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Anticipatory auditory images and temporal precision in music-like performance

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ABSTRACT
Speeded reaction time tasks in which the compatibility between brief manual response sequences and their auditory effects is manipulated have demonstrated that musicians may use auditory imagery to anticipate upcoming sounds during action planning. Specifically, action planning (indexed by reaction times to 'go' signals), but not action execution (indexed by movement duration), is typically faster when responses and their effects are compatible than when they are incompatible (e.g., in terms of spatial height and pitch height). We tested whether response-effect compatibility affects the execution of music-like sequential actions that require temporal regularity rather than rapidity. Musicians responded to metronomic visual stimuli by producing sequences of three taps at a specific tempo on three vertically-aligned keys. Each tap triggered a tone. Key-to-tone mapping was either compatible or incompatible in terms of spatial height and pitch height. The results indicate that tap timing was more accurate with compatible than with incompatible mappings both for taps produced before (tap 1) and after (taps 2 and 3) the onset of auditory feedback. Thus, the observed influence of response-effect compatibility on action execution was not due exclusively to actual auditory feedback. This provides evidence that anticipatory auditory images of forthcoming sounds may affect the dynamics of temporally precise movements.

Keywords
Music performance; Auditory imagery; Action-effect anticipation.

INTRODUCTION
Music performance can be considered, rather abstractly, to be a form of voluntary action in which prelearnt sequences of movements are carried out on an instrument in order to produce desired auditory effects, such as a melody. The current study addresses issues related to the planning and execution of such voluntary actions. We are specifically concerned with the role of representations of the movements' intended auditory effects in the cognitive plans that guide musical actions. These action-effect representations are viewed here as auditory images generated in anticipation of actual auditory feedback. Do such images automatically guide performance even in simple music-like contexts where it should be sufficient, even preferable, to focus on representations of the movements by engaging in pure motor imagery?

A theoretical backdrop to this issue is provided by the ideo-motor principle, which states that actions are triggered automatically by the anticipation of their effects (e.g., Greenwald, 1970; James, 1890; Prinz, 1987). In the case of a vocal music performance, for example, the singer needs to think "only of the perfect sound" in order to produce it (James, 1890, p. 774). Concepts related to the ideo-motor principle are pervasive in texts that document conventional wisdom among musicians (e.g., Green & Gallwey, 1986), reflecting the fact that expert musicians believe that auditory imagery plays an important role in music performance (see Trusheim, 1993). Nevertheless, the relationship between music performance and the ideo-motor principle is more often the subject of anecdotal examples than rigorous scientific study. Relevant concerns are addressed, however, in approaches to voluntary action in general.

Issues pertaining to the planning and execution of voluntary action are often studied in the laboratory with speeded reaction time (RT) tasks in which participants respond to stimuli by making pre-specified movements as quickly as possible. Research employing the speeded RT paradigm has revealed that action planning involves the anticipation of action-effects: RTs are typically faster when movements are compatible with ensuing action-effects than when movements and their effects are incompatible. For example, Kunde (2001; Kunde, Koch, & Hoffmann, 2004) has demonstrated that soft key presses are initiated more rapidly when they trigger quiet tones than when they trigger loud tones, whereas the reverse is true for forceful key presses. Thus, movement initiation times can be affected by auditory effects that are not yet physically present, which supports the ideo-motor hypothesis that the desired action-effects are imagined during action planning (Greenwald, 1970; Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1890; Prinz, 1987). Similar response-effect compatibility (REC) effects have been observed for various types of discrete actions, as well as for action sequences (for reviews see Hoffmann, Stoecker, & Kunde, 2004, and Koch, Keller, & Prinz, 2004).

The present study is concerned with the production of action sequences with music-like auditory effects. In a recent speeded RT study of auditory sequence planning, Keller and Koch (2004) required participants to respond to each of four arbitrary (colour-patch) stimuli by producing a unique sequence of three taps on three vertically-aligned keys. Action-effects consisted of tones that were triggered by the taps.

