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Research report

The ventriloquist in motion: Illusory capture of dynamic information across sensory modalities

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Abstract

Integrating dynamic information across the senses is crucial to survival. However, most laboratory studies have only examined sensory integration for *static* events. Here we demonstrate that strong crossmodal integration can also occur for an emergent attribute of *dynamic* arrays, specifically the direction of apparent motion. The results of the present study show that the perceived direction of auditory apparent motion is strongly modulated by apparent motion in vision, and that both spatial and temporal factors play a significant role in this crossmodal effect. We also demonstrate that a split-brain patient who does not perceive visual apparent motion across the midline is immune to this audiovisual dynamic capture effect, highlighting the importance of motion being experienced in order for this new multisensory illusion to occur.

Theme: Neural basis of behavior

Topic: Cognition

Keywords: Multisensory integration; Apparent motion; Split brain; Auditory perception

1. Introduction

Objects and events in our everyday environments typically produce correlated input to several sensory modalities simultaneously (i.e., they are multisensory) as well as information about movement with respect to the observer (i.e., they are dynamic). However, crossmodal interactions involving dynamic stimuli have rarely been studied in the laboratory, and are consequently poorly understood (e.g. Refs. [1,16,17,22,25,29]). Determining whether multisensory interactions occur in the domain of motion perception, and elucidating the factors that modulate this integration is important, as it should enhance our understanding of the information processing that takes place in the dynamic multisensory environments of everyday life.

Previous research using spatially static events has revealed that information presented to different modalities is frequently integrated into a unitary multisensory percept (see Refs. [7,27] for reviews). For example, in the classic ventriloquist illusion, people often misjudge the position of a static sound toward a light flash presented concurrently at a different spatial location (see Refs. [2,3,6]). The results from previous studies are not as clear, however, when motion is introduced in two sensory modalities. While some researchers have reported that concurrent visual apparent motion can modulate the ability to experience auditory apparent motion [16,29], others have found null results [1]. Moreover, past studies differ strongly about the nature of this dynamic crossmodal interaction (e.g., Refs. [1,16,29]). Some suggest that the relative direction of motion of the stimuli (whether they move in the same or different directions) may not play a critical role in the integration of information from dynamic events in different modalities [1,16], while others have reported strong con-

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gruency effects [29]. In addition to these conflicting results, all previous studies of dynamic crossmodal integration have several potential shortcomings. For instance, most of them confounded sensory modality and spatial location [1,16]: that is, stimuli in different modalities were presented from different possible spatial locations (e.g., sounds were typically presented from headphones and lights from LEDs in front of the observer). Given the important role that spatial coincidence plays in crossmodal integration (e.g., Ref. [14]), it is possible that the mixed results obtained in previous studies may reflect differences in integrating information across different physical locations. Critically, the only study in which spatial location was not confounded with sensory modality [29] relied solely on phenomenological reports from the participants, compromising the reliability and replicability of the findings (see Ref. [1] for an extended discussion).

In the present study, the perceived direction of apparent motion in audition was evaluated as a function of the direction of apparent motion in vision. *Synchrony* (sounds and lights presented synchronously versus asynchronously) and *Congruency* (sounds and lights moving in the same versus opposite directions) were factors in all the experiments. The introduction of synchrony as a factor allowed us to assess the effects of temporal coincidence in multisensory integration, and to distinguish the congruency effects due to post-perceptual stages of processing from the congruency effects due to perceptual integration. Note that post-perceptual processes include simple response biases from the irrelevant modality or confusion about which modality the participant had to respond to, and as such, their impact should be equivalent across synchronous and asynchronous conditions. By contrast, the effects due to perceptual integration should be revealed only in the synchronous condition, as crossmodal integration between two events breaks down quickly as one moves away from their simultaneous occurrence (e.g., Refs. [2,14,21,22,27]).

In Experiments 1 and 2, we tested multisensory integration of dynamic information under conditions of spatial coincidence and spatial displacement. As noted above, this factor may be a key reason for the mixed results reported in previous studies. In Experiment 3, we evaluated the degree to which the sensation of motion modulates perceptual integration in the present illusion, allowing us to test directly the role of dynamic vs. non-dynamic factors. Finally, in Experiment 4 we examined the crossmodal integration of motion information in a split-brain patient, to further evaluate the importance of dynamic properties of the visual stimulus in this type of crossmodal integration.

