Occluded motion alters event perception

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Abstract We employed audiovisual stream/bounce displays, in which two moving objects with crossing trajectories are more likely to be perceived as bouncing off, rather than streaming through, each other when a brief sound is presented at the coincidence of the two objects. However, Kawachi and Gyoba (Perception 35:1289–1294, 2006b) reported that the presence of an additional moving object near the two objects altered the perception of a bouncing event to that of a streaming event. In this study, we extended this finding and examined whether alteration of the event perception could be induced by the visual context, such as by occluded object motion near the stream/bounce display. The results demonstrated that even when the sound was presented, the continuous occluded motion strongly biased observers' percepts toward the streaming percept during a short occlusion interval (approximately 100 ms). In contrast, when the continuous occluded motion was disrupted by introducing a spatiotemporal gap in the motion trajectory or by removing occlusion cues such as deletion/accretion, the bias toward the streaming percept declined. Thus, we suggest that a representation of object motion generated under a limited occlusion interval interferes with audiovisual event perception.

Keywords Occluded motion · Streaming/bouncing event perception · Crossmodal interaction

In the real world, some moving objects are perceived to be integrated into a unitary and meaningful event or are assigned to different events. The event perception is affected by visual

context information such as surrounding objects. Previous studies have reported that visual context information constrains various perceptual and cognitive processes, such as those used in guiding visual attention, facilitating the search for objects in complex displays, and determining the direction of ambiguous apparent motion (Chun, 2000; Ramachandran & Anstis, 1983). In the present study, we examined a new type of contextual constraint—that is, the constraint produced by occluded object motion on audiovisual event perception. Moving objects are usually occluded by many other objects in the real world, and observers can see only the surfaces of the occluding objects, yet the occluded object motion is phenomenally maintained, despite the absence of its physical input (Burke, 1952; Hulme & Zeki, 2007; Kawachi & Gyoba, 2006a; Michotte, Thines, & Crabbé, 1964/1991).

Multisensory as well as visual inputs from an event are passed into the perceptual system. These sensory inputs should be selected and integrated to yield a representation of the event. In this study, we focused on the relationship between contextual occluded motion and crossmodal perception in order to examine whether audiovisual event perception can be altered by contextual occluded motion.

Stream/bounce display with a brief sound and a nearby moving object

The stream/bounce display (Metzger, 1934; Michotte, 1946/1963) can be used to induce audiovisual event perception. When two visually identical objects move toward each other, coincide, and then move apart in a two-dimensional display, observers can either perceive the objects as streaming through or bouncing off each other. Although the stream/bounce display is ambiguous, many observers tend to perceive the two objects as streaming through each other (Bertenthal, Banton, & Bradbury, 1993; A. B. Sekuler & Sekuler, 1999). However, R. Sekuler, Sekuler, and Lau (1997) reported that a brief sound (referred to as “a collision sound”) at the moment that the two objects coincide predominantly induces the

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bouncing event percept; this finding suggests that a bias toward the bouncing percept is involved in the crossmodal interaction (Watanabe & Shimojo, 2001).

Considering the importance of contextual information in the crossmodal interaction (De Gelder & Bertelson, 2003; Spence, 2007), Kawachi and Gyoba (2006b) presented a visual nearby object that moved in parallel with the stream/bounce display, as well as a collision sound when the two objects in the stream/bounce display coincided; this presentation caused the audiovisual bouncing percept to be altered toward the streaming percept (hereafter referred to as the “event alteration effect”). This finding implies that intramodal processing, such as perceptual grouping of the stream/bounce display and a nearby object, can interfere with crossmodal event perception. Recently, several studies have also explored the relationship between crossmodal interaction and intramodal grouping (Sanabria, Soto-Faraco, Chan, & Spence, 2004; Sanabria, Soto-Faraco & Spence 2004), by using crossmodal dynamic capture, in which the direction of a synchronously presented visual apparent motion modulates observers’ judgments about the direction of an auditory apparent motion. Unlike the studies by Sanabria et al., however, in Kawachi and Gyoba (2006b) and the present study, a stream/bounce display was presented with continuous motion stimuli instead of with apparent (sampled) motion stimuli, to possibly generalize the effect of perceptual grouping on the crossmodal interaction.