In a series of experiments, Keller and Koch (2004) varied the compatibility of the mapping between response location (key) and effect (tone) pitch between blocks. In a compatible condition, taps on the top, middle, and bottom keys triggered high, medium, and low pitched tones, respectively. Across several incompatible conditions, this key-to-tone mapping was reversed or scrambled (but fixed), or taps on different keys triggered the same tone (see Figure 1). This compatibility manipulation is based on the assumption that there is a 'natural' (pre-existing, instrument independent) cross-modal correspondence between pitch height and spatial height (see Mudd, 1963). Keller and Koch (2004) found that action planning was most efficient (i.e., RTs were fastest) for compatible key-to-tone mappings even though participants had been instructed that the tones were irrelevant to the task. This pitch-height REC effect was observed most strongly for participants with formal music training, suggesting that musical experience enhances the role of auditory imagery in action planning.

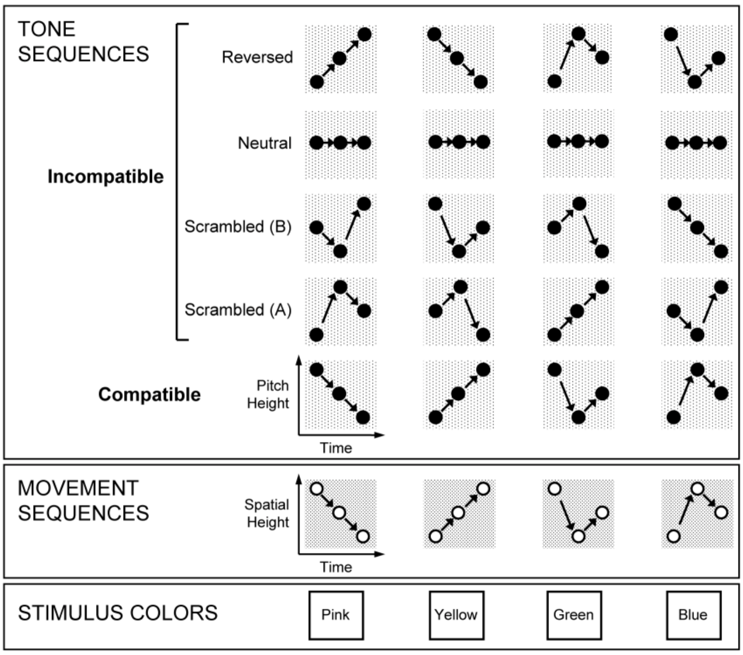

Figure 1: Stimulus-response (color-movement sequence) and response-effect (movement-tone sequence) mappings. Unfilled circles indicate finger taps on three response keys: top, middle, and bottom. Filled circles indicate tones of high, medium, or low pitch. Each stimulus color is paired with one movement sequence. Each movement sequence is paired with several tone sequences to yield REC conditions in which movement and pitch trajectories are either compatible or incompatible

(two types of scrambled mapping, a neutral mapping, and a reversed mapping).

In general, REC effects on planning in speeded RT tasks can be explained by the mutual priming of 'codes' representing a future action's proximal (proprioceptive, tactile) and distal (auditory) effects (Kunde et al., 2004). On this account, the code activation threshold at which an associated motor program is triggered is reached sooner when distal and proximal effects share similar features (e.g., an ascending key press sequence producing an ascending melodic contour) than when they are dissimilar. To account for the observed influence of musical experience on the magnitude of the REC effect, Keller and Koch (2004) argued that the improvement in auditory imagery ability that accompanies musical training (Aleman, Nieuwenstein, Boecker, & de Haan, 2000; Halpern, 2003) facilitates the activation of anticipatory auditory-effect representations, thereby heightening the degree to which these representations prime appropriate motor responses. This implies that the degree to which auditory imagery plays a role in music performance may depend on level of musical expertise.

In contrast to action planning, action execution – specifically, the speed and manner in which movements are carried out once initiated – is usually not susceptible to REC effects in speeded RT tasks. This may be because rapid movements are fully pre-planned, and then controlled in an open-loop fashion (see Schmidt & Lee, 1999). Accordingly, peak force was not affected by the compatibility between tone loudness and required force in the study by Kunde et al. (2004), and the duration of inter-tap intervals was not influenced by the various key-to-tone mappings in the study by Keller and Koch (2004). The latter finding squares with Lashley's (1951) assertion—backed up by an example citing the extreme speed with which pianists move their fingers during performance—that sensory feedback does not play a crucial role in the execution of rapid, well-learnt sequential movements.

