not triggered by an action. In other words, events that are believed to be caused by our actions are drawn forward in time towards our actions. Similarly, when a sensory event triggers an action, that event is again drawn in time towards the action and is thus perceived to have occurred later than it really did. This alteration in time perception serves to bind together events and actions that are causally linked. It is not clear, however, whether or not the perceived timing of a sensory event embedded within a longer series of actions and sensory events is also temporally bound to the actions in that sequence. In the current study, we measured the temporal binding in sequences consisting of two simple dyads of event-action and action-event in a series of manual action tasks: an event-action-event triad (Experiment 1) and an action-event-action triad (Experiment 2). Auditory tones either triggered an action or were presented 250 ms after an action was performed. To reduce the influence of sensory events other than the tone, such as a noise associated with pressing a key on a keyboard, we used an optical sensor to detect hand movements where no contact was made with a surface. In Experiment 1, there appeared to be no change in the perceived onset of an auditory tone when the onset of that tone followed a hand movement and then the tone triggered a second hand movement. It was as if the temporal binding between the action and the tone and then the tone and the subsequent action summed algebraically and cancelled each other out. In Experiment 2, both the perceived onset of an initial tone which triggered an action and the perceived onset of a second tone which was presented 250 ms after the action were temporally bound to the action. Taken together, the present study suggests that the temporal binding between our actions and sensory events occur separately in each dyad within a longer sequence of actions and events.

1. Introduction

Our perception of the timing of an event does not always correspond to the actual time that event occurred. This is particularly true of events that appear to be caused by our own actions. A number of investigators, for example, have shown that, when an individual performs a self-paced action that triggers a stimulus event (e.g., an auditory tone), the perceived time interval between the action and the event is shortened (Cravo, Claessens, & Baldo, 2009; Haggard & Clark, 2003; Haggard, Clark, & Kalogeras, 2002; Kawabe, Roseboom, & Nishida, 2013; Wohlschläger, Haggard, Gesierich, & Prinz, 2003). Put another way, the event is perceived to occur closer in time to the action that triggered it. This phenomenon has been described as intentional binding, a mental "linkage through time of representations of actions and events" (Haggard & Clark, 2003).

Several researchers have attributed this intentional binding to one's sense of agency, whereby one feels a causal role in the occurrence of external events as a result of actions they voluntarily initiate (Haggard & Chambon, 2012). The phenomenon of intentional binding in this context has been proposed to depend on prediction and/or retrospective inference. Initiating a self-paced action allows individuals to predict an outcome, and if the actual outcome matches the prediction (Moore & Haggard, 2008) or the intention (Engbert & Wohlschläger, 2007; Haggard & Clark, 2003), temporal binding of actions and events will occur. Other experiments that involved similar paradigm in which a sensory event follows a

* Corresponding author at: The Brain and Mind Institute, Natural Science Center, The University of Western Ontario, 1151 Richmond Street, London, Ontario N6A 5B7, Canada.
E-mail address: yyabe@uwo.ca (Y. Yabe).

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self-paced action, but did not allow participants to predict the outcome of their actions, also showed evidence of intentional binding, supporting the idea that retrospective inference after the event can also play a role in the binding of actions and events (Chambon, Sidarus, & Haggard, 2014). Other investigators have suggested that simple temporal contiguity of actions and events is enough to support their binding, by virtue of the perception of their causal relations (Buehner & Humphreys, 2009; Buehner & Humphreys, 2010; Cravo et al., 2009). Indeed, Buehner & Humphreys have suggested that the term "causal binding" might be more appropriate. Finally, a recent study proposed a model for the sense of agency that is based on the grouping of sensory feedback from the action, prediction about what the action might do, prior thoughts about the action, and the apparent effect of the action when it is performed (Kawabe et al., 2013). In short, researchers are still seeking a framework within which temporal binding can be explained.

In almost all these cases, the experiments have involved situations in which self-paced actions trigger sensory events. In everyday life, however, not only do humans experience events that are caused by their own actions, but they also perform actions in response to external events. Haggard, Aschersleben, Gehrke, and Prinz (2002) were the first to measure the perceived timing of sensory events that trigger actions. In their study, however, the perceived time of the triggering event showed little evidence of being shifted either towards or away from the action it triggered. Perhaps for this reason, later studies by Haggard and his colleagues (as well as others) focused entirely on the perceived timing of events that were apparently triggered by a voluntary self-paced action. Recently, however, we returned to the question as to whether or not there was any temporal distortion in the timing of events that trigger actions. We were able to show that, when one carefully controls the sensory feedback associated with making an action, the perceived timing of a sensory event that triggers an action is indeed attracted towards the action (Yabe & Goodale, 2015). This result challenges the idea that temporal binding is due to the sense of agency that arises when an event is perceived to be the results of one's action. In our experiments, the individuals were not triggering a stimulus event but were instead responding to one over which they had no control. Furthermore, in our experiments, we showed that temporal binding occurred even when an individual cancelled an action in response to a no-go signal. This suggests that temporal binding depends, not on the execution of the action, but rather on its programming (Yabe & Goodale, 2015).