2. Materials and methods

2.1. Participants

We tested undergraduates from the University of British Columbia who volunteered in exchange for course credit. All participants reported normal hearing and normal or corrected-to-normal vision.

2.2. Apparatus and materials

Two loudspeaker cones (Audax VE100AO) were positioned 15 cm to either side of the participants' midline (30 cm center to center), and each loudspeaker was connected to one channel (left/right) of the computer's soundcard (ProAudio Basic 16, MediaVision). An orange LED (64.3 cd/m^2) was centered in front of each loudspeaker cone. Two footpedals placed on the floor beneath the table were used to collect behavioral responses (see Fig. 1a). The LEDs were controlled via TTL outputs through the computer parallel port. The Expe6 programming language [18] was used to run the experimental protocol and register responses. Auditory apparent motion displays consisted of two 50-ms tones (65 dB(A) as measured from the location of the participants' head, 5-ms amplitude ramps), one tone presented from each loudspeaker cone, separated by a 100-ms ISI. The tones were generated prior to the experiment using the Cool Edit 96 sound editor (Syntrillium Software) and stored on the computer's hard disk. The pairs of auditory tones were presented at one of three possible frequencies (450, 500, or 550 Hz) selected randomly on each trial. Visual apparent motion displays consisted of two 50-ms flashes, one flash presented from each LED, separated by a 100-ms ISI.[1]

2.3. Procedure

Participants sat in front of the loudspeakers (at a distance of 40 cm), with their hands positioned by the foam blocks that mounted the LEDs. The room remained dark throughout the experiment. Participants were told to rest their feet on the footpedals (except when responding) and to look straight ahead throughout the experiment. In a typical trial, participants were presented with two apparent motion streams, one auditory and the other visual. The visual apparent motion displays were presented at either the same time (synchronous) or 500 ms after (asynchronous) the onset of the auditory apparent motion display. The direction of the visual apparent motion display could either

[1] With similar stimuli and timings, we collected data from 12 naïve participants using a psychophysical staircase procedure to find the threshold values of apparent motion using the present set up. The SOA value at which participants were as likely to say that they perceived motion as to say that they did not perceive any motion (where the staircase reached the asymptote) was 587 ms (S.D.=347) for auditory stimuli, and 468 ms (S.D.=271) for visual stimuli. For values below this threshold, motion was frequently perceived, whereas for values above it motion was rarely perceived.