The absence of REC effects on speeded action execution suggests that the role of imagery is somewhat transient in the case of brief isolated movements. Thus, images are called upon during pre-planning, but then abandoned once movement is initiated. This state of affairs is presumably useful in the context of extended sequential actions, such as those that characterize music performance, because it allows movements from an early part of a sequence to be executed while future movements are being planned (cf. Sternberg, Monsell, Knoll, & Wright, 1978).

The aim of the current study is to test whether the conclusions of the speeded RT tasks described above generalize to a music-like task that requires short auditory sequences to be produced at a specific tempo – as is typical in music performance – rather than as quickly as possible. Two questions were of primary interest.

The first concerns whether REC effects occur before the onset of actual auditory feedback under non-speeded conditions. A positive answer to this question would suggest that anticipatory auditory images affect the dynamics of action execution (perhaps in addition to affecting planning speed) when a precise temporal goal must be met. Obviously such goals are paramount in music performance.

The second question of interest concerns whether REC effects on action execution are still absent when movements are non-speeded. The requirement to be regular rather than rapid may elicit REC effects on movement execution because non-speeded sequential movements are not necessarily fully pre-planned, and/or because sensory feedback plays a role in motor control when temporal precision is required. With regard to concurrent planning and execution, it has been argued that planning and online control are distinct but temporally overlapping stages of action (Glover, 2004; Jeannerod, 1988; Rosenbaum, 1991; Wolpert & Ghahramani, 2000). Regarding the role of sensory feedback, it has been demonstrated that the addition of auditory or visual feedback can improve performance on motor tasks that require precise temporal control (Aschersleben & Prinz, 1995; Mechsner, Kerzel, Knoblich, & Prinz, 2001), and, conversely, skilled performance can be disrupted by eliminating or altering the sensory feedback that a performer is accustomed to (e.g., Pfordresher, 2003; Proteau, Marteniuk, & Lévesque, 1992).

To address the above questions, the requirements of the task employed by Keller and Koch (2004) were changed so that now participants were instructed to respond to isochronously flashing visual stimuli by making sequences of three taps at a rate that continued the tempo set by the stimuli. Similar to the situation in the Keller and Koch (2004) task, each tap triggered a tone, and REC was manipulated to be either compatible or incompatible (reversed or scrambled) in terms of the relationship between the spatial height of the response keys and the pitch height of the tones.

If REC affects the production of sequential actions that require temporal precision rather than rapidity, then tap timing should be more accurate (i.e., close to the target tempo) with the compatible key-to-tone mapping than with the incompatible mappings. Finding that REC affects timing accuracy for the first tap of each sequence would provide evidence for action-effect anticipation—auditory imagery, specifically—because auditory feedback is not presented until the finger makes contact with the response key. The finger's journey to contact the key for the first tap is made in silence. Effects of REC on timing accuracy for the second and third taps would be attributable to the influence of actual auditory feedback on online motor control and/or to a persisting influence of anticipatory auditory images.

In a somewhat exploratory fashion, we attempted to investigate the relationship between the effects of anticipatory auditory images and actual auditory feedback by examining the strength of the correlation between timing accuracy on taps 1 and 2 versus taps 2 and 3. If the effects of actual auditory feedback are to some degree independent of the effects of anticipatory auditory images, then timing accuracy should be more strongly correlated at taps 2 and 3 (both are made after the onset of auditory feedback) than at taps 1 and 2 (only the latter is made after the onset of auditory feedback).

METHOD

Participants

Eighteen musicians participated in the experiment (age range = 18-32 years). The musicians had an average of 10 years experience (range = 5-16 years) performing on a variety of instruments.

Apparatus and Stimuli

A response box with three vertically-aligned metal plates, functioning as response keys, was positioned in front of a computer screen at a comfortable height for tapping. The response box itself was 250 mm high and 150 mm wide. The metal plates embedded within its surface measured 30 x 30 mm and were separated by a vertical distance of 15 mm. The box was angled so that its surface was off-vertical by 30 degrees. Visual stimuli consisted of four patches of colour (16 x 16 mm, viewed from a distance of approximately 750 mm) presented in the centre of the black computer screen: pink, blue, yellow, or green. A white color patch with similar dimensions and presentation location served as a neutral stimulus (see Design and Procedure).

