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Compatibility of Motion Facilitates Visuomotor Synchronization

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Abstract

Prior research indicates that synchronized tapping performance is far worse with flashing visual stimuli than with auditory stimuli. This observed difference may reflect a general auditory advantage for processing temporal information, while visual processing may have an advantage with spatial information. Three finger-tapping experiments compared flashing visual metronomes with visual metronomes containing a spatial component, either compatible, incompatible, or orthogonal to the tapping action. In Experiment 1, synchronization success rates increased dramatically for spatiotemporal sequences of both geometric and biological forms over flashing sequences. In Experiment 2, synchronization performance was best when target sequences and movements were directionally compatible (i.e. simultaneously down), followed by orthogonal, action-neutral stimuli, and was poorest for incompatible moving stimuli (upward target/downward movement) and flashing target sequences. In Experiment 3, synchronization performance was best with auditory sequences, followed by compatible moving stimuli and was worst for flashing and fading sequences. Results indicate that visuomotor synchronization improves dramatically with compatible spatial information (translation over time); however, an auditory advantage in sensorimotor synchronization persists.

Keywords: sensorimotor synchronization, modality effects, rhythm, timing.

Introduction

Sensorimotor synchronization is generally found to be more difficult and more variable with visual rhythms than auditory or tactile rhythms. People rarely synchronize spontaneously with purely visual rhythms, whereas young children and adults spontaneously move to rhythms in music (e.g., Eerola, Luck, & Toiviainen, 2006). Rhythmic finger tapping has been found to be most variable with flashing visual stimuli and least variable with auditory stimuli (Chen, Repp, & Patel, 2002; Repp & Penel, 2002, 2004), with tactile stimuli intermediate (Kolers & Brewster, 1985). Moreover, reliable synchronization in 1:1 tapping is possible at rates up to an inter-onset interval (IOI) of about 200 ms for auditory sequences (e.g., Fraisse, 1982);[1] contrasted with IOIs around 460 ms IOIs for flashing visual sequences (Repp, 2003).

The apparent difficulty in synchronizing with visual stimuli has yet to be explained adequately. It may simply stem from the less frequent occurrence of visual than auditory rhythms in our environment. Another possibility is that it is based on differences in neural connectivity. Fraisse (1948) suggested that the action system is more closely linked to the auditory system than to the visual system. More recently, Thaut and colleagues (1999) proposed a comparatively direct connection between auditory cortex and spinothalamic neurons used to control movement, which results in increased sensorimotor coupling. Yet another possibility for the observed performance differences stems not from differential connectivity between motor neurons and auditory versus visual pathways, but from the inherent processing styles of those two sensory systems themselves. The auditory system is generally better at resolving temporal variation (e.g., Conway & Christiansen, 2005), whereas the visual system is better at resolving spatial variation (e.g., Posner, Nissen, & Klein, 1976). Under this account, visual information naturally dominates when one is attempting to identify the *spatial location* of a sound (as in the ventriloquism effect; Bertelson & Radeau, 1981), and auditory information naturally dominates when one is attempting to identify or behave contingent upon the *temporal incidence* of a sound (as in synchronized tapping tasks; Repp & Penel, 2002, 2004).

The observed difficulties in visuomotor synchronization may appear simply because the vast majority of studies employ purely temporal flashing stimuli devoid of spatial information. This focus on flashing stimuli dates back nearly a century (Dunlap, 1910) and more recently extends into examinations of the neural substrates of visuomotor synchronization in fMRI (e.g., Jäncke, Loose, Lutz, Specht, & Shah, 2000), PET (Penhune, Zatorre, & Evans, 1998) and

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[1] The rate limit in 1:1 tapping seems to reflect the maximum finger frequency. When tapping with every 4th onset, the auditory IOI limit decreases to 100-120 ms (Repp, 2003).

MEG (Chen, Ding, & Kelso, 2003). Repp, Patel and colleagues (Patel, Iverson, Chen, & Repp, 2005; Repp & Penel, 2004) have speculated that different types of visual stimuli, namely those employing a spatial component, might facilitate synchronization.

