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Action planning in sequential skills: Relations to music performance

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The hypothesis that planning music-like sequential actions involves anticipating their auditory effects was investigated in a series of experiments. Participants with varying levels of musical experience responded to each of four colour-patch stimuli by producing a unique sequence of three taps on three vertically aligned keys. Each tap triggered a tone in most experimental conditions. Response–effect (key-to-tone) mapping was either compatible—taps on the top, middle, and bottom keys triggered high, medium, and low pitched tones, respectively—or incompatible—key-to-tone mapping was scrambled, reversed, or neutral (taps on different keys triggered the same tone). The results suggest that action planning was faster with compatible than with incompatible mappings (and faster than with no tones). Furthermore, the size of this compatibility effect grew with increasing musical experience, which suggests that improvements in auditory imagery ability that typically accompany musical training may augment the role of anticipatory auditory-effect representations during planning.

Music performance typically involves carrying out prelearnt sequences of movements on an instrument to produce auditory effects, such as a melody. The current study addresses the role of representations of the movements' intended auditory effects in the cognitive plans that guide sequential actions. These action–effect representations are viewed here as auditory images generated in anticipation of actual auditory feedback. A theoretical basis for understanding the role of action–effect representations in action planning is provided by the *ideo-motor principle*, which states that actions are triggered by the anticipation of their effects (e.g., Greenwald, 1970; Harleß, 1861; James, 1890; Knuf, Aschersleben, & Prinz, 2001; Lotze, 1852; 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). Support for the ideo-motor principle has been

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found in studies of stimulus–response compatibility and response–effect compatibility.

Stimulus–response (S–R) compatibility refers to the degree to which features of a stimulus correspond to, or overlap with, features of its target response (e.g., Kornblum, Hasbroucq, & Osman, 1990). Typically, responses are faster with compatible than with incompatible S–R mappings (for reviews, see Hommel & Prinz, 1997, and Proctor & Reeve, 1990), suggesting that movements can be primed by the prior perception of stimuli whose features resemble the features of a target response and its effects in the environment (see Drost, Rieger, Braß, Gunter, & Prinz, 2005a, 2005b, for examples from the music domain). It has been claimed that such priming occurs automatically for arbitrary action–effect associations once they are learnt (e.g., Elsner & Hommel, 2001; Elsner et al., 2002; Hommel, Müsseler, Aschersleben, & Prinz, 2001).

While research on S–R compatibility has demonstrated that responses can be primed by *perceiving* stimuli that resemble forthcoming action-effects, work on response–effect (R–E) compatibility has shown that responses can also be primed by merely *imagining* upcoming action effects (e.g., Keller & Koch, 2006; Koch & Kunde, 2002; Kunde, 2001, 2003; Kunde, Koch, & Hoffmann, 2004; Stöcker, Sebald, & Hoffmann, 2003; for reviews, see Hoffmann, Stöcker, & Kunde, 2004, and Koch, Keller, & Prinz, 2004). The standard procedure in R–E compatibility paradigms entails responding to arbitrary imperative stimuli while the compatibility between these responses and their distal effects is manipulated (between experimental blocks). For example, Kunde (2001, Exp. 2) required participants to respond to each of two stimulus colours by pressing a key either forcefully or softly. In a compatible condition, a forceful key-press predictably triggered a loud tone, and a soft key-press triggered a quiet tone, as is the case when one plays the piano. These response(force)–effect(loudness) contingencies were reversed in an incompatible condition, and the two R–E compatibility conditions were presented in separate halves of the experimental sessions, with condition order counterbalanced across participants. Kunde (2001) found that key-presses were initiated faster in the compatible than in the incompatible condition. This finding demonstrates that action planning—that is, selecting which of several potential responses to execute—involves the anticipation of forthcoming action effects because the (predictable) tones were not yet present at the point when the responses were initiated.

Kunde et al. (2004) investigated the degree to which R–E compatibility effects are attributable to benefits associated with compatible mappings versus costs associated with incompatible mappings by adding to the Kunde (2001) design a "mixed" condition in which compatible and incompatible R–E mappings occurred unpredictably within blocks. When comparing performance in pure compatible and incompatible blocks with performance in the mixed blocks, Kunde et al. (2004) found that benefits (faster response initiation) arising with compatible R–E mappings were larger than costs (slower response initiation) associated with incompatible mappings. Stöcker et al. (2003) also found that R–E compatibility effects are attributable to benefits associated with compatible R–E mappings in a study that employed a control condition in which responses did not produce salient distal effects.

According to a model proposed by Kunde et al. (2004; also see Hoffmann et al., 2004), the influence of R–E compatibility on planning can be explained by the mutual priming of "codes" representing a future action's proximal (proprioceptive, tactile) and distal (auditory) effects. On this account, the code activation threshold at which an associated motor programme is triggered is reached sooner when distal and proximal effects share similar features (e.g., high finger pressure and high sound intensity) than when they are dissimilar (e.g., high finger pressure but low sound intensity). Thus, R–E compatibility effects derive from response priming that occurs when images of an imminent movement's distal effects are evoked. Because participants are typically instructed to ignore the distal action effects in R–E compatibility studies, it can be assumed that these images are evoked automatically by arbitrary imperative stimuli that become associated with predictable action effects (cf. Hommel et al., 2001).