The tones used as response effects were presented through PRO-10 earphones in a marimba timbre at a comfortable loudness level (about 60 dBA). Three different tone pitches were used: low = F4 (349 Hz), medium = G4 (392 Hz), and high = A4 (440 Hz).

Design and Procedure

We employed a single-factor repeated measures design, in which REC was manipulated by varying the relationship between response key location and feedback tone pitch to form three conditions: compatible, incompatible-reversed, incompatible-scrambled.

Participants were tested individually, and each received both written and oral instructions before beginning the task. The experiment consisted of 13 (1 practice plus 12 test) blocks of 20 trials, and typically took 30-40 minutes to complete (plus approximately 15 minutes of instruction time, during which the participants memorized the stimulus-response sequence mappings). At the start of each trial, a fixation cross appeared at the centre of the computer screen. When the participant was ready, he or she depressed the spacebar on the computer keyboard, which immediately triggered the following sequence of events. First, one of the four imperative stimulus color patches appeared in place of the fixation cross and flashed three times with a 600 ms inter-onset interval (IOI; including 200 ms of color patch plus 400 ms of blank screen). Then the neutral (white square) stimulus flashed three times in the same manner as the imperative stimulus (200 ms on, 400 ms off). Thus, a six-element visual pacing signal composed of five IOIs of 600 ms was presented (see Figure 2).

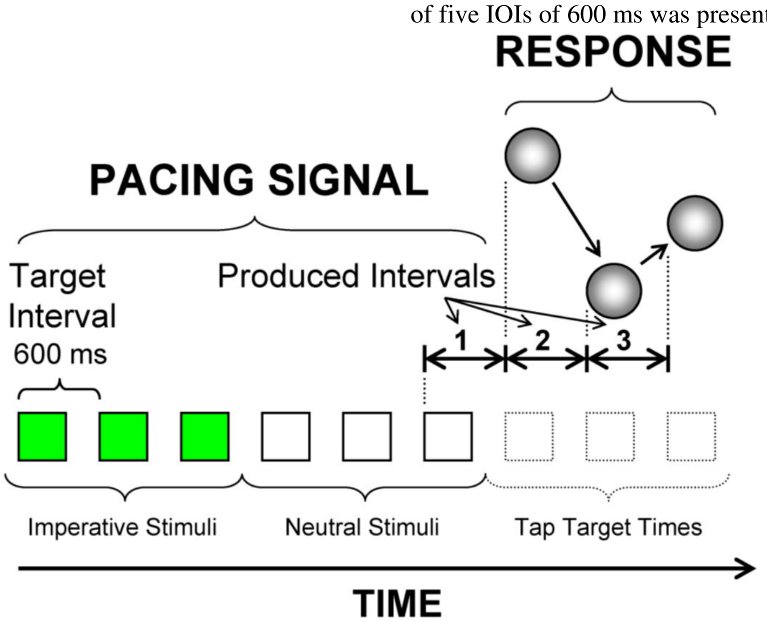

Figure 2: An example of the experimental procedure in a single trial. A visual pacing signal with 600 ms inter-onset intervals was presented, wherein three flashes of a colored imperative stimulus (green, yellow, pink, or blue) were followed by three flashes of a neutral (white) stimulus. Participants responded to the pacing signal by making three consecutive finger taps on three vertically aligned response keys at a rate that continued the tempo set by the signal. The response keys were tapped in

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four different orders, with each order being associated with a different colored imperative stimulus. Each tap triggered a tone, and key-to-tone mapping was manipulated between blocks to be either compatible or incompatible in terms of spatial height and pitch height.

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 neutral stimulus in the pacing signal (see Figure 2). For the pink stimulus, the correct tap sequence was top -> middle -> bottom; for yellow the correct order was bottom -> middle -> top; for green it was top -> bottom -> middle; and for blue it was bottom -> top -> middle. The trial ended 500 ms after the third tap was registered by the computer.