The effect of occluded motion on event perception

To expand on the event alteration effect described previously and reveal a new contextual constraint of occluded motion in crossmodal perception, we examined whether the occluded motion of a nearby object affects the perception of the stream/bounce event.

Occlusion is one of the most fundamental visual events (Shimojo & Nakayama, 1990). Moving objects are often occluded, temporally interrupting the visual inputs for the objects. Take, for example, an object that moves and gradually disappears at one side of an occluder. Imagine that it later reappears at the other side of the occluder. Although the object cannot be seen temporarily, we perceive the reappearing object as being identical to the object that had previously disappeared. This phenomenon is called the “tunnel effect” (Burke, 1952; Michotte et al., 1964/1991). The visual system generates a representation of the hidden object on the basis of various sensory inputs before and after the occlusion, allowing us to perceive continuity in the visual environment and to behave appropriately (Kawachi & Gyoba, 2006a). A great number of previous studies have specified the critical factors that mediate the tunnel effect, such as the spatiotemporal continuity of a moving object before and after the occlusion.

In addition, a few previous studies have reported that occluded motion is induced by surrounding apparent motion stimuli (Ramachandran, Inada, & Kiama, 1986) and that the perception of occluded motion is modulated by Michotte’s launching effect (Bae & Flombaum, 2011). However, the effect on event perception that is associated with or induced by motion representation in the tunnel effect remains to be elucidated. Our focus here has been on examining the contextual effect that the tunnel effect has on the perception of a distinct event.

The present study

In Experiment 1, we demonstrated that despite the presentation of the collision sound, the presentation of occluded object motion can alter the audiovisual bouncing percept toward the streaming percept at short occlusion intervals (approximately 100 ms). In Experiments 2 and 3, the spatiotemporal continuity of occluded motion trajectories was disrupted by inserting a temporal gap (Exp. 2) and a spatial gap (Exp. 3) behind the occluder. Previous studies have indicated that these disruptions can cause observers to perceive a hitch or stopping of the object, or discontinuous motion involving multiple objects, rather than the continuous occluded motion of a single object (Burke, 1952; Flombaum & Scholl, 2006; Kawachi & Gyoba, 2006a; Michotte et al., 1964/1991). In Experiment 4, the deletion/accretion cues along the contour of the occluder were removed by creating a false-deletion/accretion condition (Kawachi & Gyoba, 2006a; Scholl & Pylyshyn, 1999). “Deletion” of the object surface occurs when a moving object gradually disappears behind an occluder; “accretion” occurs when the moving object gradually appears. The deletion/accretion cues along the boundaries of an occluder as well as the spatiotemporal continuity of motion trajectories are critical for the tunnel effect (Gibson, Kaplan, Reynolds, & Wheeler, 1969; Kawachi & Gyoba 2006a; Scholl & Pylyshyn, 1999). The results of Experiments 2, 3, and 4 indicated that the event alteration effect was attenuated, suggesting that audiovisual stream/bounce event perception can be modulated by continuous occluded motion in context.

Experiment 1: stream/bounce percept altered by occluded motion

Method

Participants A group of 12 students from Tohoku University who were naive as to the purpose of the experiment participated in Experiment 1. All had either normal or corrected-to-normal vision.

Stimuli Examples of the stimuli used in the present study are shown in Fig. 1. The two objects in the stream/bounce display and a nearby moving object were white squares (0.33×0.33 deg; 125.56 cd/m^2) generated by a personal computer (SHARP X68030) and presented on a CRT monitor (SHARP CZ-621Z; 55.5-Hz vertical refresh rate). The background was black (0.52 cd/m^2). The two objects appeared on the opposite sides of the monitor. They moved horizontally toward each other at $5.64^\circ/\text{s}$, coincided at the center of the screen, and then continued to move away from each other. The sound (60 dB, 10 ms, 455 Hz) was always presented at the moment that the two objects in the stream/bounce display coincided and was provided through speakers (ALTEC LANSING A215) placed on both sides of the monitor. The physical simultaneity of the auditory and visual stimuli was assessed with a synchroscope (Iwatsu Electric Co., Ltd SS-5116). The deviations from simultaneity did not exceed 5 ms. A nearby moving object moved horizontally at $6.58^\circ/\text{s}$ below one of the two objects in the stream/bounce display.¹ All of the objects were vertically aligned at their point of coincidence. A vertical blank space (0.33 deg) was always present between the lower edges of the two objects in the stream/bounce display and the upper edge of the nearby object. Five occlusion-interval conditions were presented: 0.00 ms (no occluder), 50.15 ms (occluder width: 0.33 deg), 75.99 ms (occluder width: 0.50 deg), 121.58 ms (occluder width: 0.80 deg), and 253.80 ms (occluder width: 1.67 deg). The occlusion intervals were defined as the intervals during which the leading edge of the nearby object was assumed to be occluded. The vertical height of the occluder (11.18 cd/m^2) was always 0.67 deg. The vertical center of the occluder was 0.67 deg below the point of coincidence of the objects of the stream/bounce display.