In the current article, we report a series of experiments that used an R–E compatibility paradigm to investigate the role of auditory action–effect anticipation in the planning of short music-like action sequences. A primary question was whether the influence of auditory action–effect anticipation on planning varies as a function of musical experience (i.e., number of years playing a musical instrument). We assume that action–effect anticipation in musical contexts requires auditory imagery and that in most cases such imagery involves bringing specific musical pitches to mind. Furthermore, based on the findings of behavioural and brain imaging studies (Aleman, Nieuwenstein, Boecker, & de Haan, 2000; Halpern, 2003), we assume that the ability to engage in auditory imagery improves with musical training. These assumptions lead to the hypothesis that the degree to which action–effect anticipation plays a role in planning the production of musical sequences should increase with increasing musical experience. Thus, the benefits of compatible R–E mappings (see Kunde et al., 2004; Stöcker et al., 2003) may be larger in musically trained individuals than in untrained individuals.

The use of short sequences of actions also allowed us to examine the relationship between R–E compatibility effects on action planning and action execution. This was an important question because the results of previous studies using single key-press responses suggest that R–E compatibility effects might be confined to planning. For example, in the Kunde et al. (2004) study, R–E compatibility affected the time taken to reach peak force but not the intensity of peak force. However, recent studies designed to address sequential action execution (but not preplanning) have revealed that altering the feedback pitches produced during the performance of piano melodies at regular tempi can disrupt accuracy and timing regularity (Pfordresher, 2003, 2005). Thus, effects of R–E compatibility on action execution may emerge with sequential key-press responses through the involvement of serial chaining mechanisms (see Greenwald, 1970) and online planning and control processes that make use of actual auditory feedback (see Wolpert & Ghahramani, 2000).

To examine the above issues, we employed an R–E compatibility paradigm that manipulated the compatibility between movement trajectories produced by sequential key-press responses and melodic pitch contours presented as action effects. Participants were required to respond as quickly as possible to each of four arbitrary colour patch stimuli by producing a unique sequence of three taps on three vertically aligned response keys, with each tap potentially triggering a tone. The compatibility of the relationship between responses and their auditory effects was manipulated on the "height" dimension, assuming that there is a conceptual correspondence between spatial height and pitch height (e.g., see Eitan & Granot, 2006). In a compatible condition, taps on the top, middle, and bottom keys triggered tones of high, medium, and low pitch, respectively. There were three different types of incompatible condition: scrambled (Experiments 1, 2a/b, and 3), neutral (Experiment 2a), and reversed (Experiments 2b and 3). These conditions, which are illustrated in Figure 1, differ in the degree of correlation between movement trajectories and auditory effect pitch contours. Experiment 3 included a silent condition in which taps did not trigger tones.

The various types of incompatible condition and the silent condition were included to determine whether any observed R–E compatibility effects should be attributed to facilitation by the compatible mapping or impairment by incompatible mappings. We assumed that facilitation by compatible mappings should result in faster response initiation in the compatible condition than in the silent condition. We also assumed that if incompatible mappings interfere with action planning, then responses should be initiated more slowly in incompatible conditions than in the silent condition, and that response initiation times might vary as a function of the type of incompatible condition. Finding that planning is