In sum, although previous studies have focused on the temporal binding that occurs when a self-paced action triggers an event, it is also the case that temporal binding occurs when an external event triggers an action. The demonstration that temporal binding occurs in an event-action dyad as well as in an action-event dyad offers a new approach to understanding the underlying mechanism of temporal binding by opening the door for us to ask a new question: Will our sense of agency or our perception of a causal link between events and actions be disrupted when we are required to respond to sensory events in succession – or will they simply summate in some fashion? In the real world, we typically experience, not simple dyads of actions and events in isolation, but rather multiple actions and multiple events in longer sequences – such as what might occur on a football field, a crowded street, or in a busy factory or office. In the present study, therefore we attempted to emulate these real-world sequences by studying the perceived timing of a sensory event embedded within a series of actions and sensory events. The approach was straightforward; we combined the event-action sequence based on the paradigms of Yabe and Goodale (2015) and the action-event sequence based on the paradigms of Haggard, Aschersleben, et al. (2002). In Experiment 1 (Fig. 1C), we measured the perceived onset of an auditory tone in a sequence in which a voluntary hand movement triggered a tone after a 250 ms delay (Haggard, Clark, et al., 2002) and then that tone in turn triggered another hand movement. In Experiment 2 (Fig. 3), an auditory tone triggered a hand movement. Following that movement, another tone was presented 250 ms later. In this experiment, participants were required to report the timing of the first tone in one condition and the timing of the second tone in another condition.

Our experiments also included one other important methodological feature. In previous studies of intentional binding, the key-press/release tasks that have typically been used could have resulted in movement-related sensory feedback, including noise from the finger hitting or releasing the keyboard and/or changes in tactile input from the fingers, both of which could have been perceived as the effect of the action. This additional sensory feedback could have modulated the amount of the temporal binding between the action and either the triggering or the triggered sensory event of interest. Thus, in the present study, we used an optical sensor device to detect hand movements which resulted in far less movement-related sensory feedback than would be associated with a key-press.

2. Experiment 1

2.1. Materials and methods

2.1.1. Participants

We tested 20 naïve participants (15 females) aged 18–44 years with normal or corrected-to-normal vision. All participants were required to read a letter of information about the study and then to sign a consent form. The study was approved by the Ethics Review Board of The University of Western Ontario.

2.1.2. Apparatus

Experiments were carried out in a quiet, dark room. Participants sat on an adjustable chair with their chin in a chin rest to maintain stability. On the table in front of them was computer monitor (G90f, ViewSonic, USA; resolution: 1024 $\times$ 768 pixels; refresh rate: 100 Hz) on which the clock used to measure the perception of time was presented. The clock was viewed binocularly at a distance of 60 cm. Auditory tones were presented on a pair of speakers located on the left and right of the monitor. Programming of the presentation of the clock and the auditory tones was done in MATLAB 8.1.0.604 (MathWorks), assisted by Psychotoolbox 3.0.9 (Brainard, 1997; Pelli, 1997).

2.1.2.1. Hand movement recording. The hand movements that were used in each task were detected by a special optical sensor device (Fig. 1A). In both experiments, subjects held a stiff piece of felt cloth in their right hand that was positioned between emitter and sensor of the optical sensor, interrupting the infrared beam. During action-execution trials, participants lifted their hand up from the line of the infrared beam, thereby registering the hand movement but at the same time minimizing auditory and tactile feedback.

2.1.3. Tasks

Participants were instructed to place the piece of felt in the optical sensor. The word 'Rest' was displayed on the monitor. Participants initiated a trial by lifting the piece of felt and then placing it back immediately in the optical sensor. Following this, the phrase 'Hold still' was displayed for 2 s. At the end of this 2 s period, a clock (1.8° in diameter) was displayed at the centre of the monitor. Participants were required to fixate their eyes on a black dot (1° in diameter) in the centre of the clock. The second hand of the clock rotated around the black dot at a frequency of 2560 ms/

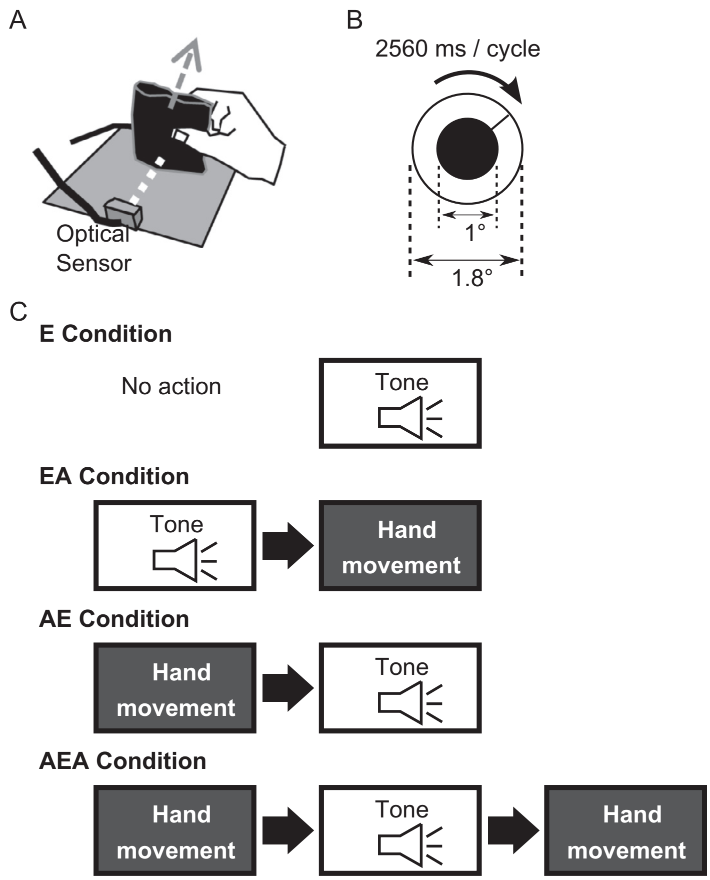

Fig. 1. Schematics of experimental methods. (a) The optical sensor device. (b) The Libet clock (Libet, Gleason, Wright, & Pearl, 1983). (c) Schematic of Experiment 1.