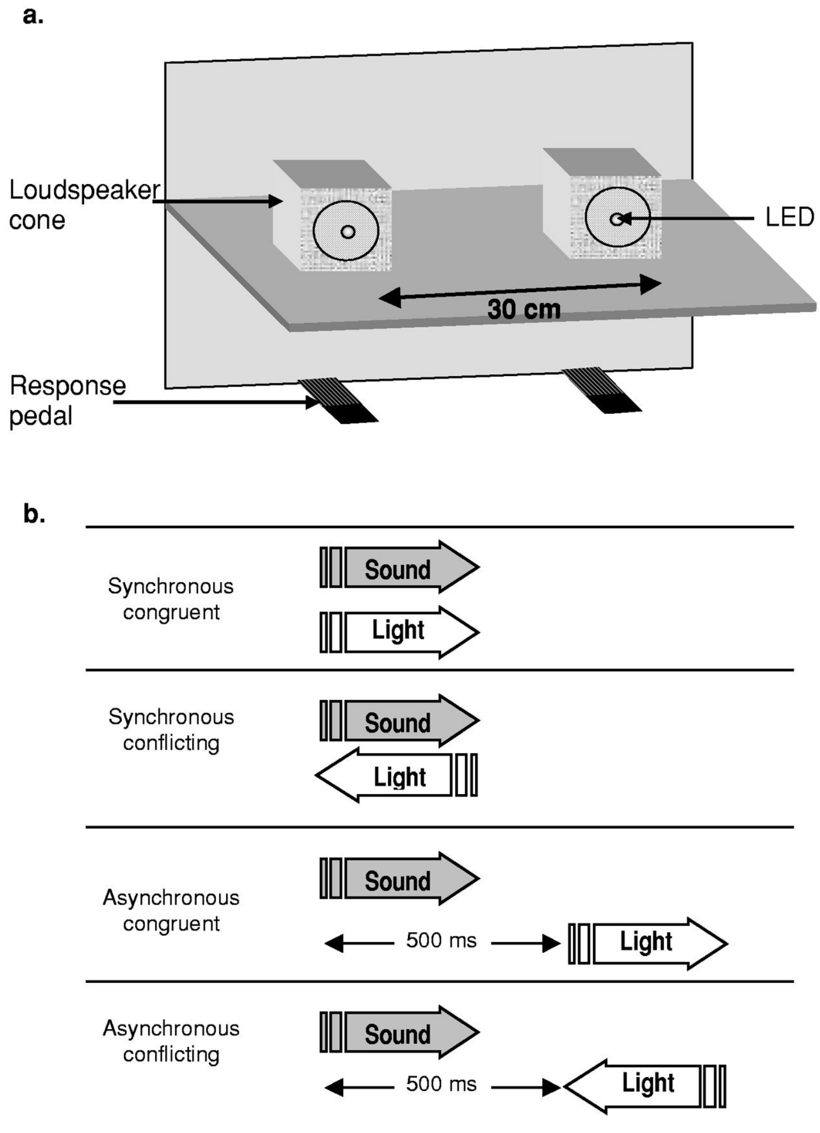

Fig. 1. Experimental methods. (a) Schematic view of the apparatus (not to scale). (b) Summary of conditions included in Experiment 1. The direction of the arrows indicates the direction in which light and sound pairs were presented in each condition (the example shows trials in which sounds moved to the right; left-moving sounds were equiprobable).

be the same (congruent) or opposite (conflicting) to that of auditory apparent motion (see Fig. 1b). Synchrony and congruency were randomly mixed (12 trials of each combination, resulting in a total of 48 test trials). The direction of apparent motion (left or right) for sounds and lights was randomly selected on each trial and equiprobable across the experimental session. Participants were instructed to ignore the lights and to lift their left foot after leftward moving tones, and their right foot after rightward moving tones, prioritizing accuracy over response latency. Ten practice trials were presented at the start of each experiment in which participants responded to auditory apparent motion streams in the absence of visual stimulation to familiarize them with the task.

3. Experiment 1

This experiment ($n=25$) included two separate blocks of trials (13 participants ran the two blocks in one order and the rest in the reverse order): these two blocks were identical except for the fact that auditory stimuli were presented over headphones in one block, and from loudspeakers situated directly behind the LEDs in the other block.

Individual accuracy in determining the direction of auditory apparent motion for each condition was submitted to an analysis of variance (ANOVA) including sound source (loudspeakers versus headphones), congruency, and synchrony as within-participants factors (see Fig. 2). The

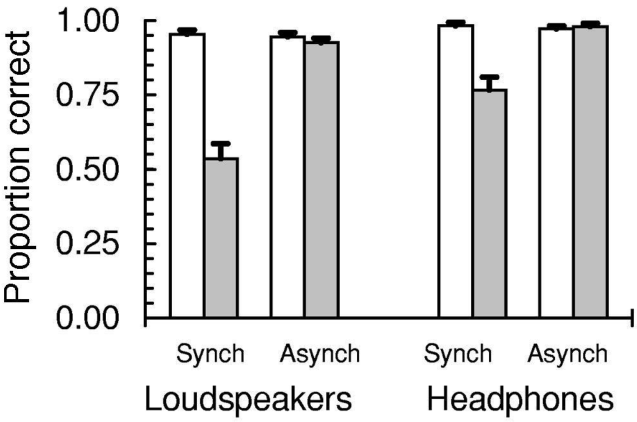

Fig. 2. Mean accuracy (±S.E.) in discriminating the direction of auditory apparent motion as a function of congruency (white bars represent congruent trials, shaded bars represent conflicting trials) and synchrony (Synch, synchronous trials; Asynch, asynchronous trials) of visual apparent motion, for each sound source in Experiment 1.