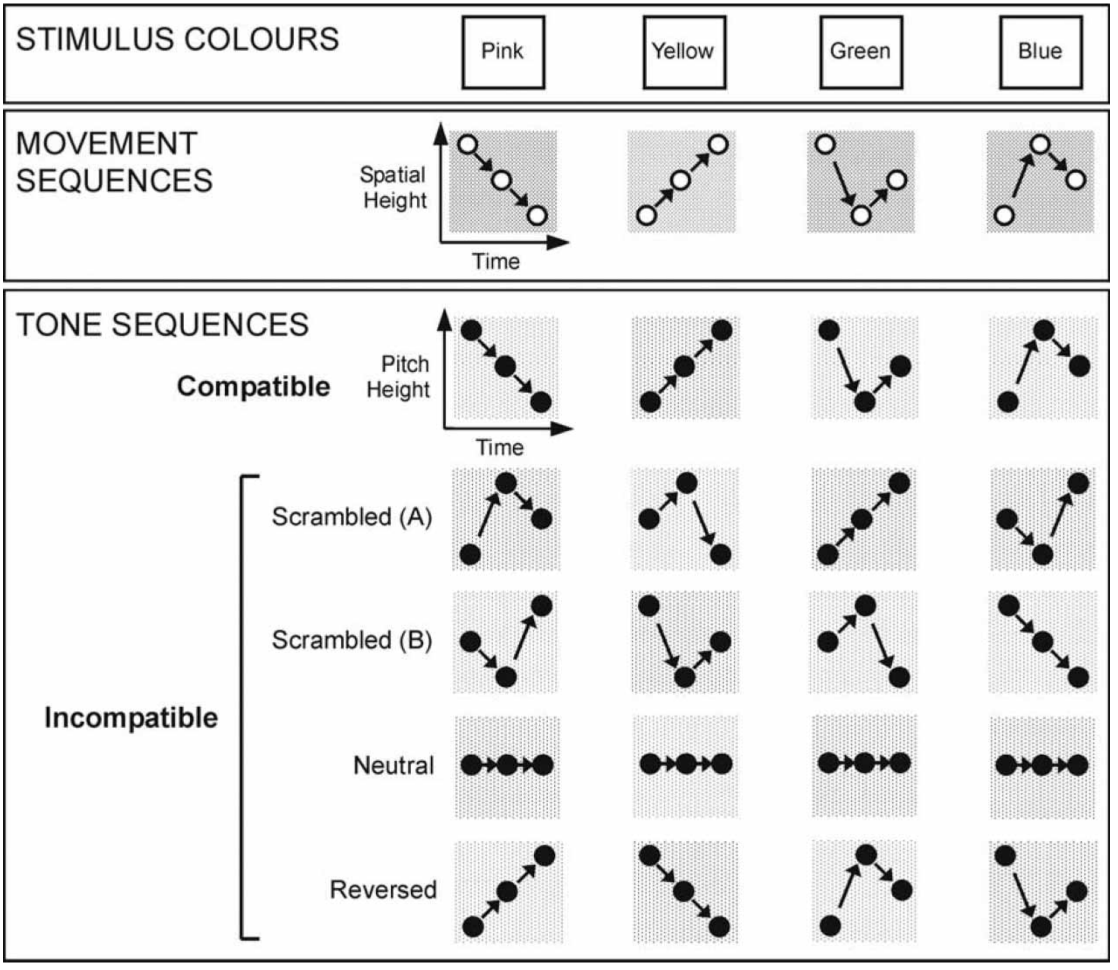

Figure 1. *Stimulus–response (colour–movement sequence) and response–effect (movement–tone sequence) mappings. Unfilled circles indicate finger taps on three response keys: top, middle, and bottom. Filled circles indicate tones of high, medium, or low pitch. Each stimulus colour is paired with one movement sequence. Each movement sequence is paired with several tone sequences to yield R–E compatibility conditions in which movement and pitch trajectories are either compatible (all experiments included this condition) or incompatible; two types of scrambled mapping (used in Experiments 1, 2a, and 2b), a neutral mapping (Experiment 2a), and a reversed mapping (Experiments 2b and 3).*

faster with the compatible mapping than with silence and the incompatible mappings alike, and that the time required for planning does not differ for the various incompatible mappings, would suggest that the R–E compatibility effect reflects a benefit associated with the compatible mapping rather than costs arising with incompatible mappings (see Kunde et al., 2004; Stöcker et al., 2003).

Finally, if R–E compatibility effects extend from action planning to action execution, then response sequences should not only be initiated more quickly in the compatible condition than in the incompatible conditions, but responses should also be completed most rapidly in the compatible condition. This direct effect of R–E compatibility on action execution is not the only potentially informative outcome, however.

Finding that R–E compatibility effects are confined to response selection and initiation in our task would suggest that the response sequences were fully preplanned (with the involvement of auditory imagery) and then controlled in an open-loop fashion (see Lashley, 1951; Schmidt, 1975; Schmidt & Lee, 1999). If such preplanning functions to facilitate rapid response execution, then individuals who display relatively large R–E compatibility effects on planning should be relatively fast at response execution in general (i.e., irrespective of R–E compatibility).

EXPERIMENT 1

In Experiment 1, individuals with varying amounts of musical experience were required to react to arbitrary imperative stimuli by producing action sequences in which movements and their auditory effects were compatible or incompatible in terms of their trajectories. We expected that reaction times (and perhaps response execution times) would be faster for compatible mappings than for incompatible mappings. Furthermore, we were interested to see whether the magnitude of this R–E compatibility effect grows larger with increasing years of musical experience, as may be expected due to the effects of musical experience on the vividness of auditory images.

Method

Participants

A total of 28 participants took part in Experiment 1, but data from only 26 participants (20 female and 6 male; age range = 19–30 years) are reported here (see below). A total of 3 participants in the final sample reported having no formal musical training, and the remainder reported varying amounts of musical experience (2–24 years of playing regularly; $M = 10.6$, $SD = 6.9$) on a variety of instruments. All were paid in return for participation.

Apparatus and stimuli

The experiment took place in a dimly lit, sound-attenuated room. Participants sat, wearing PRO-10 earphones, in front of a screen of an IBM-compatible PC. A custom-built response box with three vertically aligned metal plates, serving as response keys, was positioned in front of the participant at a comfortable height for tapping. The response box was 250 mm high and 150 mm wide. The metal plates measured 30 × 30 mm and were separated from one another by a vertical distance of 15 mm. The box was angled so that its surface was off-vertical (by approx. 30 degrees) to avoid excessive fatigue in the participant's tapping arm. Imperative stimuli consisted of four colour patches (16 × 16 mm, viewed from a distance of approx. 750 mm) presented in the centre of the screen: pink, blue, yellow, or green. The tones used as response effects were presented in a marimba timbre at a comfortable loudness level (60 dBA). Three different tone pitches were used: high = A4 (440 Hz), medium = G4 (392 Hz), and low = F4 (349 Hz). All tones had a sharp onset followed by natural decay lasting approximately 500 ms if not interrupted by the presentation of another tone. Stimulus presentation and response registration were controlled by Experimental Run Time System software (Version 3.34; BeriSoft Cooperation), and tones were generated by a SoundBlaster ISA soundcard.