A great deal of literature explores stimulus-response compatibility effects but such compatibility has not yet been demonstrated in the synchronized tapping paradigm. Studies of the synchronization of hand movements with an oscillating visual target found that in-phase movements were more stable than anti-phase movements (Roerdink, Peper, & Beek, 2005). However, it remains unclear how such results would compare with purely temporal flashes or action-neutral moving stimuli. Additionally, facilitative effects of compatibility between dynamic visual displays and finger movements have been observed in reaction time tasks (Brass, Bekkering, & Prinz, 2001), and may extend to synchronization performance. Finally, the extrastriate body area (EBA) in human occipital cortex responds selectively to images of the human body (Downing, Jiang, Shuman, & Kanwisher, 2001) and also is active during limb movements (Astafiev, Stanley, Shulman, & Corbetta, 2004). This suggests a link between perceptual and action-based body representations, and might potentially translate into different synchronization performance with human body images versus geometric images. In the following experiments, we investigate whether certain types of spatially varying and compatible visual information enable better synchronization than simple flashing lights.

Experiment 1

Experiment 1 investigated sensorimotor synchronization with visual metronomes that were either purely temporal or contained additional spatial information. Those containing spatial information showed motion of either geometric or biological forms, which might afford different performance. Sequences were presented at 2 tempi: 500 ms inter-onset-interval (IOI) and 400 ms IOI; one above and one below the previously ascertained 460 ms rate limit for flashing visual stimuli (Repp, 2003). The primary measures of performance were the success rate of synchronizing with the stimuli (i.e. had consistent tap-to-target asynchronies) and the average magnitude of those asynchronies.

Method

Participants Eleven right-handed Cornell students (6 women) aged 19 to 23 years participated in the study. They were previously unfamiliar with the tapping task. Musical training ranged from 0-12 years (*M* = 4.1), though most were no longer active musicians; musical training yielded no significant effects. Participants received course credit or were paid $6.

Materials The four stimulus sequences were QuickTime movies produced using the animation software, After Effects. They were presented on a computer screen in a 10 cm x 8 cm viewing window. Videos lasted 26 cycles and each cycle consisted of 20 frames. In the *Slow* tempo condition (500 ms IOI), videos were played at a frame rate of 40 frames per second (fps), and in the *Fast* tempo (400 ms IOI), the same videos were played at 50 fps.[2] The four visual metronomes are shown as still pictures in Fig. 1.

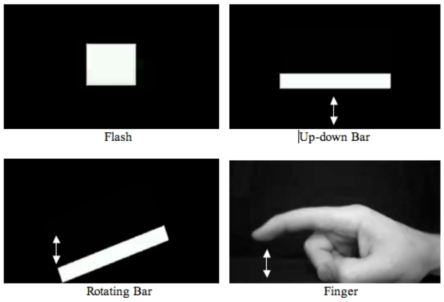

Figure 1: Stills from the four metronomes in Experiment 1; arrows added to depict motion.

a) The *Flash* was a 2 cm x 2 cm stationary white square that remained on screen for 2 video frames. b) The *Up-down Bar* was a 5 cm x 1 cm white bar that moved down frame-by-frame from its initial position 2.5 cm above the bottom of the viewing window to the bottom of the viewing window and back again. c) The *Rotating Bar* utilized the same bar and initial position as the Up-down Bar, but the bar pivoted from its right edge until the left edge touched the bottom of the viewing window, then returned to its initial horizontal position. d) The *Finger* used spliced images of a right index finger (5 cm x 1 cm) tapping in the same configuration as the participant's finger; the Finger's vertical trajectory matched the Rotating and Up-down bars frame-by-frame, thereby isolating the effect of the image of bodily form, without confounding the acceleration and deceleration of biological motion. The target position (for signaling the time to tap) in all the spatial metronomes was contact with the bottom of the screen; this was displayed for 2 frames to match the *Flash* target duration.

Procedure Participants sat approximately 75 cm in front of a computer monitor that displayed the visual sequences at eye level. They positioned their right hand in front of themselves at approximately waist level perpendicular to the screen (pointing to the left) and tapped with their right index finger on a Roland Handsonic HPD-15 drum pad. Sequences were presented and taps were recorded using a MAX/Jitter program running on a Macintosh G4.

Participants were instructed to start tapping with the 5th cycle in the 26-cycle sequence; thus each trial consisted of 22 taps. Each of the eight trial types (2 tempi x 4 metronome types) was presented in random order in a block. The experiment consisted of twenty blocks, including one training block, thus leaving 152 analyzed trials per participant. The entire experiment lasted approximately 45 minutes.