three-way interaction between sound source, congruency, and synchrony was significant ($F(1,24)=4.9$, MSE=0.094, $P<0.05$). In the external loudspeaker block, synchronous-congruent trials nearly always produced the correct response regarding the direction of auditory apparent motion. However, when synchronous lights moved in the conflicting direction participants erroneously reported that the sound moved in the direction of the lights on 47% of trials, demonstrating a strong crossmodal capture of dynamic information ($F(1,24)=56.8$, MSE=2.17, $P<0.001$, congruency effect on synchronous trials). In the headphone-presentation block, the synchronous condition also showed a significant, albeit reduced congruency effect (22%; $F(1,24)=20.5$, MSE=0.58, $P<0.001$) that was significantly smaller than that observed in the loudspeaker block ($F(1,24)=7.05$, MSE=0.25, $P<0.05$, for the interaction between congruency and sound source in the synchronous trials). Overall, the direction of auditory apparent motion was near-perfectly reported in the asynchronous trials, whether the sounds were presented from the external loudspeakers or over headphones ($M=94\%$, S.E.=1, and $M=98\%$, S.E.=0.7, respectively). In this type of trials (asynchronous), there was no main effect of congruency for either sound source ($F(1,24)=1.8$, MSE=0.005, $P=0.185$; and $F<1$), nor interaction between congruency and sound source ($F(1,24)=2.1$, MSE=0.004, $P=0.16$).

Experiment 1 demonstrates a strong integration of information for dynamic stimuli moving in different sensory modalities. Even though the direction of auditory apparent motion was unambiguous and easy to discriminate (as demonstrated by the high accuracy in the asynchronous condition), temporally coincident lights moving in the opposite direction to the sounds often reversed the direction in which the sounds appeared to move. The lack of a congruency effect in asynchronous trials shows that the dynamic capture effect was not due simply to people responding to the visual stimuli. Rather, the present results appear to reflect integration at a *perceptual* level.[2] Another important finding to emerge from Experiment 1 is that, as for other crossmodal effects, the spatial coincidence of information sources in different modalities is important for integration (cf. Ref. [23]). This supports the notion that the weak and often conflicting data obtained in previous studies is attributable to the fact that stimuli in different modalities were presented from different spatial locations (e.g., sounds over headphones and lights from in front of participants). In Experiment 2, we investigated further the role of spatial position on the integration of dynamic information across modalities by addressing how sensitive the present illusion is to the magnitude of spatial mismatch between the two modalities.

4. Experiment 2

In this experiment ($n=12$), sounds were always presented from external loudspeakers placed 30 cm apart (as in Experiment 1, see Fig. 1) while the location of the LEDs was varied systematically: The *Overlapping Close* arrangement (LEDs placed 10 cm apart, centered between the two loudspeakers); the *Overlapping Far* arrangement (LEDs 50 cm apart, each placed 10 cm outside of each loudspeaker); and the *Orthogonal* arrangement (LEDs placed 30 cm apart, centered vertically on the midline of the setup). These spatial arrangements were run in separate blocks (order counterbalanced across participants) and included the factors congruency and synchrony. In the orthogonal arrangement, the congruency factor was substituted by elevation (up versus down) as the trajectories of visual and auditory motion were orthogonal. With the overlapping arrangements we tested whether the illusion obtained in Experiment 1 was sensitive to small spatial displacements within a common trajectory. With the orthogonal arrangement, we addressed the question of whether the illusion observed in Experiment 1 requires any spatial coincidence between the visual and the auditory movement. It could be, for instance, that the presence of any visual movement during the auditory display would disrupt

[2] We also conducted a control experiment to rule out the possibility that overt visual orienting (i.e., eye movements in the direction of visual motion) might account for our results. Participants completed an experimental block identical to that described in the Materials and methods section in which eye movements were monitored using an infrared eye tracker (Applied Science Laboratories, Model 210). We excluded all trials in which eye movements were detected from stimulus onset to response execution (less than 8% of trials). Analyses of the data revealed exactly the same pattern of data as in the loudspeaker block of Experiment 1. In particular, congruency was highly significant in the synchronous trials ($F(1,8)=13.9$, MSE=0.47, $P<0.01$) but not in the asynchronous trials ($F<1$). Therefore, the execution of eye movements cannot account for the dynamic capture effects observed here.

the correct perception of the direction of auditory motion (see Ref. [16]).