Procedure

Participants received both written and oral instructions about the task. The instructions specified the order in which the three keys should be tapped for each stimulus colour and that these S–R mappings should be memorized. A sheet of paper showing the response order for each stimulus colour (e.g., a picture of a pink square followed by the German equivalents for "Top → Middle → Bottom") was also provided. Once the participant had memorized the S–R mappings, the experimenter conducted an informal test by naming each colour and checking that the participant was able to respond reliably by tapping the keys in the correct order. The instruction phase typically lasted about 10 minutes.

The experiment consisted of eight blocks of 56 trials. Participants were allowed to rest between blocks. The sheet of paper showing the S–R mappings was visible throughout the entire first block, but was then hidden for the remainder of the experimental session. At the end of the session, participants were asked to complete a questionnaire that included items about musical experience.

At the start of each trial, a fixation cross appeared at the screen centre. When the participant was ready, he or she rested the index finger of the preferred hand on the middle of the three vertically aligned keys. Then, after a variable time interval, one of the four stimulus colour patches appeared in place of the fixation cross. The possible values of this variable ready-to-stimulus interval were 100 or 1,000 ms (occurring with equal frequency within a block, but randomly ordered). This interval was varied to counter the tendency (observed in pilot testing) for participants to respond with temporal regularity rather than speed when stimulus onset was predictable.

The participant was required to react as quickly as possible by tapping the keys in a different order for each stimulus colour. The participant's tapping style was unconstrained apart from the instruction to use the index finger of the preferred hand. For the pink colour patch, the correct tap sequence was top → middle → bottom; for yellow, the sequence was bottom → middle → top; for green, it was top → bottom → middle; and for blue it was bottom → top → middle (see Figure 1). The trial ended 500 ms after the third tap was registered by the computer. If a tap was made out of order, a feedback message ("Fehler"—German for "error") appeared at the screen centre and remained for 750 ms. The screen then went blank for 500 ms before the next fixation cross appeared (or the block ended if all trials were complete). A blank screen also intervened for 500 ms between correctly performed trials. Throughout the experiment, each tap on a key triggered the presentation of a tone of high, medium, or low pitch (though not when the participant rested his or her finger on the middle key to indicate readiness at start of each trial).

The R–E mappings can be seen in Figure 1. In the compatible mapping, 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. This mapping resulted in movement sequences and effect sequences that were perfectly positively correlated in terms of direction changes in spatial height and pitch height. There were two different incompatible mappings, in which taps on the top, middle, and bottom keys were associated with low-, high-, and medium-pitched tones, respectively (Type A), or medium, low, and high tones, respectively (Type B). These incompatible mappings resulted in movement and effect sequences that were imperfectly and in general negatively correlated on the height dimension. The general negativity of these correlations derived from the fact that stepwise movements were often accompanied by pitch leaps in the opposite direction.

Consistent with previous studies (e.g., Koch & Kunde, 2002; Kunde, 2001, 2003), the R–E (key-to-tone) mapping changed from being compatible to incompatible, or vice versa (counterbalanced across participants), half-way through the experimental session (i.e., after the fourth block). Participants were told that the relationship between keys and tones would change but the task would remain unchanged: to respond as quickly and accurately as possible to the stimulus colour by tapping the instructed key sequence. Participants were also told that the tones were irrelevant to the task.

Design

R–E compatibility (compatible vs. incompatible) was varied within participants, with presentation order counterbalanced. In addition, for control purposes the type of incompatible mapping (A vs. B) was counterbalanced between participants, and the "ready-to-stimulus" interval (100 ms vs. 1,000 ms) was varied within participants. Thus, the experimental design was in effect a $2 \times 2 \times 2 \times 2$ mixed factorial, with within-participant independent variables R–E compatibility and ready-to-stimulus interval and between-participant independent variables presentation order and type of incompatible mapping.

However, only the R−E compatibility variable was of theoretical interest.

Dependent variables were reaction time (RT), movement time (MT), response duration (RD), and error rate (ER). RT, defined as the time taken to lift the tapping finger from the middle (home) key following stimulus presentation, was assumed to be an index of the amount of time required for response selection and movement preparation and initiation. MT and RD, the time taken to make the first tap after leaving the home key and the time between the first and third taps, respectively, are measures of the amount of time required for response execution. ER reflects the proportion of trials on which keys were tapped in the incorrect order. The criterion for statistical significance was set at $\alpha = .05$.

Table 1. *Mean reaction time, movement time, response duration, and error rate in compatible and incompatible conditions from Experiment 1*

Dependent variable	*Compatible*	*Incompatible*
RT[a]	529 (162)	575 (165)
MT[a]	332 (226)	314 (189)
RD[a]	414 (81)	411 (76)
ER[b]	3.6 (2.8)	3.5 (2.8)

Note: RT = mean reaction time; MT = movement time; RD = response duration; ER = error. Standard deviations in parentheses.
[a]In ms. [b]In percentages.