Procedure The participants were seated approximately 172 cm away from the CRT monitor, with their heads resting on a chinrest. They fixated the center of the display, where the two objects coincided, and were asked to judge whether the two objects bounced off or streamed through each other by pressing the appropriate response keys. They

¹ We used different speeds for the stream/bounce objects and the nearby object, and wanted to extend our previous findings by using the same speed for them that we had in Kawachi and Gyoba (2006b). Using nearby objects with different speeds, our preliminary observations indicated that an important factor in the event alternation effect may be a close temporal correspondence between the timing of coincidence and the passing of a nearby object through the horizontal center of the display. In other words, it might be necessary for all of the objects to be vertically aligned at and near the coincidence timing. We suggest that it is not necessary for them to have the same speed to produce the event alternation effect.

Fig. 1 Examples of the stimuli used in the present study. The white arrows indicate object motion trajectories

were told that the sound and the nearby moving object were unrelated to their task in this experiment. Each participant executed at least ten practice trials before the experimental trials. A total of 20 trials were presented for each occlusion condition. Each block of 50 trials, which consisted of a block of the nearby moving object in leftward motion and a block of the nearby moving object in rightward motion, was counterbalanced for every participant, in order to minimize potential eye movements in the direction of a nearby object that was presented in a random order. The order of trials in each block was random, and the participants completed 100 trials.

Results

Figure 2 shows the mean percentages of the streaming percept across all of the participants as a function of the occlusion interval. A single-factor repeated measures analysis of variance (ANOVA) was conducted for the percentages of the streaming percept. The results showed a significant main effect of the occlusion interval, $F(4, 44) = 11.58$, $p < .001$. Post hoc analyses (Ryan's method) showed that the participants tended to perceive the streaming percept to a greater extent in the 0.00-ms condition than in the 121.58-ms condition, $t(44) = 3.13$, $p < .05$ (adjusted p value $< .005$), and the 253.80-ms condition, $t(44) = 6.17$, $p < .05$ (adjusted p value $< .001$). They also perceived it more in the 50.15-ms than in the 253.80-ms condition, $t(44) = 4.92$, $p < .05$ (adjusted p value $< .001$); more in the 75.99-ms than in the 253.80-ms condition, $t(44) = 4.92$, $p < .05$ (adjusted p value $< .001$); and more in the 121.58-ms than in the 253.80-ms condition, $t(44) = 3.05$, $p < .05$ (adjusted p value $< .005$).

Fig. 2 Mean percentages of the streaming percept for each occlusion interval condition in Experiment 1. Error bars indicate 95 % confidence intervals ($N = 12$). The dotted line indicates the percentage of the streaming percept under the sound-only condition of Kawachi and Gyoba (2006b), in which the collision sound was presented at the point of coincidence of the stream/bounce display and the nearby object was not presented

Discussion

Experiment 1 confirmed that, even if the nearby moving object was temporally occluded and became invisible, the audiovisual bouncing percept could be robustly altered by the presentation of the nearby object. That is, participants perceived the streaming event, despite the facts that the presentation of a collision sound generally promotes the bouncing percept (R. Sekuler et al., 1997; Watanabe & Shimojo, 2001) and that we had previously confirmed that the percentage of bouncing percepts was significantly higher when the sound was presented at the coincidence of the stream/bounce display than when it was not presented by using a stream/bounce display and collision sound identical to those of the present study (Kawachi & Gyoba, 2006b).² This result replicated and extended those of our previous study, which showed that the streaming/bouncing percept can be altered by the presentation of a fully visible object (Kawachi & Gyoba, 2006b).³

² In this study, we considered the cognitive-bias hypothesis that the percentage of bouncing percept may increase simply because participants tend to report bouncing percept on the basis of explicit inference that a sound and a reversal of the objects' motion directions would accompany a physical collision event (Watanabe & Shimojo, 2001). Therefore, to minimize the effect of the cognitive bias, a collision sound was presented across all conditions in Experiments 1, 2, and 3. Owing to this manipulation, the participants could not make a stream/bounce judgment on the basis of whether a sound was presented.