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[2] The monitor refresh rate of 85 Hz (11.7 ms) led to slight deviations of frame timing. However, no systematic error or drift occurred. Timing perturbations on this order were recently shown to have no effect on variability of inter-tap-interval (ITI) or tap-to-target asynchrony (Madison & Merker, 2004).

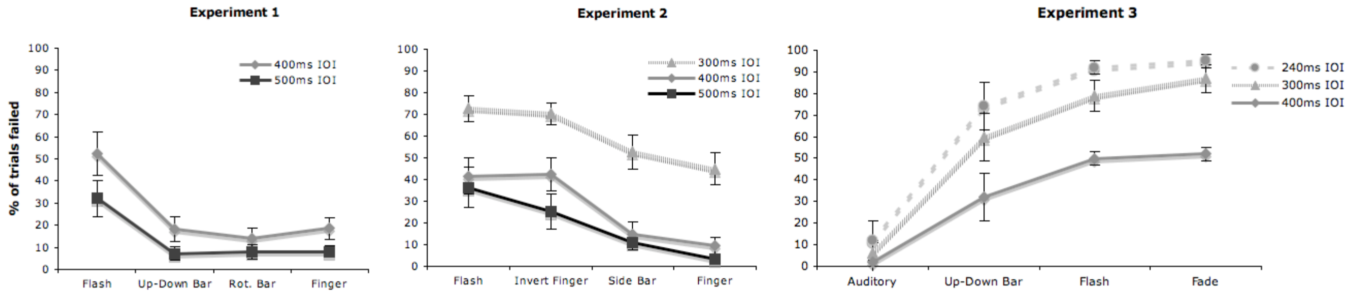

Figure 2: Percentage of trials failed for Experiments 1-3.

Results and Discussion

Asynchronies between taps and targets and inter-tap-intervals (ITIs) within trials were calculated prior to analyses. Synchronization typically requires a few taps to stabilize, so taps corresponding to the first 10 video cycles (the first 6 taps) were omitted.

An indicative measure of synchronization performance is the percentage of trials in which tap-to-target asynchronies never stabilize (Repp, 2003). Unsuccessful trials (those with irregular tapping or phase drift) were defined as those with standard deviations of tap-to-target asynchrony greater than 67 ms for 400 ms IOI trials (16.7% of IOI, following Repp, 2003); the same 67-ms criterion was used for the 500 ms IOI trials. The average percentage of unsuccessful trials is shown in Fig. 2. A 2 (tempo) x 4 (metronome type) repeated measures analysis of variance (ANOVA) revealed a main effect of metronome type, where unsuccessful trials were more frequent for the Flash metronome than the spatial metronomes, $F(3,30) = 28.3$, $p < .001$, $\eta_p^2 = .74$. No significant differences among the spatial metronomes were found in pair-wise comparisons (Bonferroni corrected, as are similar subsequent comparisons). Additionally, there was a main effect of tempo; unsuccessful trials were more frequent at the Fast tempo than at the Slow tempo, $F(1, 10) = 13.7$, $p < .01$, $\eta_p^2 = .58$. The Metronome x Tempo interaction was not significant. Consistent with Repp (2003), the Flash metronome in the Fast tempo condition had a failure rate higher than the 50% "synchronization threshold." However, failure rates for the three spatial metronomes were well below the 50% synchronization threshold even in the Fast tempo condition. This indicates that visuomotor synchronization rate limits for spatially varying metronomes are lower than the previously measured rate limits for flashing metronomes.

Taps tended to precede targets, as is commonly found (e.g., Aschersleben, 2002), although means of asynchrony are generally not considered an index of synchronization success. An ANOVA revealed a main effect of tempo on mean asynchrony; participants anticipated the target to a greater extent at the Slow tempo, $F(1,10) = 76.4$, $p < .001$, $\eta_p^2 = .88$. This decrease in anticipation tendency is common at faster tempi (e.g., Repp, 2003), but the reason for this remains unclear (see Repp, 2005, for a recent review of competing explanations). The main effect of metronome type was also significant, $F(3, 30) = 18.1$, $p < .001$, $\eta_p^2 = .64$. Planned pair-wise comparisons revealed later tapping with the Flash than with the spatial metronomes (*p*s < .05). This is consistent with motion prediction in the flash-lag effect (Nijhawan, 1994). The Metronome x Tempo interaction was not significant.