Results and discussion

Our analysis focuses on data from only the last two blocks of 56 trials from each compatibility condition (i.e., Blocks 3, 4, 7, and 8 of the procedure), with the first two blocks in each condition being considered as practice and an opportunity to acquire the current key-to-tone associations (see Koch & Kunde, 2002). RTs, MTs, and RDs for incorrect responses (errors: 3.6% of trials) and values more than three standard deviations from the respective means of each individual participant (outliers: a further 2.9% of trials) were excluded from analyses. Data from 2 participants (from the presentation order group that started with the incompatible condition) were excluded from analyses because they made errors on more than 15% of trials in the blocks that were analysed. Mean RT, MT, RD, and ER (minus outliers) in compatible and incompatible conditions are shown in Table 1. These data were subjected to separate 2 × 2 × 2 × 2 analyses of variance (ANOVAs) with within-participant variables compatibility and ready-to-stimulus interval and between-participant variables presentation order and type of incompatible mapping. The ANOVAs revealed no statistically significant effects of the order in which the compatibility conditions were run and the type of incompatible mapping used, and the interaction between these variables was also not significant for any dependent variable (ps > .09, η_p^2s < .12). With regard to our other control variable, the ANOVA on RTs revealed that mean RT was 74 ms faster at the long (1,000-ms) ready-to-stimulus interval than at the short (100-ms) interval, $F(1, 22) = 27.55$, $p < .001$, $\eta_p^2 = .56$. This is consistent with work on the "aging foreperiod" effect (e.g., Drazin, 1961). Ready-to-stimulus interval did not enter into a significant interaction with compatibility (neither here nor in subsequent experiments), $p > .1$, $\eta_p^2 = .10$, so results pertaining to this control variable are not mentioned further.

In accordance with predictions, RTs were significantly shorter for the compatible R−E mapping than for the incompatible mappings, $F(1, 22) = 15.58$, $p = .001$, $\eta_p^2 = .42$, with the mean size of the R−E compatibility effect (i.e., incompatible RTs minus compatible RTs) being 46 ms. R−E compatibility did not interact reliably with any of the control variables, (ps > .1, η_p^2s < .11). To determine whether the magnitude of the effect of R−E compatibility on RT varied as a function of musical experience, we computed the Pearson correlation coefficient between amount of instrumental experience and R−E compatibility effect size. The correlation was significant ($r = .46$, $N = 26$, $p < .05$), indicating that the magnitude of the R−E compatibility effect increased with increasing musical experience.

In contrast to the above results for response selection and initiation (RT), we found no significant effects of R–E compatibility on MT, RD, or ER, $ps > .2$, $\eta_p^2 s < .06$. This absence of R–E compatibility effects at stages later than response initiation in the current results suggests that the movement sequences were planned as a chunk—rather than just, say, the first tap—before overt movement began (for detailed discussions of related issues, see Rosenbaum, Hindorff, & Munro, 1987, and Stöcker & Hoffmann, 2004).

In sum, finding a significant R–E compatibility effect in RTs suggests that planning a sequence of movements with auditory effects involves the anticipation of these effects. Furthermore, our results demonstrate that musical expertise modulates the influence of R–E compatibility on the planning of movement sequences with auditory effects. Specifically, the positive correlation between R–E compatibility and musical experience suggests that playing an instrument may promote proficiency at action–effect anticipation by improving one's ability to engage in auditory imagery. Experiments 2a and 2b were conducted to provide converging evidence for this suggestion.

EXPERIMENTS 2A AND 2B

Experiment 2a and 2b were very similar to one another and differed from Experiment 1 in two main ways. First, they included a larger proportion of participants who had little experience playing a musical instrument, yielding two groups: musicians and nonmusicians. Second, to test the degree to which the results of Experiment 1 generalize beyond the scrambled incompatible mappings, Experiments 2a and 2b included incompatible key-to-tone mappings in which the trajectories of movement and effect sequences were either completely uncorrelated ("incompatible-neutral"; Experiment 2a) or perfectly negatively correlated ("incompatible-reversed"; Experiment 2b). In the incompatible-neutral condition, all three response keys were mapped to the same (medium-pitched) effect tone, and in the incompatible-reversed condition, the compatible key-to-tone mapping was simply inverted. In addition to these new conditions, Experiment 2a and 2b included the compatible and incompatible-scrambled conditions from Experiment 1. Thus, each participant encountered three conditions: compatible, incompatible-scrambled, and either incompatible-neutral (Experiment 2a) or incompatible-reversed (Experiment 2b).

Method

Participants

A total of 78 new participants took part in Experiments 2a and 2b, but data from only 60 participants (45 female and 15 male; age range = 16–34 years) are described here (see below). Participants were divided into groups of 15 musicians and 15 nonmusicians in each experiment. Musicians had 3 or more years of experience on a variety of instruments: 4–21 years ($M = 11.1$, $SD = 5.7$) in Experiment 2a; 3–22 years ($M = 10.5$, $SD = 5.7$) in Experiment 2b. Instrumental experience ranged from 0 to 2 years for nonmusicians. All participants (apart from one nonmusician in Experiment 2a) preferred to tap with the right hand. All participants were paid.