³ We have previously reported that motion reversal (without occlusion) induces the bouncing percept (Kawachi & Gyoba, 2006b). Our informal observation also showed that an occluded-reversed motion could promote the bouncing percept. However, it remains unclear whether the effects of occluded motion and occluded-reversed motion can be explained by similar processing.

This event alteration effect by the occluded motion remained stable under the 75.99-ms occlusion interval condition, as did the alteration effect of a fully visible object (the 0.00-ms condition), and persisted up to approximately the 120-ms occlusion interval condition. However, although participants' introspective reports indicated a tunnel effect across all occlusion conditions, the event alteration effect significantly diminished in the 253.80-ms occlusion interval condition.⁴ We suggest that the limitation of the event alteration effect may not be due to the involvement of higher-level visual processing, such as visual short-term memory for several seconds; rather, it may be due to relatively lower-level motion processing, as we will discuss later in the General Discussion section. In the following experiments, we showed that the event alteration effect can be attenuated by interrupting the spatiotemporal continuity of the motion trajectories critical for the tunnel effect.

Experiment 2: temporal discontinuity of motion trajectories

It has been reported that if an object reappears from the occluder after an extended delay interval (especially one that is more than about 200 ms), observers perceive the event as involving two different objects (Burke, 1952; Flombaum & Scholl, 2006; Michotte et al., 1964/1991). Therefore, if continuous occluded motion causes the event alteration effect, introducing a delay interval during occlusion may decrease the effect to some extent. That is, the bouncing percept may be dominant in the delay-interval conditions.

Method

Participants Eight of the students from Experiment 1, along with an additional four students from Tohoku University who were naive as to the purpose of the experiment, participated in Experiment 2. All of the participants had either normal or corrected-to-normal vision.

Stimuli The stimuli were identical to those described in Experiment 1, with the following exceptions. The occlusion horizontal width was always 0.33 deg (occlusion interval: 50.15 ms). In Experiment 2, we introduced five delay intervals (0.00, 54.05, 108.11, 198.20, and 342.34 ms) to the nearby

⁴ Although we would need precise eye movement monitoring to rule out the potential effect of eye movements, on the basis of the results of Experiment 1, the potential effect might be almost negligible. If eye movements affected the present results, then similar results should have been obtained for all of the occlusion interval conditions of Experiment 1, which could potentially induce similar patterns of eye movements along with the motion direction of the nearby object. However, the proportions of the streaming percept varied considerably.

object during the occlusion; these delay intervals occurred at and after the coincidence of the stream/bounce display. Thus, we ensured that the nearby object would arrive at the center of the screen when the two objects in the stream/bounce display coincided. It has been shown that asynchrony between the coincidence of objects and the arrival of the nearby object, not temporal discontinuity of the occluded motion, may lead to interference with the event alteration effect (Scholl & Nakayama, 2002, 2004). The 0.00-ms delay-interval condition implied that the nearby object was occluded for only 50.15 ms. The collision sound was always presented for all the conditions at the moment that the two objects in the stream/bounce display coincided and that the nearby object arrived at the horizontal center of the occluder.

Procedure The procedure was identical to that of Experiment 1.

Results

Figure 3 illustrates the mean percentages of the streaming percept across all of the participants as a function of delay interval. A single-factor repeated measures ANOVA was conducted. The results showed a significant main effect of delay interval during the occlusion, $F(4, 44) = 10.66, p < .001$. Post hoc analyses (Ryan's method) revealed the following results: Participants tended to perceive the streaming percept at the 0.00-ms delay, as compared with the 108.11-ms, $t(44) = 3.77, p < .05$ (adjusted p value $< .001$), 198.20-ms, $t(44) = 5.18, p < .05$ (adjusted p value $< .001$), and 342.34-ms, $t(44) = 5.12, p < .05$ (adjusted p value $< .001$) conditions, and also to perceive streaming at the 54.05-ms delay, as compared with the 198.20-ms condition, $t(44) = 3.77, p < .05$ (adjusted p value $< .001$), and the 342.34-ms condition, $t(44) = 3.71, p < .05$ (adjusted p value $< .001$).