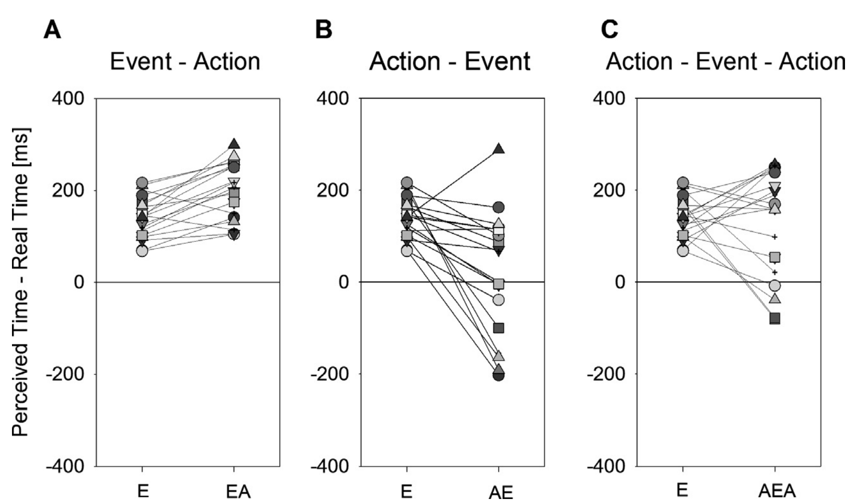

Fig. 2. The perceived timing of the first tone relative to actual timing in Experiment 1 (n = 19). Each line represents a different participant. Same symbols among (A)–(C) represent a same participant. (A) E and EA conditions. (B) E and AE conditions. (C) E and AEA conditions.

rev (Libet, Gleason, Wright, & Pearl, 1983; Fig. 1B). On each trial, the second hand started at a random position.

Four conditions were included (Fig. 1C): Event (E), Event-Action (EA), Action-Event (AE) and Action-Event-Action (AEA). In the E condition, the participants simply listened to a brief (100 ms) 1000 Hz tone that was played from the speakers at a random time 2560–5120 ms after the clock onset but were not required to do anything. In the EA condition, participants were required to make a motor response by lifting the piece of cloth in response to the tone. In the AE and AEA conditions, participants were instructed to perform the action after the first rotation of the clock was complete and before the second one was complete. Additionally, participants were instructed to avoid responding in a stereotyped way, at a pre-decided clock time. In other words, they were told to vary the time they initiated the hand movement within the specified interval. These instructions were the same as those used by Haggard,

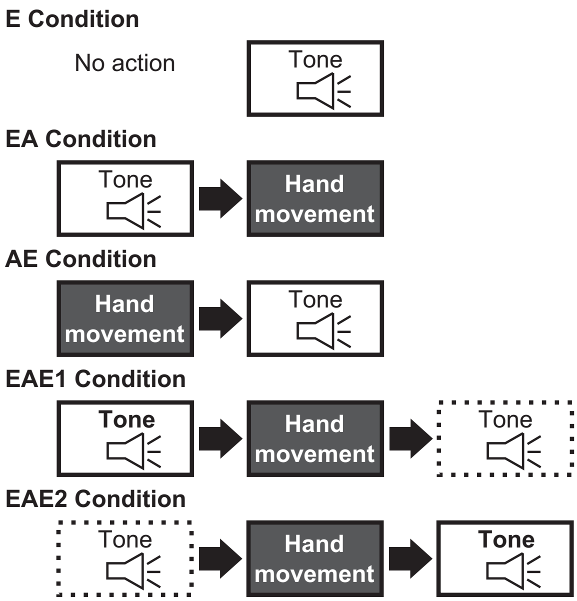

Fig. 3. Schematic of Experiment 2.

Aschersleben, et al. (2002). This initial hand movement was followed by a tone after a 250 ms delay (Haggard, Clark, et al., 2002). In the AE condition, after performing the hand movement, participants placed their hand back immediately in the optical sensor device and kept their hand there until the clock came to a stop. In the AEA condition, after performing the hand movement, participants were required to lower their hand back in the sensor immediately and then lift it up again in response to the tone which occurred 250 ms after their initial hand motion. Participants were consistently reminded to ensure that the second movement was made in response to the tone, as opposed to being a simple repetition of their first hand movement. The second-hand disappeared briefly and appeared on a random position again at a random time between 1280 ms and 1920 ms after the presentation of the tone. Participants were required to repeat a trial if they had not performed the hand motion during the second rotation of the clock in AE and AEA conditions.

