

Auditory Imagery Shapes Movement Timing and Kinematics: Evidence From a Musical Task

Peter E. Keller

Max Planck Institute for Human Cognitive and Brain Sciences

Simone Dalla Bella

University of Finance and Management in Warsaw, and
International Laboratory for Brain, Music, and Sound Research,
Montreal, Quebec, Canada

Iring Koch

RWTH Aachen University

The role of anticipatory auditory imagery in music-like sequential action was investigated by examining timing accuracy and kinematics using a motion capture system. Musicians responded to metronomic pacing signals by producing three unpaced taps on three vertically aligned keys at the given tempo. Taps triggered tones in two out of three blocked feedback conditions, where key-to-tone mappings were compatible or incompatible in terms of spatial and pitch height. Results indicate that, while timing was most accurate without tones, movements were smaller in amplitude and less forceful (i.e., acceleration prior to impact was lowest) when tones were present. Moreover, timing was more accurate and movements were less forceful with compatible than with incompatible auditory feedback. Observing these effects at the first tap (before tone onset) suggests that anticipatory auditory imagery modulates the temporal kinematics of regularly timed auditory action sequences, like those found in music. Such cross-modal ideomotor processes may function to facilitate planning efficiency and biomechanical economy in voluntary action.

Keywords: motor performance, auditory feedback, imagery, tempo, music

The mental antecedents of goal-directed action have long been viewed as anticipatory images of intended action outcomes (e.g., James, 1890). Although such anticipatory imagery presumably plays a role in everyday activities, we believe that it can be studied most profitably in skill domains such as sport, dance, and music, where task-specific imagery abilities are deliberately trained. Accordingly, the present study investigates how voluntary movements are shaped by anticipatory images of intended action outcomes in a music-related context. Music performance requires the precise control of body movements in order to realize specific auditory goals. These goals typically are tone sequences in which elements have prescribed relations in terms of event order, rhythmic timing, and acoustic parameters, such as intensity (loudness). Expert performers claim that the production of musical sequences is facilitated by the generation of auditory images while playing (e.g., Trusheim, 1993), and the results of recent experimental

studies employing simple music-like tasks support these claims (Keller & Koch, 2006b, 2008).

One way in which auditory imagery may benefit music performance is by enabling rapid and thorough action preplanning, as demonstrated in speeded reaction time tasks (e.g., Keller & Koch, 2008; Kunde, Koch, & Hoffmann, 2004). For example, Keller and Koch (2008) found evidence that anticipatory auditory images prime appropriate movements for producing desired sounds via an “ideomotor” mechanism (see Hoffmann, Stöcker, & Kunde, 2004; James, 1890; Koch, Keller, & Prinz, 2004; Prinz, Aschersleben, & Koch, 2009). Furthermore, the efficiency of this mechanism increased with musical experience, which may be due to the effects of music training on the vividness of auditory images (Halpern, 2003; Janata & Paroo, 2006) and/or functional links between auditory and motor brain regions (Bangert et al., 2006). The benefits of anticipatory auditory imagery may, however, extend beyond the preplanning of speeded actions. Indeed, sheer speed is not the goal in most music. It is more often the case that precise timing goals must be met, such as particular expressive timing profiles (e.g., rubato when playing a Chopin Nocturne) or simply a steady tempo (as in marches or dance music).

To investigate the effects of anticipatory auditory imagery upon temporal precision, Keller and Koch (2006b) required musicians to respond to each of four color-patch stimuli by producing a unique sequence of three taps on three vertically aligned keys. The color-patch stimulus in each trial flashed three times with a 600 ms inter-onset interval (IOI), and participants tapped their responses as regularly as possible at this tempo after a further three flashes of

Peter E. Keller, Music Cognition and Action Group, Max Planck Institute for Human Cognitive and Brain Sciences; Simone Dalla Bella, Department of Cognitive Psychology, University of Finance and Management in Warsaw, Poland, and International Laboratory for Brain, Music, and Sound Research, Montreal, Quebec, Canada; and Iring Koch, Institute of Psychology, RWTH Aachen University.

We thank Wenke Moehring, Nadine Seeger, and Kerstin Traeger for their help with running the experiment.