Fig. 3 Mean percentages of the streaming percept for each occlusion interval condition in Experiment 2. Error bars indicate 95 % confidence intervals ($N = 12$). The dotted line indicates the percentage of the streaming percept under the sound-only condition of Kawachi and Gyoba (2006b), in which the collision sound was presented at the point of coincidence of the stream/bounce display and the nearby object was not presented

Discussion

In Experiment 2, various delay intervals were introduced during the occlusion. The results indicated that the event alteration effect could be maintained even in the 54.05-ms delay-interval condition (introducing a 54.05-ms delay interval results in an approximately 100-ms occlusion interval). However, in both the 198.20-ms and the 342.34-ms delay-interval conditions, the event alteration effect was attenuated significantly. This finding may be due to interference with the continuous occluded motion because of disruption of the temporal continuity of the object motion trajectories (Burke, 1952; Flombaum & Scholl, 2006; Michotte et al., 1964/1991). Burke reported that when the delay interval was more than 200 ms, observers could perceive a moving object stopping behind an occluder. We clearly replicated the findings of these previous studies. In fact, the participants reported that they had the impression that the nearby moving object stopped behind the occluder in the 198.20-ms delay-interval condition of Experiment 2.

Experiment 3: spatial discontinuity of motion trajectories

In Experiment 3, the spatial continuity of the object motion was disrupted. That is, the moving object reappeared from behind the occluder at an improper place. This manipulation has been shown to cause interference with continuous occluded motion behind an occluder (Flombaum & Scholl, 2006; Kawachi & Gyoba, 2006a). Therefore, if continuous occluded motion causes the event alteration effect, a possible effect of the spatial discontinuity could be a reduction in the event alteration effect.

Method

Participants Five of the students from Experiments 1 and 2, along with seven additional students from Tohoku University who were naive as to the purpose of the experiment, participated in Experiment 3. All of the participants had either normal or corrected-to-normal vision.

Stimuli The stimuli were identical to those described in Experiment 1, with the following exceptions. The occlusion was always 0.33 deg in width and 1.33 deg in height, and the occlusion interval was 50.15 ms. In Experiment 3, we also manipulated the vertical distance between the trajectory of the two objects in the stream/bounce display and the reappearing nearby object; this manipulation resulted in two conditions: the near condition (0.67 deg) and the far condition (1.33 deg). The vertical center of the occluder was 0.99 deg below the point of coincidence. We focused on the

motion of the nearby object after the coincidence of the two objects because it has been shown the event alteration effect can be affected by the motion after the coincidence (Kawachi & Gyoba, 2006b). We manipulated the spatial continuity of the motion trajectories before and after the occlusion under the following conditions: continuous condition (near–near/far–far) and discontinuous condition (far–near/near–far). The right side of Fig. 4 indicates the motion trajectory of the nearby object for each condition.

Procedure The procedure was identical to those of all of the previous experiments, with following exceptions. Two blocks of 40 trials were presented, one block of the nearby moving object in leftward motion and another of the nearby moving object in rightward motion, and were counterbalanced for every participant. The participants completed 80 trials.

Results

Figure 4 illustrates the mean percentages of the streaming percept across all the participants for each condition. A two-factor repeated measures ANOVA was conducted. The results showed significant main effects of distance between the trajectories and spatial continuity, $F(1, 11) = 5.56, p < .05$, and $F(1, 11) = 7.54, p < .05$, respectively. No significant interaction were observed between the distance between the trajectories and spatial continuity, $F(1, 11) = 1.23, p = .29$.

Discussion

Similar to the disruption of temporal continuity in Experiment 2, the disruption of spatial continuity in Experiment 3 resulted

Fig. 4 Mean percentages of the streaming percept for each condition in Experiment 3. Error bars indicate 95 % confidence intervals ($N = 12$). Stimulus examples for each condition are shown on the right side of this figure, with white arrows indicating object motion trajectories

in the attenuation of the event alteration effect; one possible explanation is that the disruption of spatial continuity may interfere with the object motion hidden by the occluder (Flombaum & Scholl, 2006; Kawachi & Gyoba, 2006a). Participants reported having the impression that a different object suddenly appeared from behind the occluder in the discontinuous conditions. The distance between the trajectories also had an influence on the event alteration effect—a finding that is consistent with those of the previous studies (Choi & Scholl, 2004; Kawachi & Gyoba, 2006b)⁵: As the distance between the nearby object and the two objects in the stream/bounce display was increased, the percentage of the streaming percept decreased.