Apparatus, stimuli, procedure, and design

The apparatus, stimuli, procedure, and design were the same as those used in Experiment 1 with the exception that extra blocks of trials were added to accommodate the incompatible-neutral and incompatible-reversed R–E compatibility conditions in Experiments 2a and 2b, respectively. In Experiment 2a, the medium-pitched tone was presented irrespective of which key was tapped in incompatible-neutral trials, and the incompatible-scrambled condition used the Type A key-to-tone mappings from Experiment 1. In Experiment 2b, taps on the top, middle, and bottom key triggered low, medium, and high tones, respectively, in the incompatible-reversed condition, and the incompatible-scrambled condition used the Type B key-to-tone mapping from Experiment 1.

In total, there were 12 blocks of 56 trials in each experiment, with 4 consecutive blocks per R–E compatibility condition. In Experiment 2a, the incompatible-neutral blocks were presented either at the beginning or the end of the experimental test session—that is, either before or after the compatible and incompatible-scrambled blocks (which were counterbalanced as in Experiment 1), yielding four orders. In Experiment 2b, the order in which the R−E compatibility conditions were run was fully counterbalanced, yielding six orders. This difference in counterbalancing procedure across Experiments 2a and 2b was not expected to have any important effects on the results.

Results and discussion

As in Experiment 1, we focus on data from the last two blocks of 56 trials from each compatibility condition (i.e., Blocks 3, 4, 7, 8, 11, and 12 of the procedure). Data from 18 participants (9 per experiment) were not analysed because 10 made errors on more than 15% of these trials, 2 responded too quickly for their RT values (*M*s < 100 ms) to be used as an index of time required for response selection, 3 registered unusually long RTs (*M*s $>$ 900 ms), 1 produced unusually long MTs ($M >$ 1,500 ms), and 2 did not provide enough details in the questionnaire for their musical experience to be assessed. The number of participants in each of the condition order groups was well matched in the final sample. RTs, MTs, and RDs for incorrect responses (a total of 4.4% and 3.4% of trials from Experiments 2a and 2b, respectively) and values more than three standard deviations from the respective means of each individual participant (2.7% and 1.5% of correct trials from Experiments 2a and 2b, respectively) were excluded from analyses.

Data from Experiments 2a and 2b were initially analysed in separate ANOVAs with within-participant variables R−E compatibility and ready-to-stimulus interval, and between-participant variables musical experience and R−E compatibility condition order. The results were similar across experiments, so the data were pooled for the analyses reported below. The condition order variable produced no reliable main effects and did not enter into any significant interactions with R−E compatibility in the separate analyses (ps $> .1$, η_p^2s $<$ .34), so we collapsed across this control variable in the pooled analyses. We also collapsed across ready-to-stimulus interval.

RT, MT, RD, and ER data from Experiments 2a and 2b are shown in Table 2. Data for each dependent variable were analysed in a separate $3 \times 2 \times 2$ ANOVA, with the within-participant variable R−E compatibility, and between-participant variables musical experience and experiment. The Greenhouse−Geisser correction was applied when the degrees of freedom numerator exceeded one in analyses reported throughout this article (the reported p-values are corrected, but the reported degrees of freedom values are uncorrected).

The ANOVA for RTs yielded a significant main effect of R−E compatibility, $F(2, 112) = 8.94$, $p < .001$, $\eta_p^2 = .14$. The main effect of musical experience was not significant, $F(1, 56) < 1$, $\eta_p^2 = .001$, but the R−E compatibility by experience interaction was, $F(2, 112) = 4.05$, $p < .05$, $\eta_p^2 = .07$. The main effect of experiment was not significant, and it did not enter into any significant interactions with the other variables (ps $> .5$, η_p^2s $< .01$).

The R−E compatibility main effect was unpacked using two planned orthogonal contrasts. The first contrast compared performance in the compatible condition with performance in the combined incompatible conditions (scrambled and neutral from Experiment 2a and scrambled and reversed from Experiment 2b). The second contrast compared performance between the incompatible-scrambled and the other (neutral and reversed) incompatible conditions. Musical experience was included as a between-participants variable in this contrast analysis.

An ANOVA on the first contrast yielded a significant effect of R−E compatibility, $F(1, 58) = 16.45$, $p < .001$, $\eta_p^2 = .22$, indicating that RTs were faster (by 48 ms on average) in the compatible condition than in the incompatible conditions. The R−E compatibility by musical experience interaction was also significant for this contrast, $F(1, 58) = 7.25$, $p < .01$, $\eta_p^2 = .11$. Paired-sample t tests revealed that musicians' mean RTs

Table 2. *Mean reaction time, movement time, response duration, and error rate for musicians and nonmusicians in the various conditions of Experiments 2a, 2b, and 3*