In summary, the addition of a spatial component facilitated visuomotor synchronization success and participants easily synchronized with these metronomes even at the fast tempo. No advantage for tapping with biological forms over geometric forms was observed. The anticipation tendency was greater at the slow tempo and for moving metronomes.

Experiment 2

Experiment 2 investigated whether the spatial visual metronome's degree of compatibility with the to-be-performed movement influenced synchronization performance. Participants synchronized finger tapping with 4 types of visual metronome. Sequences were presented at three tempi: the two from Experiment 1, plus a faster tempo in order to examine whether synchronization might be possible at even higher rates.

Method

Participants Thirteen right-handed Cornell undergraduates (8 women) aged 19 to 21 years participated in the study. They were previously unfamiliar with the tapping task. Musical training ranged from 0-10 years ($M = 4.6$), though most were no longer active musicians; musical training yielded no significant effects. Participants received course credit or $6.

Materials The QuickTime videos were played at 3 IOIs: 500 ms (*Slow*); 400 ms (*Fast*); and 300 ms (*Very Fast*). The four metronome types are shown in Fig. 3. The Flash and Finger videos from Experiment 1 were used. The left-and-right moving bar (*Side Bar*) was the Up-down Bar from Experiment 1 rotated 90 degrees counter-clockwise, so the target for tapping occurred when the bar struck the viewer window's right edge. The *Inverted Finger* was the Finger video flipped upside down; the target occurred when the finger contacted the top of the window. The three spatial videos had identical trajectories and tested the degree of compatibility between stimuli and movement.

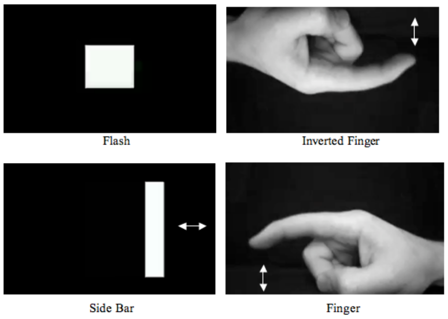

Figure 3: Stills from the four metronomes in Experiment 2; arrows added to depict motion.

Procedure The procedure was identical to Experiment 1, except that there were 15 blocks containing each of the 12 trial types (3 tempi x 4 metronome types) in random order. The first block was considered training, thus leaving 168 analyzed trials. The experiment lasted approximately 50 minutes.

Results and Discussion

The data were preprocessed as before. The percentage of unsuccessful trials by condition is shown in Fig. 2. A 3 (tempo) x 4 (metronome type) ANOVA found a main effect of metronome type, $F(3, 36) = 19.5, p < .001, \eta_p^2 = .62$. The pair-wise comparisons showed best synchronization performance for the compatibly moving Finger than all other metronomes (*p*s < .05). The neutral Side Bar yielded better performance than the incompatible Inverted Finger and non-spatial Flash (*p*s < .01). There was no difference between the Flash and the Inverted Finger ($p > .9$). The main effect of tempo was also significant, $F(2, 24) = 45.0, p < .001, \eta_p^2 = .79$. Pair-wise comparisons showed the most failed trials at the Very Fast (300 ms IOI) tempo (*p*s < .001); and more failed trials at Fast (400 ms IOI) than Slow (500 ms IOI) ($p < .01$). The Metronome x Tempo interaction was not significant. Failure rates for the compatible Finger metronome are under Repp's (2003) 50% "synchronization threshold" even at the fastest 300 ms IOI.

Taps tended to precede targets. An ANOVA revealed a main effect of tempo, $F(2, 24) = 29.7, p < .001, \eta_p^2 = .71$; participants tapped significantly earlier at the slow tempo than at the other two tempi, *p*s < .001. There was also a main effect of metronome on mean asynchrony, $F(3, 36) = 3.5, p < .05, \eta_p^2 = .22$. Planned pair-wise comparisons again revealed earlier tapping for the compatible Finger than the Flash ($p < .05$), consistent with the aforementioned motion-prediction (flash-lag) interpretation. However, asynchronies for the Inverted Finger did not differ from the Flash, and were later than the compatible Finger and orthogonal Sidebar (*p*s < .05). The Tempo x Metronome interaction was significant, $p < .001$. This interaction arose largely from the highly variable and erratic performance at the Very Fast tempo.