Correspondence concerning this article should be addressed to Peter E. Keller, Max Planck Institute for Human Cognitive and Brain Sciences, Stephanstr. 1a, D-04103 Leipzig, Germany. E-mail: keller@cbs.mpg.de

a neutral white stimulus. Taps triggered tones in such a way that the resultant melodic contours and movement transitions were compatible (top, middle, and bottom keys triggered high, medium, and low pitched tones, respectively) or incompatible (key-to-tone mapping was scrambled or reversed) on the “height” dimension. Thus, cross-modal compatibility was varied between blocks of trials by utilizing the well-established correspondence between pitch and spatial height (see Keller & Koch, 2006a; Rusconi, Kwan, Giordano, Umiltá, & Butterworth, 2006).

Keller and Koch (2006b) found that timing was more accurate in compatible than in incompatible conditions from the first tap on. The presence of a compatibility effect on the first tap suggests that anticipatory auditory imagery played a role in controlling the temporal precision with which movements were executed, as the first tone appeared only after the finger contacted the response key. Compatibility effects on the second and third taps may reflect the combined effects of imagery and actual auditory feedback from the preceding tap(s) (see Pfordresher, 2008). Keller and Koch (2006b) took the result for the first tap as evidence that the benefits of ideomotor priming—which is especially effective with compatible key-to-tone mappings—may extend beyond efficiency in selecting and planning an action (Keller & Koch, 2008) to include the fine-tuning of motor control processes that regulate the action’s spatial and temporal evolution when precise timing is required. However, the exact nature of this fine-tuning remains an open question. The current study addressed this issue—which is relevant not only to music performance but to rhythmic action in general—by using a motion capture system to examine movement kinematics, in addition to timing, as musicians performed a sequence production task based on Keller and Koch’s (2006b) paradigm.

Two classes of kinematic variable are of primary interest. The first is spatial in nature, and pertains to movement trajectory path. To travel smoothly between locations in space in a given amount of time, the optimal path is determined largely by laws governing the relationship between the curvature and speed of biological movements (e.g., Atkeson & Hollerbach, 1985; Viviani & Flash, 1995). Assuming that the results of studies of interactions between visual perception and action (e.g., Grosjean, Zwicker, & Prinz, 2009; Welsh & Elliott, 2004) generalize to the auditory domain, we hypothesized that incompatible mappings may disrupt timing by warping movements away from their optimal paths, producing a “contrast” effect. Specifically, imagining an incompatible low tone while planning an upward movement may increase movement amplitude (vertical extent) relative to when a high tone is imagined, and imagining an incompatible high tone while planning a downward movement may decrease amplitude.

The second class of kinematic variable that could affect timing accuracy relates to force control. Based on findings from a study of piano performance, Goebel and Palmer (2008) proposed that increased acceleration at key contact serves to improve timing accuracy for the next keystroke by increasing tactile feedback from the current keystroke. Other studies have shown that auditory feedback, which is perceived more rapidly and with greater temporal accuracy than tactile feedback, contributes to timing regulation when finger taps trigger tones during synchronization with a metronome (Aschersleben, Gehrke, & Prinz, 2004). We hypothesized that the manipulation

of auditory feedback would affect the weighting of tactile feedback in multisensory representations (see Ernst & Bühlhoff, 2004) that guide music-like action. Specifically, the presence of auditory feedback should reduce reliance upon tactile feedback, thereby lessening the need for forceful movements. Furthermore, auditory information may carry more weight when melodic contours are compatible with movement transitions than when they are incompatible, leading to reduced force in the former case. Accordingly, less extreme values of downward acceleration (which is proportional to force) may be observed during the arrival phase for taps that produce tones than for those made in silence, and, when taps trigger tones, for compatible key-to-tone mappings than for incompatible mappings.

Method

Participants

Thirty musicians with an average of 18 years of experience (range = 11–29 years) on a variety of instruments participated in the experiment (16 females; median age = 24, range = 20–36 years).