		Experiment 2a			*Experiment 2b*			*Experiment 3*		
Group	*Dependent variable*	*Compatible*	*Incompatible-scrambled*	*Incompatible-neutral*	*Compatible*	*Incompatible-scrambled*	*Incompatible-reversed*	*Compatible*	*Incompatible-reversed*	*Silent*
Musicians	RT[a]	478 (167)	573 (251)	578 (244)	501 (124)	567 (122)	561 (144)	507 (104)	539 (122)	545 (151)
	MT[a]	360 (207)	303 (164)	356 (151)	306 (142)	278 (108)	274 (132)	263 (79)	260 (63)	272 (83)
	RD[a]	443 (138)	424 (147)	453 (161)	451 (146)	471 (152)	462 (117)	417 (57)	431 (66)	468 (89)
	ER[b]	3.9 (3.7)	4.2 (3.6)	5.7 (7.7)	3.9 (4.6)	4.2 (3.4)	3.9 (4.6)	1.6 (1.5)	1.8 (1.9)	1.5 (1.5)
Nonmusicians	RT[a]	526 (188)	527 (257)	543 (193)	520 (169)	533 (143)	552 (171)	515 (107)	504 (129)	505 (122)
	MT[a]	438 (281)	463 (329)	460 (370)	372 (185)	363 (152)	364 (166)	304 (161)	298 (110)	306 (136)
	RD[a]	455 (104)	469 (110)	461 (92)	465 (72)	449 (49)	449 (51)	457 (108)	464 (112)	482 (76)
	ER[b]	3.9 (2.8)	4.3 (3.8)	4.5 (4.1)	2.3 (2.3)	3.5 (2.9)	2.4 (2.6)	2.1 (2.1)	1.6 (1.5)	2.0 (2.3)

Note: RT = Mean reaction time; MT = movement time; RD = response duration; ER = error rate; Standard deviations in parentheses.
[a]In ms. [b]In percentages.

were reliably faster in the compatible condition than in the combined incompatible conditions, $t(29) = -3.93$, two-tailed $p < .001$, whereas the corresponding (16-ms) difference was not reliable in nonmusicians, $t(29) = -1.33$, $p = .19$. The failure to detect an R–E compatibility effect in nonmusicians may be due to insufficient statistical power. The size of the R–E compatibility effect for the full sample of musicians and nonmusicians ($N = 60$) is Cohen's $f = .50$ (Cohen, 1988), which means that power ($1-\beta$) would be only .75 for a sample size of $n = 30$ (computed using GPOWER; Faul & Erdfelder, 1992; see Erdfelder, Faul, & Buchner, 1996). Nevertheless, the results were overall similar to those in Experiment 1: Response selection was influenced by pitch-based R–E compatibility, requiring less time with compatible (positively correlated) key-to-tone mappings than with incompatible (negatively correlated and uncorrelated) mappings. This influence varied as a function of musical experience, although it should be noted that response selection took similar amounts of time on average for musicians (530 ms) and nonmusicians (531 ms).

The second contrast revealed that RTs in the incompatible-scrambled condition did not differ reliably from RTs in the other (neutral and reversed) incompatible conditions, $F(1, 58) = 0.48$, $p = .49$, $\eta_p^2 = .01$. This finding suggests that the type of incompatible mapping had little bearing on the time required for response selection. Musical experience did not affect this outcome, as evidenced by the absence of a reliable R–E compatibility by experience interaction for this contrast, $F(1, 58) = 0.51$, $p = .48$, $\eta_p^2 = .01$.

MT, RD, and ER were not affected reliably by R–E compatibility, musical experience, experiment, or the interaction of these variables, ps $> .16$, η_p^2s $<$ .04, although the main effect of musical experience on MT approached significance, $F(1, 56) = 3.17$, $p = .08$, $\eta_p^2 = .05$. As can be seen in Table 2, average MTs and RDs are numerically shorter for musicians than for nonmusicians. This may indicate that although musicians and nonmusicians spent similar amounts of time selecting their responses, musicians were faster once they got moving. Indeed, the main effect of musical experience fell just short of significance in an additional ANOVA that was run on overall response execution time (MT + RD), $F(1, 56) = 3.64$, $p = .06$, $\eta_p^2 = .06$.

The results of Experiments 2a and 2b suggest that musicians are faster at planning sequential actions when movement trajectories and melodic contours are compatible than when they are incompatible. Although this R–E compatibility effect was observed across different types of incompatible mapping, it is still unclear whether it reflects a special benefit associated with the compatible mapping or general costs associated with incompatible mappings. Experiment 3 was designed to address this question.

EXPERIMENT 3

A silent condition was introduced in Experiment 3 in order to gauge whether the R–E compatibility effects observed in the previous experiments stemmed from relatively fast planning under compatible conditions or relatively slow planning under incompatible conditions. Finding that RTs are faster in the compatible condition than in the incompatible and silent conditions would suggest that compatible key-to-tone mappings facilitate action planning. Finding that RTs are slower in the incompatible than in the silent condition would suggest than incompatible key-to-tone mappings interfere with planning.