Experiment 2 demonstrated that the mere addition of spatial information on its own does not improve synchronization performance over flashing metronomes, as indicated by the equally poor synchronization for the incompatibly moving Inverted Finger and non-spatial Flash. Synchronization was greatly improved with spatial stimuli moving orthogonally to the to-be-produced movement; and compatible motion further facilitated synchronization performance.

Experiment 3

In light of the facilitation observed in the first two experiments, Experiment 3 probed whether visuomotor synchronization with compatibly moving targets could approach auditory-motor synchronization. Participants synchronized finger tapping with four types of metronomes: 1) auditory beeps; 2) an up-down moving bar compatible with finger movements; 3) a Flash; and 4) a Flash target interspersed with predictably intensifying "snowflakes," dubbed *Fade.* The Fade metronome controlled for the possibility that the facilitation with moving metronomes stemmed from their continuous and predictable nature, rather than their spatial translation (moving metronomes and the Snowflake metronome have a trackable cycle and, in a sense, more predictable target than the Flash). Sequences were presented at even faster tempi: Target IOIs were 400 ms, 300 ms, and 240 ms.

Method

Participants Ten Cornell students (3 women) aged 19-32 participated (including author MJH). Musical training ranged from 0-20 years (*M* = 6.5) and produced no significant results. Participants received $4.

Materials Stimulus sequences were presented with Matlab's PsychToolbox running on a 2.4 GHz MacBook Pro (NVIDIA GeForce 9600 video card) with its lid closed and driving an external CRT monitor at a refresh rate of 100 Hz (10 ms). PsychToolbox syncs to the refresh rate allowing millisecond accurate timing for visual presentation, as well as auditory presentation. All sequences lasted 26 cycles. Visual metronomes at the 400 ms and 300 ms target IOIs consisted of 10 images per cycle, with each image lasting 40 ms and 30 ms, respectively; the 240 ms IOI sequences consisted of 6 images/cycle, with each image presented for 40 ms. Sequences are depicted in Fig. 4.

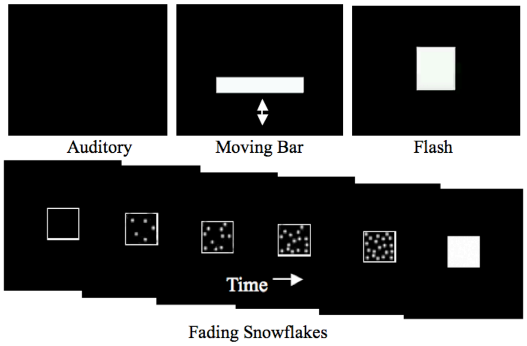

Figure 4: The four metronomes from Experiment 3.

a) Auditory sequences consisted of 40 ms long sine wave beeps at 440 Hz. b) The up-down moving bar was a 5 x 1 cm bar, with a 2.5 cm max displacement above the bottom of the screen for the 400 and 300 ms IOI trials and a 1.5 cm max displacement for the 240 ms IOI trials. c) The Flash was a 2 cm x 2 cm white square. d) The Fade metronome consisted of the Flash target interspersed with dots; it started with a blank screen, then added dots each successive image until the Flash onset, then subtracted dots until the blank (i.e. blank, 5 dots, 10 dots, 15 dots, 20 dots, FLASH, 20 dots, 15 dots,… etc. for 400 and 300 ms IOI trials, and blank, 10 dots, 20 dots, FLASH, 20 dots, 10 dots… for 240 ms IOI trials).

Procedure Participants sat in front of a computer monitor wearing Beyer Dynamic circumaural headphones and tapped on a light cardboard box fitted with a microphone. On a separate Mac G4 computer running Audacity at an 8000 Hz sample rate, taps were recorded on one channel, and trial onset markers from the stimulus computer were recorded on the other channel.

Each of the twelve trial types (3 tempi x 4 metronome types) was presented in random order in a block. The experiment consisted of 1 practice block and 10 experimental blocks (120 analyzed trials). The experiment lasted approximately 25 minutes.