At the end of each trial, the participants were required to report what the position of the clock's second-hand was when they heard the tone. They did this by pressing the spacebar of the keyboard by their right index fingers to move the second-hand slowly back to where it was when they heard the tone. After completing these tasks in the EA and AEA conditions, the participants received feedback on that trial about the reaction time (in ms) following the tone. This feedback was presented on the computer screen. Following the presentation of the feedback, the word 'Rest' was again displayed and participants initiated the next trial.

In summary, the E and EA conditions replicated the conditions used in our previous study (Yabe & Goodale, 2015) while the AE condition replicated the voluntary action condition of Haggard, Aschersleben, et al. (2002). The difference between the E and EA conditions in the current study and those used in our previous study was the nature of the stimulus: a tone in the current study and a visual stimulus in the Yabe & Goodale study. The AEA condition was a combination of the AE and EA conditions in which a tone that was apparently caused by an action triggered another action. In other words, a self-paced hand movement was followed 250 ms later by a tone (Haggard, Clark, et al., 2002) and this tone triggered a second movement. Thus, the effect of an action was a trigger for a second action.

2.1.4. Procedure

All experiments were performed in a dark room. After going through the instructions, participants began with a practice session that included all four experimental conditions presented in the order E, EA, AE and AEA. Participants were told which condition was going to be presented at the beginning of each block. They continued practicing until their performance became stable. Following the practice session, there were three experimental sessions, each consisting of 21 trials each of conditions E, EA, AE and AEA for a total of 84 trials per session, and therefore, 252 trials overall. The order of the four conditions in a session was randomized for each participant.

Participants were told which condition was going to be presented in each 21-trial block. Participants were offered the opportunity of taking a rest at any point after each 21-trial block.

2.1.5. Data analysis

Trials were excluded from the analysis if participants initiated a hand movement in the E condition or if they failed to initiate a hand movement after the tone in the EA and AEA conditions. Trials with very short (<100 ms) or large (>1000 ms) delays in response time were also excluded.

After the exclusion of those trials, the difference between the reported position and the actual position of the second hand of the clock when the tone was presented was calculated for each trial for each participant in each condition. These difference scores provided a measure of any temporal distortion that might have occurred. If the perceived time was later than the actual time, this value would be positive, and if earlier, the value would be negative. Next, the average difference scores in each condition was calculated for each participant. Then, these average difference scores for conditions EA, AE and AEA for each participant were standardized by subtracting from each of them the average difference scores for condition E. Thus, if an average difference score for a participant in the EA, AE or AEA conditions was larger (more positive) than the average difference in the E condition, this standardized measure would be positive, and if smaller, then this value would be negative. A one-way ANOVA was conducted on these standardized values to measure differences in temporal distortion in the EA, AE and AEA conditions. Post hoc comparisons were based on the Shaffer's modified sequentially rejective Bonferroni's procedure.

2.2. Results

We excluded trials from analysis if the participant did not make a hand movement between 100 ms and 1000 ms after the tone in EA and AEA conditions (the mean ± SD was 0.8 ± 1.0 trials in the EA condition and 4.7 ± 5.0 trials in the AEA condition). We also excluded trials if the participant made a hand movement after the tone in E and AE condition (2.3 ± 2.6 trials in the E condition and 1.4 ± 2.0 trials in the AE condition).

All the participants initiated their actions during the second rotation of the Libet clock in the AE and AEA conditions. In addition, the response times for the second movement in the AEA condition suggest that participants had followed the instruction to respond to the tone rather than simply making two movements, one after the other without reference to the tone. [If the time between the tone and the second movement was 100 ms or less, then that trial was excluded from analysis.] On average, the response time to the tone was 310 ± 67 ms, a value that is consistent with reacting to the tone rather than simply making a 'double' movement. This means that the average interval between the two movements was more than 500 ms, given that the tone always occurred 250 ms after the first movement – an inter-movement interval that suggests that the movements were independent rather than linked. Moreover, after excluding one outlier, the

Pearson Product Moment correlation (r) across participants between response times in the EA condition and the AEA condition was 0.54 ($p < 0.05$), again suggesting that the second action in AEA condition was a reaction to the tone as was the action in EA condition. Fig. 2 depicts the mean difference scores (perceived minus real stimulus onsets) for all participants across conditions. The data from one participant who did not understand the task was excluded. The mean ± SD difference scores for the E, EA, AE and AEA conditions were 141.2 ± 45.1 ms, 200.5 ± 61.8 ms, 20.5 ± 134.3 ms, and 129.4 ± 116.2 ms respectively. The perceived delay in the tone was larger in the EA condition ($p = 0.002$) and smaller in the AE condition ($p = 0.001$) than in the E condition. There was no significant difference between the perceived delay in the AEA condition and that in the E condition ($p = 0.683$).

A one-way ANOVA revealed a significant effect of conditions ($F(2,36) = 20.62$, $p < 0.001$) on the standardized difference scores (where the difference scores for each participant in the E condition was subtracted from his or her difference score in the EA, AE, and AEA conditions). The post hoc tests revealed that the standardized difference scores were larger (more positive) in the EA condition than in the AE and AEA conditions ($p = 0.000$ and $p = 0.012$ respectively). The standardized difference score was smaller (less positive) in the AE condition than in the AEA condition ($p = 0.003$). In summary, temporal binding occurred both when an action triggered an event and when an event triggered an action. However, the binding (as indicated by a smaller perceived delay) was decreased when an action followed an action – event sequence.