Apparatus and Stimuli

A response box with three vertically aligned metal plates was positioned at a comfortable height for tapping in front of a computer monitor (resting on a table). The response box was 250 mm high and 150 mm wide. The metal plates embedded in its surface measured 30 × 30 mm and were separated by 15 mm. The top of the box was tilted away from the participant so that its surface was off-vertical by ~60°. Imperative stimuli consisted of four color patches (16 × 16 mm, viewed from a distance of approximately 750 mm) presented in the center of the black computer screen: pink, yellow, green, or blue. The numbers 1, 2, and 3, appearing in white 30-point font at the center of the screen, served as “lead-in” stimuli. The tones used as auditory feedback were presented through Sennheiser HD 270 headphones in a marimba timbre at a comfortable loudness level. Three different tone pitches were used: high = 440 Hz, medium = 392 Hz, and low = 349 Hz. Tones had sharp onsets and decayed rapidly. Stimulus presentation and response registration were controlled by Experimental Run Time System (ERTS) software and tones were generated by a SoundBlaster ISA soundcard on a DOS computer.

An Optotrak Certus motion capture system recorded participants’ finger movements at a sampling rate of 250 Hz. The Optotrak camera tracked the motion of an infrared-light emitting diode (“marker”) attached to participants’ fingers relative to four reference markers on the response box. Information about the position of each marker in 3-D space was sent to a PC via an Optotrak System Control Unit (SCU). Motion data and events in ERTS were synchronized offline based on digital triggers that issued from the parallel port of the DOS computer to the SCU via an Optotrak Data Acquisition Unit II.

Procedure and Design

Participants were tested individually while seated in a quiet room. They received both written and oral instructions, and were

allowed time to memorize the stimulus–response sequence mappings before commencing the task. A marker was attached to the participant’s right index finger at the midpoint of the left portion of the fingernail.

The experimental session consisted of one block of 16 practice trials (without auditory feedback) and six blocks of 44 test trials. At the start of each trial, a white fixation cross appeared at the center of the computer screen. When the participant was ready, he or she rested the right index finger on the middle response key. Immediately, one of the four imperative stimulus color patches appeared in place of the fixation cross and flashed three times with a 600 ms IOI (including 200 ms of color plus 400 ms of blank screen). Then the numbers 1, 2, and 3 appeared in succession at the same tempo (200 ms on, 400 ms off). A medium pitched tone was presented simultaneously with the appearance of each number. Thus, a pacing signal composed of three visual stimuli followed by three auditory-visual “lead-in” events was presented.

The participant was required to respond to the pacing signal by tapping the three response keys in one of four prescribed orders, depending on the color of the imperative stimulus, at the tempo set by the pacing signal. Perfect performance would entail tapping with a 600 ms IOI, starting 600 ms after the onset of the final event in the pacing signal. The correct tap sequences for each color were as follows: *pink* = top → middle → bottom; *yellow* = bottom → middle → top; *green* = top → bottom → middle; and, *blue* = bottom → top → middle. The trial ended 500 ms after the third tap was registered by the computer. If a tap was made out of order, a visual error message was presented for 500 ms. A blank screen intervened for 500 ms between trials. Pacing signals with pink, yellow, green, and blue imperative stimuli appeared twice each (in random order) across the first eight trials, and nine times each (in random order) across the remaining 36 trials, within each test block. The first eight trials gave the participant the opportunity to adapt to the current auditory feedback condition (data from these trials were not analyzed).

Auditory feedback was manipulated to yield three conditions in a repeated measures design. In trials from the compatible feedback condition, a tap on the top key triggered the presentation of the high-pitched tone, a tap on the middle key triggered the medium-pitched tone, and a tap on the bottom key triggered the low tone. In the incompatible condition, taps on the top, middle, and bottom key triggered low, medium, and high tones, respectively. Taps did not trigger tones in the silent condition. Trials from each feedback condition were presented in separate blocks. Each condition appeared once across the first three blocks of test trials, with presentation order fully counterbalanced across participants. The three conditions were presented again across the final three test blocks in the same order.