Experiment 4: removal of the deletion/accretion cues along the occluder

The previous experiments demonstrated that continuous occluded motion can alter the audiovisual bouncing percept. Experiment 4 provides additional evidence to support this finding. The deletion/accretion cues along the occluder are critical for the percept of continuous motion behind an occluder (Gibson et al., 1969). As can be seen in Fig. 5, the deletion/accretion cues were improperly given in this experiment (Kawachi & Gyoba, 2006a; Scholl & Pylyshyn, 1999). If continuous occluded motion causes the event alteration effect, then the removal of the appropriate deletion/accretion cues would attenuate this effect.

Method

Participants Eight of the students from the previous experiments, along with four additional students from Tohoku University who were naive as to the purpose of the study, participated in Experiment 4. All of the participants had either normal or corrected-to-normal vision.

Stimuli The stimuli were identical to those described in Experiment 1, with the following exceptions. The two objects in the stream/bounce display and the nearby moving object were white squares (0.37×0.37 deg, 83.62 cd/m^2) constructed using the MATLAB (The MathWorks Inc.) and Cogent Graphics (www.vislab.ucl.ac.uk/cogent.php) software packages, and were presented on a CRT monitor (SONY GDM-F520; 60-Hz vertical refresh rate). The velocity of the two objects was $2.80^\circ/\text{s}$. The velocity of the nearby moving object was $3.36^\circ/\text{s}$. The background was

⁵ Although the near/far conditions in the present and in our previous studies (Kawachi & Gyoba, 2006b) could induce similar smooth pursuit eye movements, the near condition had a larger event alteration effect. Therefore, eye movements probably had little effect on the results of the present study.

Fig. 5 Schematic representations of the nearby moving object in the occluded-object and false-deletion/accretion-object conditions in Experiment 4 (cf. Kawachi & Gyoba, 2006a; Scholl & Pylyshyn, 1999)

black (1.77 cd/m^2), and the occluder (29.95 cd/m^2) was 0.37 deg in width and 0.75 deg in height. The occlusion interval was 110.12 ms . The vertical center of the occluder was 0.75 deg below the point of coincidence of the objects in the stream/bounce display.

In Experiment 4, we used false deletion/accretion cues, explained below, as well as the deletion/accretion cues normally associated with occlusion in previous experiments. Figure 5 displays examples of the stimulus sequences used in Experiment 4 (see also at the demonstration at <http://sites.google.com/site/yousukekawachi/false-deletion-accretion-demo>). When the right edge of the rightward-moving object (or the left edge of the leftward-moving object) hit the left (or right) edge of the occluder, the object stopped, with only the right (left) edge of the object moving back toward the object's left (right) edge; that is, the object horizontally shrank and disappeared. Then, on the other side of the occluder, part of the object reappeared, and the left (right) edge of the object expanded until it hit the right (left) edge of the occluder; that is, the object horizontally dilated. Finally, the object resumed its motion in the same direction. The objects with false deletion/accretion cues disappeared and reappeared gradually, at the same rates as those with the appropriate deletion/accretion cues.

Procedure The procedure was identical to that of all of the previous experiments, with the following exceptions. On half of the trials, the collision sound was presented at the moment that the two objects in the stream/bounce display coincided and the nearby object arrived at the horizontal center of the occluder. No sound was presented on the other half of the trials. In this experiment, we introduced the no-sound condition in order to replicate the effect of the collision sound on the perception of the stream/bounce display using the new experimental apparatus described above. There were three conditions of the nearby object (control [no nearby object], occluded object, and false deletion/accretion object), combined with two sound conditions (sound and no sound). Each combination of conditions was repeated over 20 trials. Two blocks of 60 trials, consisting of a block of the nearby moving object in leftward motion and a block of the nearby moving object in rightward motion,

were counterbalanced for every participant. The participants completed 120 trials.