Throughout the 12 test blocks, each tap on a key triggered the presentation of a tone of high, medium, or low pitch. Three different types of key-to-tone mapping were employed in the test blocks, yielding one compatible and two incompatible (reversed and scrambled) REC conditions. In the compatible 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-reversed condition, taps on the top, middle, and bottom key triggered low, medium, and high tones, respectively. In the incompatible-scrambled condition, taps on the top, middle, and bottom keys were associated with medium, low, and high tones, respectively. (We included two types of incompatible mapping to test whether people are sensitive to different degrees of incompatibility. Keller & Koch [2004] discuss this issue in more detail.) Conditions (key-to-tone mapping) changed every four test blocks but remained fixed within each group of four blocks. The order in which conditions were run was fully counterbalanced across participants. Instructions emphasized that participants should focus on tapping as regularly as possible in all conditions and that the changes in key-to-tone mapping were irrelevant to the task.

RESULTS

Timing accuracy in each of the three REC conditions was assessed by examining mean produced IOIs and average absolute IOI error (i.e., the absolute value of the difference between produced IOIs and target IOIs) at each of the three tap positions within the response sequences. Absolute IOI error is potentially most informative because it reflects deviations from target tempo. Trials in which the keys were tapped in the incorrect order (3% of trials) and trials in which any of the produced IOIs were longer than 900 ms (a further 7% of trials) were not analysed. Remaining data from all but the first block in each REC condition were subjected to analyses of variance (ANOVAs) with the criterion for statistical significance set at $\alpha = .05$, and the Greenhouse-Geisser correction applied.

A 3 x 3 ANOVA with factors REC (compatible, reversed, scrambled) and tap number (1, 2, 3) on mean IOIs revealed that only the main effect of tap number was statistically significant, $F(2, 34) = 20.64$, $p < .001$. The first IOI (693 ms) was longer than the second and third IOIs (485 ms and 478 ms, respectively). The REC main effect and the REC by tap number interaction were not significant, *p*s > .1. The significant main effect of tap number on mean IOIs may reflect a start up cost (lengthening of the first IOI) associated with beginning to tap after the cessation of the pacing sequence, followed by an overly zealous attempt to compensate for this start up cost by shortening the IOIs on subsequent taps.

Figure 3 shows average absolute IOI error across the three tap positions in each REC condition. Here it can be seen that absolute IOI error was generally smaller in the compatible condition than in the incompatible conditions. This was confirmed by a significant main effect of REC in a 3 (REC) x 3 (tap number) ANOVA on these data, $F(2, 34) = 9.89$, $p < .001$. Pairwise comparisons revealed that the increase in absolute IOI error from compatible to scrambled conditions was significant, $F(1, 17) = 9.16$, $p < .01$, but the increase from scrambled to reversed was not reliable, $p > .1$. The tap number main effect and the REC by tap number interaction were both far from significance, *p*s > .7. Thus, the advantage enjoyed in the compatible condition was present across the three taps within the response sequences. Indeed, separate single-factor ANOVAs conducted on absolute IOI errors at each tap number all yielded a significant effect of REC, *p*s < .05.

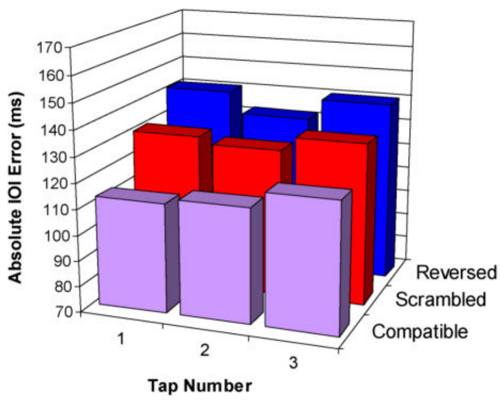

Figure 3: Average absolute IOI error (produced IOI minus target IOI) across the three sequential taps for each REC condition.

Finally, a correlation analysis was conducted to explore the relationship between the effects of REC before and after the onset of auditory feedback. The degree of correlation between absolute IOI errors at tap positions 1 and 2, and at tap positions 2 and 3, was estimated across trials within each of the three REC conditions separately for each participant. The resulting Pearson correlation coefficients were then converted to Fisher z' scores before being entered into a 3 x 2 ANOVA with factors REC condition and tap pair (1,2 vs. 2,3). This analysis revealed that correlations between taps 2 and 3 (M $r = .48$) are reliably stronger than correlations between taps 1 and 2 (M $r = .08$), $F(1, 17) = 23.77$, $p < .001$ (the main effect of REC and the REC x tap pair interaction were not significant, *p*s > .4).