Dependent Measures

Timing accuracy in each of the three feedback conditions was assessed by examining produced IOIs at each of the three tap positions within the response sequences. In addition, 3-D position data were collected from the finger marker starting at the first frame after the finger lost contact with one key and ending at the frame before it made contact with the next (target) key. Information about movement amplitude and acceleration just prior to

arrival at the target key was extracted from these position data after they had been smoothed using Functional Data Analysis techniques (Ramsay & Silverman, 2005).¹

Results

Data from 2.57% of trials were not analyzed because keys were tapped in the incorrect order and/or produced IOIs were longer than 800 ms. Timing, movement amplitude, and acceleration measures were averaged across the remaining trials for each combination of feedback condition and tap number separately for each participant. Averaged data for the three taps from responses in the three feedback conditions are shown for each dependent measure in Figure 1.

Timing

Produced IOIs were on average shorter than the 600-ms target, indicating a general tendency to respond at a tempo that was slightly faster than the pacing signal (cf. Flach, 2005). A 3×3 repeated measures omnibus analysis of variance (ANOVA) with variables feedback condition (compatible, incompatible, silent) and tap number (1, 2, 3) revealed a significant main effect of feedback condition on produced IOIs, $F(2, 58) = 13.76, p < .001$.² As can be seen in Figure 1, IOIs were generally shorter when auditory feedback was present than when it was absent. The reliability of this result was confirmed by a simple contrast, $F(1, 29) = 15.64, p < .001$. Furthermore, when auditory feedback was present, IOIs were reliably shorter in the incompatible than in the compatible condition, as confirmed by a second, orthogonal contrast, $F(1, 29) = 6.01, p < .05$. These simple effects remained significant when only data from the first tap were considered ($ps < .05$). The main effect of tap number and the interaction between feedback condition and tap number were not significant in the omnibus ANOVA ($ps > .20$).

Movement Amplitude

Movement amplitude refers to the maximum height, relative to initial position, attained in the vertical dimension during the finger’s journey from one key to the next. The omnibus ANOVA on movement amplitude data detected a statistically significant main effect of feedback condition, $F(2, 58) = 4.96, p = .01$. Movement amplitudes were smaller when auditory feedback was present than when it was absent, $F(1, 29) = 7.54, p = .01$ (this effect was significant for the first tap, $p < .001$), while there were no reliable differences in movement amplitude for compatible versus incompatible feedback, $F(1, 29) = .56, p = .46$. An additional analysis was run to check whether compatible and incompatible feedback produced differential effects on upward and downward movements, but no evidence

¹ Position trajectories were smoothed taking order-6 splines as basis functions and with a smoothing parameter (lambda) equal to -19 , which smoothes the acceleration (second derivative) curves. This parameter value yielded fits which fell within the generalized cross-validation score that estimates the optimal threshold by minimizing the expected mean square error between raw and fitted data (see Ramsay & Silverman, 2005).

² The Greenhouse-Geisser correction was applied here and hereafter.