Results

Figure 6 shows the mean percentages of the streaming percept across all of the participants for each condition. A two-factor repeated measures ANOVA on percentages of the streaming percept was conducted, with nearby object type and presence/absence of the sound as factors. Significant main effects emerged of both nearby object type and presence/absence of the sound, $F(2, 22) = 6.48$, $p < .01$, and $F(1, 11) = 69.30$, $p < .001$, respectively. There was also a significant interaction between the two factors, $F(2, 22) = 4.52$, $p < .05$. Post hoc analyses (Ryan's method) showed the following results. Analysis of the simple main effects of the interaction revealed that the streaming percept was more dominant without sound than with sound: control, $F(1, 33) = 67.86$, $p < .001$; occluded object, $F(1, 33) = 28.56$, $p < .001$; false deletion/accretion object, $F(1, 33) = 50.55$, $p < .001$. More importantly, in the presence of sound, participants tended to perceive the streaming event in the occluded-object condition more than in the control condition, $t(44) = 4.35$, $p < .05$ (adjusted p value $< .001$). This result replicated the event alteration effect shown in the previous experiments. However, in the false-deletion/accretion-object condition as compared with the occluded-object condition, the participants tended to perceive the bouncing event, $t(44) = 3.51$, $p < .05$ (adjusted p value $< .005$). No significant difference was found in the percentages of the streaming percept between the control and false-deletion/accretion-object conditions, $t(44) = 0.83$, $p > .05$ (adjusted p value $= .41$).

Discussion

Although the results of Experiment 4 clearly indicated that sound can sufficiently induce the bouncing percept, the event

Fig. 6 Mean percentages of the streaming percept for each condition in Experiment 4. Error bars indicate 95 % confidence intervals ($N = 12$). D/A = deletion/accretion

alteration effect was replicated in the occluded object condition. Correspondingly, participants informally reported that the tunnel effect occurred only in the occluded-object conditions. The findings of Experiment 4 suggest that the participants' task performance was not necessarily dependent on explicit inference based on the physical relationship between a sound and the bouncing event. Although the removal of the deletion/accretion cues in itself did not significantly bias participants' percepts toward bouncing (in the false-deletion/accretion-object combined with no-sound condition), the removal of the cues did interrupt the continuous occluded motion to reduce the event alteration effect significantly (in the false-deletion/accretion-object combined with sound condition). We suggest that although a continuous motion might modulate and attenuate the crossmodal effect of the collision sound on the stream/bounce display, the interruption of the continuous motion by the removal of cues can weaken the modulation of the crossmodal effect. The results of Experiment 4 robustly suggest that continuous occluded motion behind an occluder is necessary for the event alteration effect to occur.

General discussion

We explored the possibility that object motion hidden by an occluder has an effect on audiovisual stream/bounce event perception. The results of Experiment 1 indicated that the motion of an occluded object altered the percept of the audiovisual bouncing event to that of the streaming event, as did a fully visible object. However, when the occluded motion trajectory was spatiotemporally discontinuous, the event alteration effect decreased (Experiments 2 and 3). In addition, Experiment 4 revealed that the event alteration effect resulted from the percept of continuous occluded motion based on the deletion/accretion cues along the contour of the occluder. These four experiments indicated that processing the context of continuous occluded motion can interfere with the generation of crossmodal event perception.

Participants reported a clear tunnel effect across all occlusion conditions in Experiment 1. However, the results demonstrated that the event alteration effect by occluded motion was observed in conditions in which the interval was approximately 100 ms. These temporal constraints may not be sufficiently explained only by the account of the tunnel effect based on visual short-term memory and attentive tracking of objects (Kawachi & Gyoba, 2006a; Saiki, 2003; Scholl & Pylyshyn, 1999).

The event alteration effect is more likely to be related to relatively low-level motion processing. Watamaniuk and McKee (1995) suggested that continuous occluded motion is supported by the trajectory network. In the trajectory network, for a limited amount of time and space, and even under occlusion, when motion detectors are not stimulated,

the currently stimulated motion detectors can facilitate the next motion detectors along the motion path. Thus, the motion signals can propagate across the occlusion. Although the temporal limitation has yet to be clearly resolved, it has been reported that an interval of about 100 ms is essential for the visual system to integrate and utilize motion signals to update the locations of the moving object (Burr, 1981; Eagleman & Sejnowski, 2007; Maus, Ward, Nijhawan & Whitney, 2012).