An ANOVA including congruency and synchrony as within-participant factors was run on the accuracy data from the overlapping arrangements (see Fig. 3). The interaction between congruency and synchrony was significant ($F(1,11)=20.1$, MSE$=0.463$, $P=0.001$). In both overlapping arrangements, the congruency effect was significant in the synchronous condition (22%; $F(1,11)=17.5$, MSE$=0.617$, $P<0.005$; and 19%; $F(1,11)=11.5$, MSE$=0.531$, $P<0.01$, for lights close and lights far, respectively) but not in the asynchronous condition ($F<1$; and $F(1,11)=1.25$, MSE$=0.0145$, $P=0.287$, respectively). The three-way interaction was not significant ($F<1$), indicating that both arrangements had a similar effect on performance. In the orthogonal arrangement, neither the main effects nor the interaction were significant (overall accuracy 94%, S.D.$=8$, all $F<1$). The congruency effect found in the overlap blocks was compared to that in the external loudspeakers condition of Experiment 1 (where spatial match across modalities was more marked). In both overlap blocks (close and far lights), the congruency effect was smaller than in Experiment 1 yielding a significant interaction between Experiment and congruency for the synchronous trials ($F(1,35)=2.06$, $P<0.001$, for close lights, and $F(1,35)=58.9$, MSE$=2.20$, $P<0.001$, for far lights).

The outcome of the present experiment shows that when lights and sounds move in synchrony and their trajectories are orthogonal, no interaction or general decrement in performance is observed. This indicates that the presence of visual motion per se does not influence the ability to perceive the direction in which sounds move; instead, some degree of spatial coincidence in the trajectories is required for dynamic capture to occur. Our findings also reveal a significant decrease in the magnitude of the effect for small spatial offsets even when the trajectories of sounds and lights overlap spatially. This shows that spatial coincidence is important to the magnitude of the dynamic capture effect, with the greatest perceptual integration across modalities occurring when motion vectors conform across space.

Finally, and in support of the conclusion above, our finding that orthogonal visual motion does not capture moving sounds reveals that the present illusion is sensitive to the actual trajectories rather than just spatial conflict in the position of the individual lights (as would occur if this effect was explained by simple ventriloquism). In Experiment 3, we tested directly whether the present effect reflects the integration of dynamic information.

5. Experiment 3

In Experiment 3 ($n=24$), we kept the spatial arrangement fixed and varied the interstimulus interval (ISI) between the two pairs of events (first and second light, and first and second hearing). We used the known relationship between ISI and strength of apparent motion (with apparent motion decreasing as the ISI between the two events increases; e.g., Refs. [11,28] in vision; [4] in hearing) to measure dynamic capture at different degrees of perceived motion. The ISIs used were 50, 100, 300, 600 and 900 ms (with 12 trials per each ISI and congruency condition mixed randomly in one block). Note that in this experiment the lights were always presented simultaneously with the sounds (no asynchronous trials were included), and the ISI refers to the interval between the first sound/light pair and the second sound/light pair. If the present phenomenon reflects integration of dynamic information, then its magnitude should decrease as the likelihood of experiencing apparent motion decreases. However, if it can be accounted for by some other crossmodal interaction occurring individually for each sound/light pairing that is independent of dynamic properties, then the effect should remain constant regardless of ISI.

The data were submitted to an ANOVA with congruency and ISI as within-participant variables. The results (see

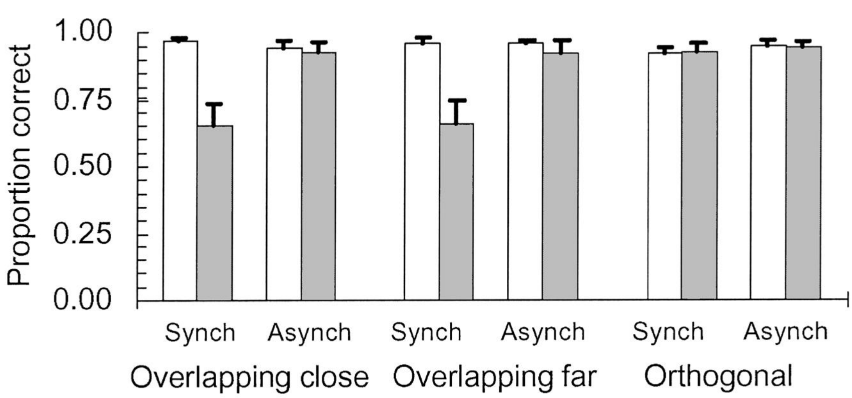

Fig. 3. Mean accuracy (±S.E.) in discriminating the direction of auditory apparent motion as a function of congruency (white bars represent congruent trials, shaded bars represent conflicting trials) and synchrony (Synch, synchronous trials; Asynch, asynchronous trials) by visual apparent motion, at the different LED arrangements in Experiment 2.