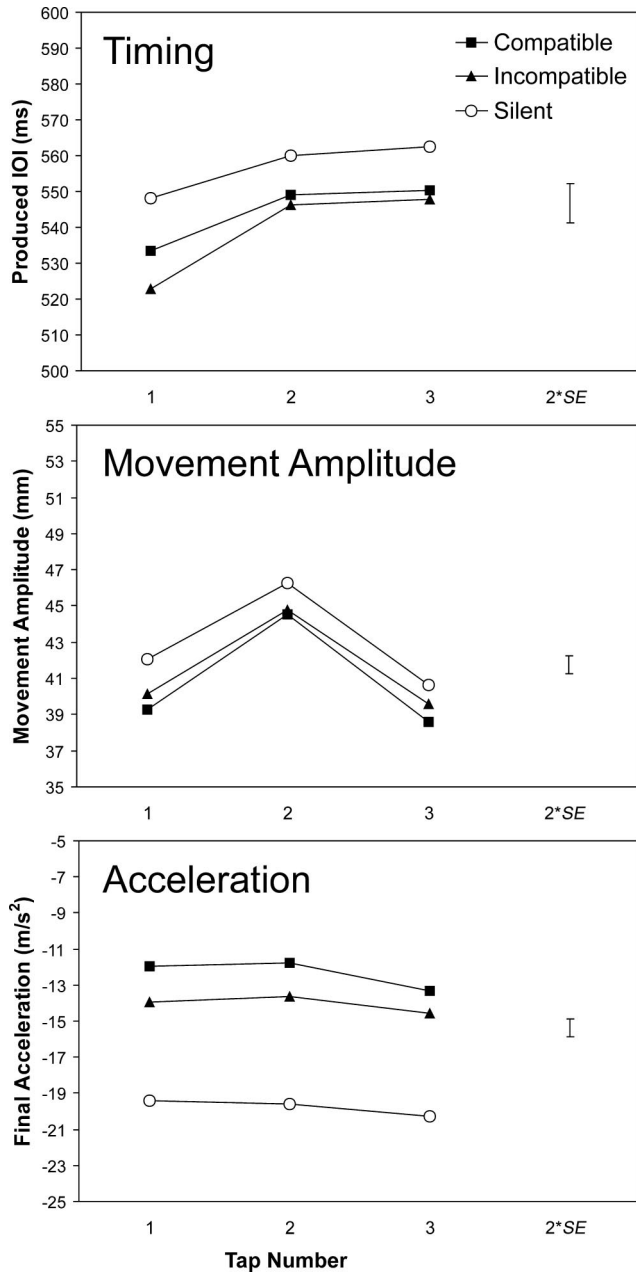


Figure 1. Average timing data (produced IOIs; top panel, in ms), movement amplitude (middle panel, in mm), and acceleration during the final 5% of each trajectory (bottom panel, in m/s^2) for the three taps in each feedback condition (compatible; incompatible; silent). The error bar on the right—labeled $2 * SE$ —represents double the standard error of the mean. The standard error was computed in the manner suggested by Masson and Loftus (2003) for repeated-measures designs.

for the predicted contrast effects was found. The omnibus ANOVA also revealed a significant main effect of tap number, $F(2, 58) = 80.05, p < .001$, reflecting the fact that movement amplitude was larger for tap 2 (which necessitated a leap over the middle key in green and blue response sequences) than for taps 1 and 3. The interaction between tap number and feedback condition fell short of significance, $F(4, 116) = 2.39, p = .08$.

Acceleration

Mean acceleration was computed for the final 5% of each movement trajectory. This measure of “final acceleration” is informative about net force just prior to the finger’s impact with the target response key. Final acceleration was generally negative, indicating that the finger increased in speed as it moved downward toward the target key. An omnibus ANOVA revealed a significant main effect of feedback condition, $F(2, 58) = 38.46, p < .001$. Final acceleration was greater (i.e., more negative) when feedback was absent than when it was present, $F(1, 29) = 46.95, p < .001$, and when feedback was incompatible than when it was compatible, $F(1, 29) = 10.45, p < .01$. Thus, movements were generally characterized by less acceleration—hence, less net force—when feedback was present, especially when it was compatible. These effects were present at the first tap ($ps \leq .001$). The omnibus ANOVA also detected a significant effect of tap number, $F(2, 58) = 8.51, p < .01$, indicating that final acceleration was greater for tap 3 than for taps 1 and 2 (as if participants were accenting the last beat in a musical phrase). The interaction between tap number and feedback condition was not significant, $F(4, 116) = 1.19, p = .31$.

Discussion

The effects of anticipatory auditory imagery on movement timing and kinematics were investigated by requiring musicians to produce short sequences of taps on vertically aligned keys at a tempo set by “lead-in” pacing signals. It was found that movement timing and kinematics were affected by whether taps triggered tones, and, when this was the case, whether the resultant melodic contours were compatible or incompatible with movement transitions on the height dimension. Specifically, timing was more accurate (produced IOIs were closer to the target IOI), movement amplitudes were larger, and acceleration towards the target key was greater in the silent condition than in conditions where taps triggered tones. Furthermore, higher timing accuracy and less acceleration towards the target key—but no evidence for differences in movement amplitude—were found for compatible versus incompatible key-to-tone mappings. The above effects can be attributed to anticipatory auditory imagery because they were observed for the first tap within sequences (i.e., before the onset of the first tone in conditions with auditory feedback) and they were not modulated by auditory feedback on subsequent taps.