Iwasaki and Maruyama (1974) suggested that the process operating for an occlusion interval of approximately 120 ms may be different from that operating for an occlusion interval that is more than 200 ms; in particular, the process for the latter range may be of a higher-cognitive, inferential nature. Yantis (1995) also reported that when an object that was occluded for a short occlusion duration (almost 100 ms) reappeared, the object tended to be perceived as the same object with the near absence of attention. In Experiment 1, the finding of the occurrence of the event alteration effect only with occlusions of no less than 121.58-ms corresponded with the finding of Yantis. Similarly, in Experiment 2, the 50-ms delays behind the occluder led to the maintenance of the event alteration effect. Furthermore, Kawachi and Gyoba (2006b) reported that the event alteration effect cannot be affected by the visual field in which the nearby object is presented. Those results did not correspond to findings that attentional resolution is higher in the lower than in the upper visual field (He, Cavanagh, & Intriligator, 1996). Other recent studies that have used an audiovisual apparent-motion display have also demonstrated that the modulation of crossmodal integration by visual grouping is preattentive (Sanabria, Soto-Faraco, Chan, & Spence, 2004; Sanabria, Soto-Faraco, & Spence, 2004; Vroomen & de Gelder, 2000).

In line with our account of motion processing, the dominance of the streaming percept has been accounted for by the spatiotemporal integration of local motion signals along the trajectories of each object (Bertenthal et al., 1993; Kawabe & Miura, 2006). The potential grouping of multiple object motion directions (an occluded object and either of the two objects in the stream/bounce display, in the present study) is also expected to strongly facilitate spatiotemporal motion integration (e.g., Yuille & Grzywacz, 1988). Moreover, although a collision sound blocks spatiotemporal motion integration, leading to the hindering of the correspondence of objects in a straight-motion path and the bouncing percept (Watanabe, 2001), strong motion integration strengthens the object correspondence and has a relatively attenuating effect on the crossmodal effect of the sound (Kawabe & Miura, 2006). Considering these factors, we are led to speculate that strong motion integration caused by the grouping of a nearby object and either of the stream/bounce objects may have interfered with the crossmodal

effect of the collision sound on the stream/bounce display, resulting in the streaming percept.

Experiments 2, 3, and 4 clearly revealed that the event alteration effect stemmed from the continuous occluded motion of the nearby object. These experiments demonstrated that spatiotemporal discontinuity and removal of the deletion/accretion cues (replacing them with false deletion/accretion cues) resulted in the attenuation of the event alteration effect. These manipulations may interrupt the integration of motion signals and then disrupt the continuous motion behind the occluder and the grouping of multiple motion directions.

Thus, the present study clearly indicates that occluded motion, in the absence of physical input, has a modulatory effect on the generation of crossmodal event perception, depending on a few spatiotemporal constraints. The present finding suggests that the establishment of crossmodal event perception takes into account the representation of occluded motion through the integration of motion signals before and after the occluder, beyond the detection of motion signals for the perception of visible motion. In the future, a further and more detailed investigation will determine at which processing levels and in what order contextual modulation is established. In a related vein, it may be useful to examine whether motion information can modulate the percept of crossmodal events at sensory, decisional levels or at a combination of both levels, as described in the terminology of signal detection theory (e.g., Grassi & Casco, 2012; Grove, Ashton, Kawachi, & Sakurai, 2012). Although a few researchers have demonstrated the influence of each level, auditory and visual signals may interact at both sensory and decisional levels, depending on the experimental conditions (Alais, Newell, & Mamassian, 2010; Sanabria, Spence, & Soto-Faraco, 2007).

Conclusion

The present study clearly indicates that the continuous motion of an occluded object is used as contextual information to judge a crossmodal streaming/bouncing event. Within a limited occlusion interval of about 100 ms, contextual occluded motion can alter the audiovisual bouncing percept such that it promotes the streaming percept. In contrast, when the continuous motion is disrupted by introducing spatiotemporal discontinuity or removing the deletion/accretion cues, the contextual motion has a reduced effect on crossmodal perception. We suggest the possibility that continuous occluded motion based on relatively low-level motion processing modulates the generation of crossmodal event perception. The psychophysical approach to crossmodal perception in combination with other perceptual phenomena in the present study provides useful clues to elucidate the underlying mechanisms of crossmodal perception.

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