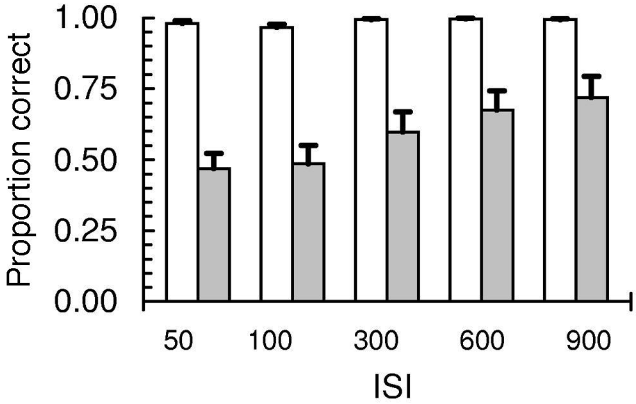

Fig. 4. Mean accuracy (±S.E.) in discriminating the direction of auditory apparent motion as a function of congruency (white bars represent congruent trials, shaded bars represent conflicting trials) and synchrony (Synch, synchronous trials; Asynch, asynchronous trials) of visual apparent motion, at the different ISI levels in Experiment 3.

Fig. 4) revealed a significant interaction between congruency and ISI ($F(4,92)=9.3$, MSE=1.22, $P<0.001$), with larger congruency effects reported at shorter ISIs (50% at an ISI of 50 ms, 47% at 100 ms, 39% at 300 ms, 32% at 600 ms, and 25% at 900 ms). The present results indicate that the magnitude of dynamic crossmodal integration increased with the likelihood of the two events being integrated in an apparent motion stream, thus directly implicating the dynamic attributes of the stimuli in this effect.

However, some degree of capture was found even at longer ISIs, perhaps reflecting some residual static ventriloquism for each of the two sounds toward each of the two lights in isolation. It is important to note though, that static ventriloquism cannot account for all the dynamic capture in these experiments, as the conditions for static ventriloquism were the same at all ISI levels, while maximum capture was found only when conditions for apparent motion were optimal. This supports the claim that dynamic capture implies integration of motion information across sensory modalities.

6. Experiment 4

The fact that cortical areas are crucial to both visual (e.g., Ref. [26]) and auditory (e.g., Refs. [10,12]) motion processing suggests that, as in many other aspects of crossmodal integration, cortical mechanisms may also be critically involved in the crossmodal integration of dynamic information [5]. Indeed, recent research using fMRI has pointed out several cortical areas potentially involved in this type of crossmodal integration (e.g., Ref. [13]). In addition, as indicated by the results of some studies testing commissurotomized (or split-brain) patients, crosscortical connections are implicated (e.g., Ref. [15]) and may even be critical for the perception of visual apparent motion across the midline (e.g., Ref. [8]; although see Ref. [20]). Given this, split-brain patients offer a chance to test further the dynamic nature of the present phenomenon, as they should not experience motion when presented with the visual displays used in Experiments 1–3, although each hemisphere will see one flashing light (the left hemisphere will see the light flashed on the right and the right hemisphere will see the light flashed on the left). We hypothesized that if the present crossmodal illusion depends on the capture of *dynamic* information across modalities, rather than on other aspects of the visual displays such as static ventriloquism, the strong influence that concurrent visual motion has on auditory motion for intact participants should be significantly reduced for a split-brain patient tested under the same conditions. If, on the contrary, the present phenomenon occurs independently of motion perception, then the performance of a split-brain patient will not differ from that of intact participants.