2.3. Discussion

Experiment 1 showed that the occurrence of an action following an action-event dyad diminished the temporal binding between the event and the action it triggered. In what way is the perceived timing of the sensory event following and then being followed by an action modulated? There are two possibilities: (1) temporal binding does not occur in a triad consisting of multiple actions and events, but only in a dyad consisting of an action and an event; (2) temporal binding occurs in each of the two dyads (i.e., action-event and event-action) within a triad but the overall binding is diminished and virtually disappears because the temporal binding in the first dyad and that in the second dyad cancel each other out.

In order to distinguish between these two possibilities, we conducted a second experiment involving five conditions. The first three conditions were essentially identical to the E, EA and AE conditions used in Experiment 1. Thus, it was expected that the perceived delay in the EA/AE condition would be larger/smaller than that in the E condition, consistent with the results from our first experiments. The fourth and fifth conditions were new conditions in which the EA dyad and the AE dyad were combined. There were two versions: EAE1 and EAE2. In both conditions, participants were required to respond to an initial auditory tone by making a hand action that triggered a subsequent tone with a delay of 250 ms. The participants were required to report the perceived onset of the first tone in the EAE1 condition and the perceived onset of the second tone in the EAE2 condition.

If temporal binding was not observed in the EAE1 and EAE2 conditions, it would suggest that possibility (1) is correct, i.e., that temporal binding occurs only in a simple dyad consisting of an action and a sensory event. Alternatively, if the standardized temporal difference score was positive in the EAE1 condition and negative in the EAE2 condition, it would suggest that the possibility (2) is correct, i.e., that temporal binding occurs in each dyad within a triad.

3. Experiment 2

3.1. Materials and methods

3.1.1. Participants

We tested 19 naïve participants (10 females) aged 17–29 years with normal or corrected-to-normal vision. All participants received a letter of information regarding the premise of the study and also signed a consent form before beginning the experiment. The study was approved by the Ethics Review Board of The University of Western Ontario.

3.1.2. Apparatus

The stimulus was presented on Diamond Pro 2060u (Mitsubishi, Japan; resolution: 1024 × 768 pixels; refresh rate: 100 Hz). Programming of the presentation of the clock and the auditory tones was done in MATLAB 8.3.0.532 (MathWorks), assisted by Psychotoolbox 3.0.11 (Brainard, 1997; Pelli, 1997). Apart from the change in the aforementioned equipment, the apparatus was the same as that used in Experiment 1.

3.1.3. Tasks

There were five different conditions (Fig. 3). The E, EA, and AE conditions were same as those used in Experiment 1. In the EAE1 and EAE2 conditions, participants initiated each trial and then a Libet clock was presented in the same way as in the other three conditions. The participants were instructed to stare a black dot in the center of the clock and to lift the cloth as quickly as soon as they heard a tone. Another tone was presented 250 ms after this hand movement. They were required to note where the second-hand was on the clock when the first tone was presented in the EAE1 condition and when the second tone was presented in the EAE2 condition. Thus, the E and EA conditions replicated the control and action conditions in our previous study (Yabe & Goodale, 2015). The AE condition replicated the voluntary action condition of Haggard, Aschersleben, et al. (2002). The EAE1 and EAE2 conditions were new conditions in which the motor response was followed by another tone. The second-hand disappeared briefly and then re-appeared at a random position and at a random time between 1280 ms and 1920 ms after the presentation of the first tone.

At the end of each trial, participants were required to report what the position of the second hand had been when they heard the first auditory tone in the E, EA, AE, EAE1 conditions, or where it had been when they heard the second tone in the EAE2 condition. They did this by pressing the spacebar of the keyboard to move the second-hand back to where it had been when they heard the tone. After completing these tasks in the EA, EAE1, and EAE2 conditions, the participants received feedback on that trial about their reaction time (in ms) following the tone. This feedback was presented on the computer screen. Following the presentation of the feedback, the word 'Rest' was again displayed and participants initiated the next trial.

3.1.4. Procedure

All experiments were performed in a dark room. After going through the instructions, participants began with a practice session, which contained identical conditions to those used in the experiment itself. In the practice session, the five conditions were presented in order of E, EA, AE, EAE1 and EAE2. They continued practicing until their performance became stable. Following the practice session, there were three experimental sessions, each consisting of 21 trials of conditions E, EA, AE, EAE1 and EAE2 for a total of 105 trials. In the three different sessions, the order of the five conditions was randomized for each participant. Thus, in total there were 315 trials overall in the experiment. Participants were told which condition was going to be presented in each 21-trial block of each condition throughout both the practice and experimental sessions. Participants were offered the opportunity to take a break at any point between each 21-trial block of a particular condition.

3.1.5. Data analysis

The data was analyzed in the same way as Experiment 1.

3.2. Results

We excluded trials from analysis if the participant did not make a hand movement between 100 ms and 1000 ms after the tone in EA, EAE1 and EAE2 conditions (the mean ± SD was 4.0 ± 2.8 trials in the EA condition, 1.9 ± 2.2 trials in the EAE1 condition and 2.2 ± 2.0 trials in the EAE2 condition). We also excluded trials if the participant made a hand movement after the tone in E and AE condition (1.1 ± 1.5 trials in the E condition and 3.1 ± 3.2 trials in the AE condition).