The finding that produced IOIs were shorter when auditory feedback was present than when it was absent (although IOIs generally undershot the target in all conditions) may be an indirect consequence of differences in force control. The relatively low acceleration observed during the arrival phase of movements in conditions where taps triggered tones suggests that the availability of auditory feedback decreased tap force. This result supports the hypothesis that (anticipated) auditory feedback reduces reliance upon tactile feedback, as less force at impact generates less tactile information. Such differences in force control may have affected timing through their influence upon movement amplitude. The relatively small movement amplitude in conditions with auditory feedback (and low force) is consistent with findings that amplitude scales with force in manual production tasks (e.g., Billon, Semjen, Cole, & Gauthier, 1996; Dahl, 2004; Dalla Bella & Palmer, 2004).

Reductions in movement amplitude lead to decreases in total distance travelled, and may affect movement duration, since traversing shorter distances requires less time (all other things being equal). Thus, factors relating to force control may have shortened produced IOs in conditions with auditory feedback. It may be the case that anticipatory auditory imagery, while not necessarily facilitating timing accuracy, generally enhances biomechanical economy by encouraging less forceful, smaller amplitude movements.

Consistent with Keller and Koch's (2006b) findings, timing was less accurate in the incompatible than in the compatible condition. However, the analysis of movement amplitude failed to find evidence for the hypothesized warping of movement trajectories. This suggests that auditory imagery does not have analogous effects on spatial kinematics to those found for visual perception (see Welsh & Elliott, 2004). Temporal kinematics, however, were affected by key-to-tone compatibility. Acceleration towards the target key, and hence force at impact, was lower in the compatible than in the incompatible condition. This finding supports the hypothesis that compatible auditory information is weighted relatively strongly during the integration of sensory feedback from different sources, thus reducing the reliance upon tactile feedback for timing control. The effects of such weighting seem to encourage greatest biomechanical economy when movements and melodies are compatible.

Taken together, the findings of the current study suggest that anticipatory auditory imagery plays a role in force control when producing temporally regular auditory sequences. Less forceful movements are programmed when the actor anticipates upcoming tones—especially when the melodic contour traced by these tones is compatible with movement transitions—than when silence is anticipated. We propose that the anticipation of auditory feedback leads to tactile feedback being weighted less strongly in multimodal sensory representations that guide movement timing and kinematics. An important aspect of this claim is that the “sensory” information that is integrated in these representations comprises *anticipated* feedback from future events (cf. Wolpert, Miall, & Kawato, 1998), in addition to actual feedback from past events. Thus, the same ideomotor mechanism that mediates cross-modal response priming in speeded tasks (e.g., Keller & Koch, 2008) influences movement dynamics when temporal precision is required. This mechanism may assist in (1) selecting which movements should be made (e.g., which keys of a musical instrument to act upon), and (2) planning how these movements should be executed in order to produce the intended distal effects (ideal sounds) in a biomechanically economical manner. In sum, cross-modal ideomotor processes may function dually to facilitate planning efficiency and biomechanical economy in voluntary action.