DISCUSSION

The current study investigated the execution of movement sequences with music-like auditory effects under conditions that required the sequences to be produced at a specific tempo rather than as quickly as possible. The results indicate that timing accuracy was better – i.e., produced IOIs were closer to their target – when the mapping between response key location and effect tone pitch was compatible in terms of 'height', than when it was incompatible in this regard (irrespective of the type of incompatibility: reversed or scrambled). This influence of REC on timing accuracy was observed across the three taps within sequences.

The presence of an REC effect on the first tap – which was made *before* the appearance of auditory feedback – is consistent with the results of work using speeded RT tasks showing that voluntary action is mediated by a mechanism that brings action-effects to mind before they actually appear (see Hoffmann et al., 2004; Koch et al., 2004). We assume that this mechanism is characterized best as anticipatory auditory imagery in the context of our task. The current finding extends the results of previous research by demonstrating that anticipatory auditory images do not only play a role in the rapid selection and initiation of speeded choice responses (e.g., Keller & Koch, 2004), but also may play a role in controlling the timing of movement so as to meet a precise temporal goal, i.e., to make a forthcoming action-effect occur 'on time'.

The presence of REC effects at the second and third taps may reflect a persisting influence of anticipatory images, the influence of actual auditory feedback from the preceding tap(s), or a combination of these factors. An exclusive influence of anticipatory images is argued against by the fact that our correlation analyses revealed little evidence that REC effects before and after the onset of auditory feedback were related to one another, even though they were similar in magnitude. Thus, anticipated auditory feedback and actual feedback may have affected movement timing differently. Although this finding seems to buttress claims that action planning and online control are distinct processes that rely on different types of information (see Glover, 2004), the results of our correlation analysis may be due at least in part to a common 'temporal compensation' process driving the second and third taps (which were rushed) that was not present in generating the first tap (which was typically late). In any case, the present results show that although REC has little effect on movement execution in speeded tasks (e.g., Keller & Koch, 2004), it can affect the execution of more music-like actions that unfold over longer timespans.

Overall, the results of the current study demonstrate that the execution of auditory sequences is influenced by the compatibility between movements and their auditory effects when emphasis is placed on temporal precision rather than swiftness. The finding that the effects of REC extended beyond response selection and initiation suggests that compatibility between proximal and distal action-effects does not only affect the speed with which response execution thresholds are reached. Such compatibility may also influence the dynamics of an unfolding action, perhaps by affecting the parameters that control movement trajectories (cf. Erlhagen & Schöner, 2002). Schubö, Aschersleben, and Prinz (2001) found that the trajectories of sinusoidal arm movements can be biased by the amplitude of simultaneously presented sinusoidally moving visual stimuli. Our finding that REC affected movement timing before the onset of auditory feedback implies that such biases may be introduced not only by the perception of distal stimuli during action execution, but also by imagining such stimuli during planning. It may be the case that the movement control parameters that specify trajectory curvature, amplitude, and velocity adopt values that are more conducive to temporal precision (see Balasubramaniam, Wing, & Darffertshofer, 2004) when anticipated proximal and distal action-effects are compatible than when they are incompatible. Thus, incompatible mappings may disrupt timing accuracy by warping movements away from their optimal trajectories.

To end, we feel the need to qualify our conclusion that temporal precision in music-like actions is influenced by the compatibility between movements and their forthcoming auditory effects. We do not claim that such specific REC effects are themselves of special relevance in music performance. Indeed, this claim would be difficult to defend in light of the pervasiveness of incompatible response-effect mappings in the design of musical instruments (e.g., valved brass instruments). Rather, we argue that the REC effects observed during the brief time window before actual auditory effects appeared generally suggest that musicians may engage in anticipatory auditory imagery while producing melodic sequences. Furthermore, the fact that the tones were ostensibly irrelevant to the instructed goal of producing regular movement sequences in our task suggests that anticipatory auditory images may be invoked automatically. Of course, numerous questions remain, including whether movement timing accuracy is better when one engages in anticipatory auditory imagery than when one does not (as would presumably be the case if responses are made on an unfamiliar silent instrument that has not previously been associated with sound). Further research along these lines may reveal an intimate relationship between auditory imagery and the motor control processes that underlie music performance.

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