We calculated the mean difference score (perceived time minus real time) for each participant. The overall mean ± SD difference score for all participants for E, EA, AE, EAE1, and EAE2 conditions were 131.4 ± 42.3 ms, 190.4 ± 64.5 ms, −24.2 ± 85.6 ms, 187.3 ± 60.3, and −14.8 ± 110.0 ms respectively (Fig. 4). The difference score was larger (i.e., more positive) in the EA and EAE1 conditions ($p < 0.001$ and $p < 0.001$ respectively) and smaller (i.e., more negative) in the AE and EAE2 conditions ($p < 0.001$ and $p < 0.001$ respectively) than in the E condition.

A one-way ANOVA revealed a significant effect of conditions ($F(3,54) = 48.85$, $p < 0.001$) on the standardized difference scores (where the difference scores for each participant in the E condition was subtracted from his or her difference score in the other four conditions). Post-hoc testing revealed that the standardized difference score was larger (more positive) in the EA condition than in the AE and EAE2 conditions ($p < 0.001$ and $p < 0.001$ respectively). The standardized difference score was larger (more positive) in the EAE1 condition than in the AE and EAE2 conditions ($p < 0.001$ and $p < 0.001$ respectively) as well. There were no significant differences between the standardized difference scores in the EA and EAE1 conditions and in the AE and EAE2 conditions ($p = 0.80$ and $p = 0.73$ respectively).

3.3. Discussion

In Experiment 1, temporal binding appeared to be absent in an AEA triad. In Experiment 2, however, temporal binding was observed not only in simple action-event and even-action dyads but also occurs in a triad consisting of both those dyads. The results from the EAE1 and EAE2 conditions indicate that the perceived onset of a sensory event is pulled towards the onset of the action in each dyad. It is not clear, however, whether or not the temporal binding observed in the event-action sequence in the EAE1 condition shares essentially the same processing as that occurring in the EA condition. The action in the EAE1 condition triggered a tone whereas the action in the EA condition did not. It is also not clear whether or not the temporal binding observed in the action-event sequence in the EAE2 condition is supported by the same processes as the temporal binding observed in the AE condition. This action in the EAE2 condition was rapidly triggered by a tone though the action in the AE condition was performed in a self-paced manner. To explore these possibilities further, we carried out a correlational analysis.

4. Correlations between the temporal binding in single dyads and complex sequences

If the temporal binding observed in the event-action and the temporal binding observed in the action-event sequences in the EAE conditions are essentially the same as those observed in the EA and AE conditions, then one might expect that the standardized temporal difference scores in the EAE1 condition to be correlated with those in the EA condition across individuals, and in the same way, the scores in the EAE2 condition to be correlated with those in the AE condition. To test this prediction, the standardized temporal difference scores in the EAE1 and the EAE2 conditions were replotted as functions of those in the EA and AE conditions (Fig. 5). Each dot in Fig. 5 represents a participant in Experiment 2. The Pearson Product Moment correlation (r) between the standardized scores in the EA and in the EAE1 conditions was 0.46 ($p = 0.04$). Similarly, there was a positive correlation of 0.36 between the standardized scores in the AE and the EAE2 conditions, although the p value did not achieve significance ($p = 0.13$). This analysis suggests that the temporal binding between events and actions in single dyads and the temporal binding between the same events and action within more complex sequences share the same underlying mechanism.

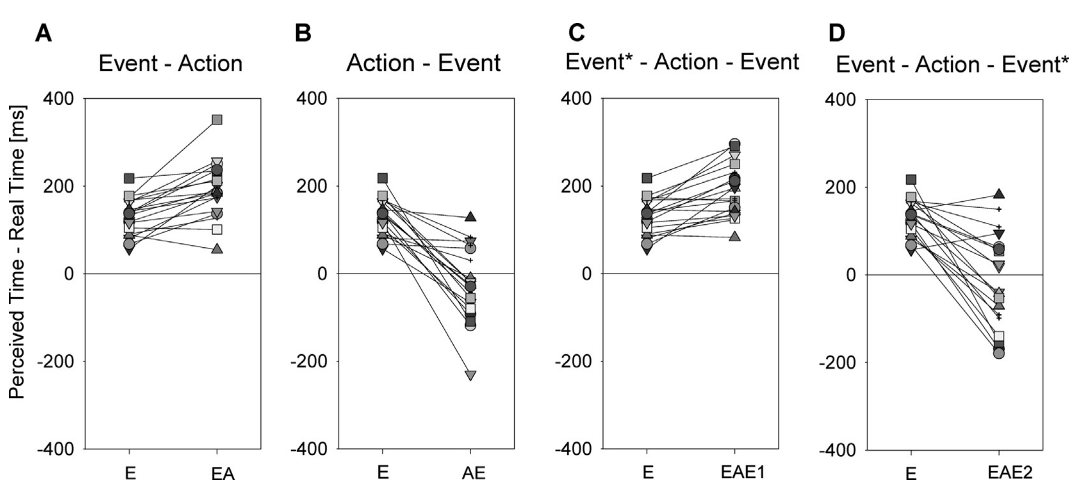

Fig. 4. The perceived timing of the first tone relative to actual timing in Experiment 2 (n = 19). Each line represents a different participant. Same symbols among (A)–(C) represent a same participant. (A) E and EA conditions. (B) E and AE conditions. (C) E and EAE1 conditions (D) E and EAE2 conditions.