References

- Aschersleben, G., Gehrke, J., & Prinz, W. (2004). A psychophysical approach to action timing. In C. Kaernbach, E. Schröger & H. Müller, (Eds.), *Psychophysics beyond sensation: Laws and invariants of human cognition* (pp. 117–136). Hillsdale, NJ: Erlbaum.
- Atkeson, C. G., & Hollerbach, J. M. (1985). Kinematic features of unrestrained vertical arm movements. *Journal of Neuroscience*, *5*, 2318–2330.
- Bangert, M., Peschel, T., Rotte, M., Drescher, D., Hinrichs, H., Schlaug, G., et al. (2006). Shared networks for auditory and motor processing in professional pianists: Evidence from fMRI conjunction. *NeuroImage*, *15*, 917–926.
- Billon, M., Semjen, A., Cole, J., & Gauthier, G. (1996). The role of sensory information in the production of periodic finger tapping sequences. *Experimental Brain Research*, *110*, 117–130.
- Dahl, S. (2004). Playing the accent—comparing striking velocity and timing in an ostinato rhythm performed by four drummers. *Acta Acustica/Acustica*, *4*, 762–776.
- Dalla Bella, S., & Palmer, C. (2004). Tempo and dynamics in piano performance: The role of movement amplitude. In S. D. Lipscomb, R. Ashley, R. O. Gjerdingen, & P. Webster (Eds.), *Proceedings of the 8th International Conference on Music Perception and Cognition* (pp. 256–257). Adelaide, Australia: Causal Productions.
- Ernst, M. O., & Bühlhoff, H. H. (2004). Merging the senses into a robust percept. *Trends in Cognitive Sciences*, *8*, 162–169.
- Flach, R. (2005). The transition from synchronization to continuation tapping. *Human Movement Science*, *24*, 465–483.
- Goebel, W., & Palmer, C. (2008). Tactile feedback and timing accuracy in piano performance. *Experimental Brain Research*, *186*, 471–479.
- Grosjean, M., Zwicker, J., & Prinz, W. (2009). Acting while perceiving: Assimilation precedes contrast. *Psychological Research*, *73*, 3–13.
- Halpern, A. R. (2003). Cerebral substrates of musical imagery. In I. Peretz & R. J. Zatorre (Eds.), *The cognitive neuroscience of music*. Oxford: Oxford University Press.
- Hoffmann, J., Stöcker, C., & Kunde, W. (2004). Anticipatory control of actions. *International Journal of Sport and Exercise Psychology*, *2*, 346–361.
- James, W. (1890). *Principles of psychology*. New York: Holt.
- Janata, P., & Paroo, K. (2006). Acuity of auditory images in pitch and time. *Perception & Psychophysics*, *68*, 829–844.
- Keller, P. E., & Koch, I. (2006a). Exogenous and endogenous response priming with auditory stimuli. *Advances in Cognitive Psychology*, *2*, 269–276.
- Keller, P. E., & Koch, I. (2006b). The planning and execution of short auditory sequences. *Psychonomic Bulletin and Review*, *13*, 711–716.
- Keller, P. E., & Koch, I. (2008). Action planning in sequential skills: Relations to music performance. *Quarterly Journal of Experimental Psychology*, *61*, 275–291.
- Koch, I., Keller, P. E., & Prinz, W. (2004). The ideomotor approach to action control: Implications for skilled performance. *International Journal of Sport and Exercise Psychology*, *2*, 362–375.
- Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *Quarterly Journal of Experimental Psychology*, *57A*, 87–106.
- Masson, M. E. J., & Loftus, G. R. (2003). Using confidence intervals for graphically based data interpretation. *Canadian Journal of Experimental Psychology*, *57*, 203–220.
- Pfordresher, P. Q. (2008). Auditory feedback in music performance: The role of transition-based similarity. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 708–725.
- Prinz, W., Aschersleben, G., & Koch, I. (2009). Cognition and action. In E. Morsella, J. A. Bargh, & P. M. Gollwitzer (Eds.), *Mechanisms of human action* (Oxford handbook of human action, Vol. 2, pp. 35–71). Oxford: Oxford University Press.
- Ramsay, J., & Silverman, B. (2005). *Functional data analysis*. New York: Springer.
- Rusconi, E., Kwan, B., Giordano, B. L., Umiltà, C., & Butterworth, B. (2006). Spatial representation of pitch height: The SMARC effect. *Cognition*, *99*, 113–129.
- Trusheim, W. H. (1993). Audiation and mental imagery: Implications for artistic performance. *The Quarterly Journal of Music Teaching and Learning*, *2*, 139–147.
- Viviani, P., & Flash, T. (1995). Minimum-jerk, two-thirds power law, and

- isochrony: Converging approaches to movement planning. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 32–53.
- Welsh, T. N., & Elliott, D. (2004). Movement trajectories in the presence of a distracting stimulus: Evidence for a response activation model of selective reaching. *The Quarterly Journal of Experimental Psychology*, 57A, 1031–1057.
- Wolpert, D. M., Miall, R. C., & Kawato, M. (1998). Internal models in the cerebellum. *Trends in Cognitive Sciences*, 2, 338–347.

Received January 9, 2009

Revision received April 27, 2009

Accepted August 6, 2009 ■