We tested split-brain patient J.W., who had his cortices surgically disconnected by the sectioning of his corpus callosum. As a result, visual information is no longer shared between J.W.'s cortices, while processing of auditory information is preserved [9]. In a series of control tests using the same apparatus and materials as described in Section 2, we showed that J.W. was able to perform perfectly (100% accurate) in a left–right visual localization task (lifting the pedal corresponding on the side at which a single 50-ms flash had occurred), and near-perfectly (96% accurate) in a visual apparent motion task within a single hemifield (lifting the pedal beneath the toe or beneath the heel in response to upward or downward direction of visual apparent motion, respectively). However, J.W. failed to perform at above chance levels ($M=54\%$, S.D.=51) when judging the direction of visual apparent motion across the midline (lifting the left or right footpedal for leftward or rightward visual apparent motion, using the parameters and distances described in Section 2). This result indicates that J.W. cannot integrate visual stimuli presented across the midline as a single moving object, replicating Gazzaniga's previous findings [8] and ensuring that J.W. meets the criterion to contrast the hypothesis that perception of dynamic information is crucial for the present crossmodal illusion to occur.

We tested J.W. using the same displays as described in Section 2, running two blocks identical to the external loudspeaker condition of Experiment 1. The results indicated that J.W.'s judgment of the direction of auditory apparent motion was hardly affected by concurrent conflicting visual apparent motion (Fig. 5; $F(1,46)=3.3$, $P=0.076$, congruency effect in the synchronous trials; $F=1$, in asynchronous trials; overall accuracy of 96%, S.D.=20). That is, in this task J.W. *outperformed* intact normal participants and moreover, the small (non-significant) congruency effect observed for J.W. was comparable to that seen in normal participants under conditions where apparent motion is not experienced (i.e., in the 900-ms ISI

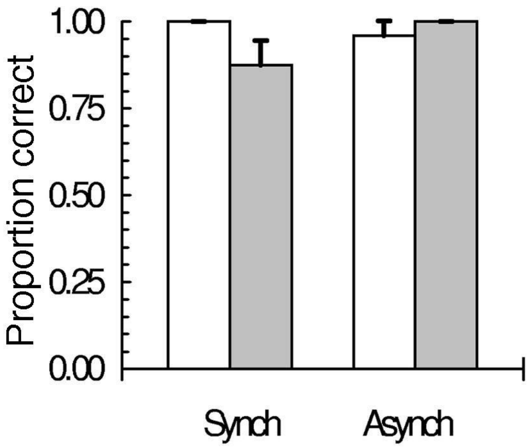

Fig. 5. J.W.'s accuracy (±S.E.) in discriminating the direction of auditory apparent motion as a function of congruency (white bars represent congruent trials, shaded bars represent conflicting trials) and synchrony (Synch, synchronous trials; Asynch, asynchronous trials) of visual apparent motion in Experiment 4.

condition of Experiment 3). Given that the perception of the static aspects of the visual stimuli on either side of the midline are preserved in J.W., but he does not experience motion, our results imply that dynamic properties of the stimulus array mediate crossmodal dynamic capture.

7. General discussion

The results of the present study demonstrate a strong crossmodal interaction in the domain of motion perception. In particular, our findings suggest the obligatory perceptual integration of dynamic information across sensory modalities, often producing an illusory reversal of the true direction of the auditory apparent motion (originally unambiguous if presented in isolation). Further, support for the uniqueness of this phenomenon comes from the fact that dynamic capture was shown to depend on apparent motion being experienced. A commissurotomized patient who could no longer determine the direction of visual apparent motion across the midline was not subject to the crossmodal dynamic capture, thus outperforming intact individuals in the perception of auditory apparent motion. Intact participants only performed in a manner similar to J.W. when the two events were separated by at least 900 ms (i.e., when apparent motion is unlikely to be experienced). The phenomenon reported here cannot be accounted for in terms of simple response biases as the effect was modulated by small temporal and spatial manipulations that should have little effect on response mechanisms. Static ventriloquism also fails to explain the present results for dynamic displays, as capture was considerably smaller when the conditions for perception of motion were weakened. In sum, dynamic capture appears to depend on apparent motion being experienced and on spatial coincidence in the trajectory of lights and sounds. This sensitivity to spatial factors may explain why previous studies that have examined the crossmodal integration of apparent motion have produced conflicting results.

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