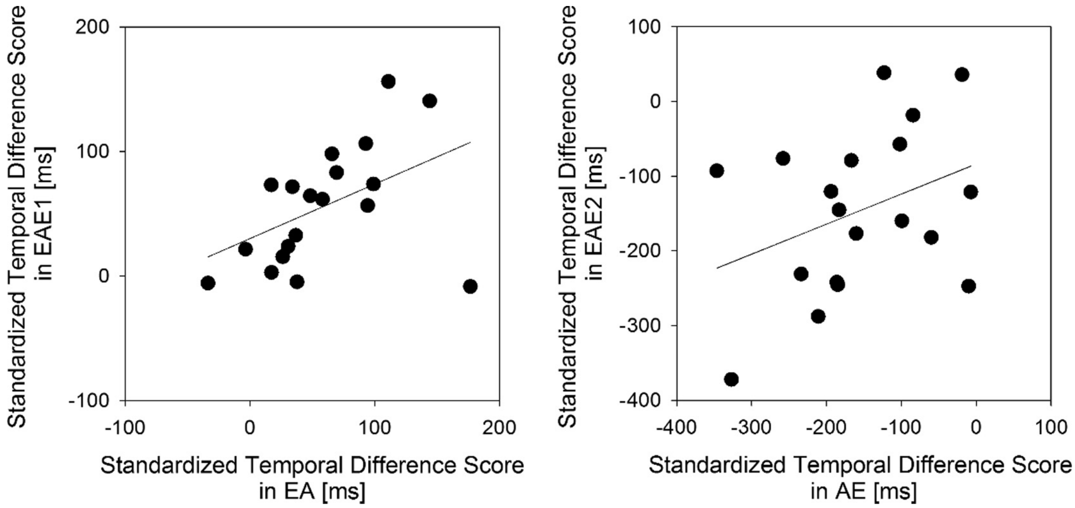

Fig. 5. Standardized temporal difference score under the EAE1 (left) and EAE2 (right) conditions for all participants as a function of that under the EA (left) and AE (right) conditions in Experiment 2.

If the suggestion above were true, our finding that temporal binding was absent in the AEA condition of Experiment 1 could have arisen because the binding in the two single dyads of action-event and event-action cancelled each other out. In other words, the perceived time of the event was simultaneously being dragged in two directions: back in time towards the initial action and forward in time towards the action it triggered. But there are other possibilities. It could have been the case that, on some trials, only the first action influenced the perceived timing of the event and that, on other trials, only the second action influenced the timing. If this had been the case for all the participants, then one might have expected to see a bi-modal distribution in the perceived timing of the tone in the AEA condition. We found no evidence for bimodality in the accumulated distribution of perceived times for all the participants (centered on either the mean or the median of the individual distributions). Instead, we found a pronounced unimodal distribution, suggesting that, on average, the perceived timing of the event was pulled simultaneously in opposite directions by the first and second actions. In any case, it is clear that across participants both actions influenced the timing of the event.

If this explanation is correct, then one would expect that the sum of the standardized temporal difference scores observed in the EA and the AE conditions separately would be equivalent to the standardized temporal difference score observed in the AEA condition. To test this idea, we re-plotted the standardized temporal difference scores in the AEA condition as a function of the sum of the standardized scores in the EA and AE conditions (Fig. 6). A significant positive correlation of 0.52 ($P = 0.02$) was found. This correlation strengthens our conclusion that in a long sequence of actions and events, a temporal binding between an action and a sensory event occurs within each dyad in the sequence.

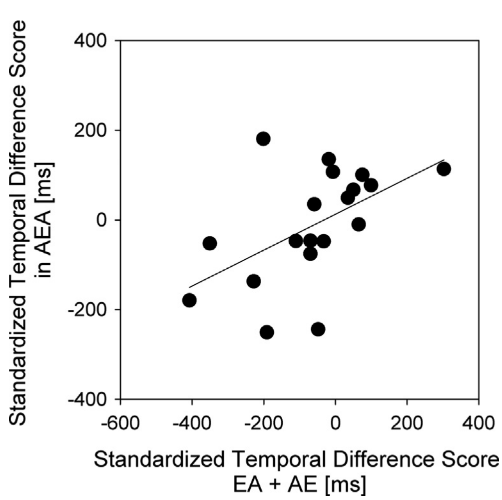

Fig. 6. Standardized temporal difference score under the AEA condition for all participants as a function of the sum of those under the AE and EA conditions in Experiment 1.