Results and Discussion

Tapping data was analyzed using circular statistical methods and the taps occurring during the first four targets of each trial were omitted from analyses. Unsuccessful trials were defined as trials with a SD of tap-to-target asynchrony greater than 16.7% of the IOI for all trials (Repp, 2003, used a stricter criterion for auditory trials, but we will held it constant to compare across modalities). The percentage of unsuccessful trials by condition is shown in Fig. 2. A 3 (tempo) x 4 (metronome type) ANOVA found a main effect of metronome type, $F(3, 27) = 46.5, p < .001, \eta_p^2 = .84$. The pair-wise comparisons showed that the synchronization performance with the Auditory metronomes was better than each visual metronome (ps $\leq$ .001). Among the visual metronomes, the moving bar yielded higher synchronization success than the Flash or the Fade (ps < .05), and no difference was observed between the Flash and the Fade ($p > .1$). Tempo also affected performance, $F(2, 18) = 22.7, p < .001, \eta_p^2 = .71$, with pairwise comparisons showing that synchronization performance was worse at faster tempi (ps < .05). The tempo x metronome interaction ($p = .04$) indicates that the fast tempos impede synchronization more for visual than auditory metronomes.

Taps again tended to precede the targets, especially in the slowest tempo. A circular ANOVA revealed a main effect of tempo on mean asynchrony, $F(2,117) = 4.34, p = .015$. A main effect of metromone type did not attain significance, $F(3,116) = 2.39, p = .072$.

Experiment 3 demonstrates that synchronization performance is more stable in the auditory domain, even compared to compatibly moving visual stimuli. The Fade metronome did not improve synchronization over the Flash, thus we can confidently conclude that the facilitation with the moving bar is due to its compatible *spatial* component, rather than its continuity and predictability.

General Discussion

These results demonstrate that compatible spatial information greatly facilitates visuomotor synchronization. In Experiment 1, participants' synchronization performance was dramatically better with the three moving metronomes (similar in amplitude, size, and trajectory) than the flashing metronome. No advantage was observed for synchronization with biological forms, despite the representational overlap for seeing bodily forms and for producing movements in the extrastriate body area. Our stimuli did not contain biological motion, but future work should explore synchronization with metronomes containing biological trajectories of acceleration/deceleration. Experiment 2 demonstrated the importance of directional compatibility between the metronome and body movement. Synchronization performance was equally poor for the action-incompatible Inverted Finger and the Flash. The directional mismatch between target stimulus (upward) and tap response (downward) presumably caused interference, thereby negating the spatial facilitation. Performance improved when tapping with an orthogonal (i.e. non-interfering and non-compatible) sideways moving bar, and best performance occurred with the highly compatible (in direction, amplitude, size, and form) Finger video.

In Experiment 3 (and much pilot work employing continuous Fading stimuli with color bursts) no advantage was observed for a predictable Fade metronome. Thus, the spatial component appears to be the crucial facilitative factor, probably due to the visual system's proficiency at processing spatial information.

Rough estimates of a "synchronization threshold" (a 50% success rate, Repp, 2003) for compatibly moving metronomes in Experiments 2 and 3 converge around 300 ms IOI for the untrained, novice-tapper participants. Two participants in Exp. 3 easily synchronized at the fastest tempo: 240 ms IOIs; and future work could examine effects of training on this uncommon task or examine performance of "hand-eye experts" such as athletes or video-gamers. While this rough threshold is much faster than previously established, the advantage for synchronization in the auditory modality remains.

The compatibility effects support the notion that temporal information for action is not coded in an independent, action-neutral domain (i.e., in a specialized, isolated timing center that extracts temporal information from perceptual systems and sends this on to an action planning system). Rather, temporal information here appears to be computed in a task-dependent, action-oriented manner (Ivry & Spencer, 2004). Additionally, the compatibility effects between perceived and produced events can be explained in terms of the common-coding theory of perception and action (Hommel, Müsseler, Aschersleben, & Prinz, 2001). In this theory, sensory and motor codes share a common representational medium; sensory information of a downward moving target converges on a shared abstract feature code, which spreads activation to the motor system, pre-specifying or biasing it toward downward action. Conversely, an upward moving sensory target will bias action toward upward movement and interfere with the downward goal.

To sum, our results demonstrate that visuomotor synchronization performance is greatly facilitated by compatible motion, possibly due to the visual system's proficiency at processing spatial information and the tight linkages between perceptual and action systems; however an auditory advantage in sensorimotor synchronization persists.

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