5. General discussion

In Experiment 1, we replicated the temporal binding that we observed in our earlier study (Yabe & Goodale, 2015) in which sensory events that trigger actions are perceived to occur significantly later (and closer in time to the action) than sensory events that are simply passively observed. We also observed that, consistent with earlier work (Haggard, Clark, et al., 2002), a sensory event thought to be triggered by a voluntary action was perceived as occurring earlier (i.e., closer in time to the action) than an event that was not triggered by an action. Finally, we found reduced temporal binding between an action and an event in a triad in which the event in turn triggered a second action. To test whether or not the temporal binding between an event and an action is always reduced in a sequence of events and actions, in Experiment 2, we measured the temporal binding in an event-action-event sequence which includes both an event-action and an action-event dyad. Here we found that the perceived onsets of the first and second events were both dragged towards the occurrence of the action. We also found that the temporal binding between the first event and the action in this sequence can be predicted by the temporal binding measured independently in the simple event-action dyad. The temporal binding between the action and the second event was also positively correlated with the binding measured independently in the simple action-event dyad although this correlation did not achieve significance. Given our findings with the correlation analysis of Experiment 2, we decided to perform a similar analysis on the results of Experiment 1. We found that when the event triggered by an action triggered a second action, the perceived time of the event was dragged in two directions: back in time towards the initial action and forward in time towards the action it triggered. All of this suggests that the temporal binding between the first action and the event in the AEA condition was retrospectively influenced by the subsequent binding between that event and the action it elicited.

Various factors have been invoked to explain the distortions in the perceived timing of a sensory event that follows an action. It has been argued that the binding arises from the 'feeling' of control that one has over one's own actions, and, through them, over events in the outside world that follow those actions. This feeling is often referred to as a "sense of agency" (Moore & Obhi, 2012). Some studies have even proposed that it is possible to measure the presence of a sense of agency implicitly by measuring the degree of temporal binding (e.g., Caspar, Christensen, Cleeremans, & Haggard, 2016; Christensen, Yoshie, Di Costa, & Haggard, 2016). It has also been suggested, however, that other factors such as temporal control or beliefs about causality, are at play (see Hughes, Desantis, & Waszak, 2013 for review). In any case, our study makes it clear that the perceived timing of a particular action and event cannot be understood unless one takes into account the sequence of events and actions in which that dyad is embedded. Of course, it is possible that the perceived timing of sensory events is the result of multiple factors, which, in combination, could give rise to a sense of interaction between our actions and events in the environment. Taken together, these considerations suggest that it is important to control for sensory feedback and actions unrelated to the main experimental task if one plans to measure the effect of single factor on temporal binding.

It is worth noting that the procedure we used in the EA condition replicated the procedure in our earlier study (Yabe & Goodale, 2015) except that an auditory stimulus rather than a visual one was used as a triggering signal for the action. Taken together, the results suggest that temporal binding occurs between events and actions independently of whether the actions are triggered by visual or auditory stimuli.

It is also worth noting that in our experiment, an auditory event that was believed to be triggered by an action was perceived to occur 137 ms earlier in Experiment 1 and 156 ms earlier in Experiment 2 than an event that was not triggered by an action. Although the size of these temporal distortions was about three times larger than the 46-ms effect reported by Haggard, Aschersleben, et al. (2002), it is important to remember that both our study and Haggard et al.'s used a Libet Clock to measure elapsed time, a paradigm known to generate considerable variability in perceived timing. In our study, for example, the effects of action on perceived timing of the tone ranged from 145 ms to −450 ms. In short, it is possible that the difference between the studies is simply due to sampling bias.

It is possible, however, that the difference in perceived timing between the two studies was due to differences in the hardware that participants used to make their voluntary actions. In most previous studies, including the one by Haggard, Aschersleben, et al. (2002), key- or button-press/release tasks have been used to measure the temporal binding between an intentional action and a sensory event thought to be caused by the action. Recently however, a few researchers studying human-computer-interaction (HCI) have begun to measure the temporal binding in an action-event sequence using devices other than keyboards or buttons. This appears to be based on their supposition that the degree of temporal binding between actions and events is a yardstick of how much the users of the new devices feel agency in their actions (Limerick, Coyle, & Moore, 2014). Coyle, Moore, Kristensson, Fletcher, and Blackwell (2012), for example, carried out an experiment on temporal binding using a skin-based input device which monitored vibrations in the users' arms. In one condition, participants were required to tap on their arm gently wearing the skin-based input device. In the other condition, they were required to press a button. Both types of hand movements were followed by a tone with a fixed delay of 250 ms. The investigators found that temporal binding was significantly greater in the task using the skin-based input device than in the task using the button-press. As Coyle et al. (2012) discuss, these new interaction devices provide quite different experiences of control which may account for the greater temporal binding between actions and stimulus events.

Another possible explanation for this difference is that, in the key- or button-press tasks, the noise from hitting a keyboard or a button box could reduce the temporal binding between the action and the tone that occurs 250 ms after the action. Kawabe et al. (2013), for example, showed that temporal binding between an action and a delayed stimulus was reduced when an additional sensory stimulus in the same modality was presented at the moment the action occurred. The skin-based input device (Coyle et al., 2012) and our optical sensor device would have greatly reduced auditory noise compared to a keyboard or button box – and thus would have allowed for a stronger temporal binding between the action and the delayed stimulus.

Taken together, the results of our study show that temporal binding can occur in longer sequences of action and events. In addition, the results show that the binding between an action and an event competes with the binding between that event and a subsequent action that it triggers, such that the perceived time of the onset of the event is dragged in opposite directions: back in time towards the initial action and forward in time towards the action that event triggered.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.10.009.

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