Method

Participants

The final participant sample in Experiment 3 consisted of 24 new musicians (19 female and 5 male; aged 19–32 years) and 24 new nonmusicians (18 female and 6 male; aged 18–35 years). (Data from an additional 7 nonmusicians were not analysed because they had combined error/outlier rates higher than 15%.) Musicians had 4–16 years of regular instrumental experience ($M = 7.75$ years, $SD = 3.4$). Nonmusicians had no regular instrumental experience. All participants with the exception of 1 musician preferred to tap with the right hand, and all were paid.

Apparatus, stimuli, procedure, and design

Experiment 3 included three R–E compatibility conditions: a compatible, an incompatible-reversed, and a silent condition. (Although the silent condition is not strictly speaking a compatibility manipulation, we refer to it as an R–E compatibility condition for convenience.) Taps did not trigger tones in the silent condition. There were 15 blocks of 48 trials, with five consecutive blocks per R–E compatibility condition. Otherwise the apparatus, stimuli, and procedure, and design were the same as those in Experiment 2b. Each participant encountered each of the three R–E compatibility conditions, with condition order counterbalanced across participants. There were equal numbers of participants in the six condition order groups.

Results and discussion

Only data from the last three blocks from each R–E compatibility condition are reported, and RTs, MTs, and RDs for incorrect responses (1.8% of trials) and outliers (2.1% of correct trials) were excluded from analyses. RT, MT, RD, and ER data (see Table 2) were analysed in separate $3 \times 2 \times 2 \times 6$ ANOVAs, with the within-participant variables R–E compatibility condition and ready-to-stimulus interval and the between-participant variables musical experience and condition order.

In the ANOVA on RTs, the absence of significant main effects of R–E compatibility, $F(2, 72) = 1.65$, $p = .20$, $\eta_p^2 = .04$, and musical experience, $F(1, 36) = 0.47$, $p = .50$, $\eta_p^2 = .01$, was qualified by a reliable interaction between these variables, $F(2, 72) = 4.89$, $p = .01$, $\eta_p^2 = .12$. The R–E compatibility effect was larger in musicians than in nonmusicians. The RT data of musicians and nonmusicians were analysed separately to gain a clearer view on this interaction.

An ANOVA on musicians' RTs yielded a significant main effect of R–E compatibility, $F(2, 36) = 4.25$, $p < .05$, $\eta_p^2 = .19$. The pattern of mean RTs shown in Table 2 suggests that this effect was due to a compatible-mapping benefit rather than incompatible-mapping costs. RTs were on average 35 ms faster in the compatible condition than in the incompatible and silent conditions combined, $F(1, 18) = 7.50$, $p = .01$, $\eta_p^2 = .29$, whereas the 6-ms difference between RTs in the incompatible condition and those in the silent condition was not only far from reliable, $p = .63$, $\eta_p^2 = .01$, but its direction was opposite to a direction that would indicate a cost associated with the incompatible mapping. In contrast to the results for musicians, the main effect of R–E compatibility was not significant in an ANOVA on nonmusicians' RTs, $F(2, 36) = 0.83$, $p = .44$, $\eta_p^2 = .04$.

In addition to the effects mentioned above, the main ANOVA on RTs revealed a significant interaction between R–E compatibility and condition order, $F(10, 72) = 4.34$, $p < .001$, $\eta_p^2 = .38$, and a significant three-way interaction between R–E compatibility, order, and musical experience, $F(10, 72) = 2.01$, $p < .05$, $\eta_p^2 = .22$. These interactions involving the order variable were unexpected (given that there were no such interactions in the previous experiments reported in this article), and they were most likely due to random sampling error (note that there were only 4 participants per cell for this particular analysis). The main effect of condition order and the interaction between order and musical experience were not significant, ps > .1, η_p^2s < .22.

MT and ER were not affected reliably by R–E compatibility, musical experience, condition order, or the interaction of these variables, ps > .22, η_p^2s < .12, although the interaction between R–E compatibility and condition order approached significance for MT, $F(10, 72) = 1.89$, $p = .07$, $\eta_p^2 = .21$. However, a significant main effect of R–E compatibility was observed for RD, $F(2, 72) = 7.42$, $p < .01$, $\eta_p^2 = .17$, indicating that the time required to execute response sequences was shorter when tones were present than when they were absent (see Table 2). The increase in RD from the compatible condition to the incompatible condition was not significant, $t(47) = -0.94$, $p = .35$, but the increase in RD from incompatible to silent conditions was, $t(47) = -2.40$, $p < .05$. These results suggest that auditory effects—regardless of their compatibility—spur on the participant during the execution of sequential responses (see Stöcker & Hoffmann, 2004, for a similar finding). The main effects of musical experience and order and the interaction effects involving R–E compatibility, musical experience, and order were not significant for RD, *p*s > .1, η_p^2s < .2. However, as was the case in Experiments 2a and 2b, there was a tendency for musicians to be quicker than nonmusicians in terms of overall response execution (MT + RD), $F(1, 46) = 3.44$, $p = .07$, $\eta_p^2 = .07$. Thus, although the process of action–effect anticipation may not have made musicians faster than nonmusicians at response planning, action–effect anticipation during planning may have paved the way for faster response execution. We conducted analyses on pooled data from Experiments 1–3 to gain a clearer view of the differences in musicians' and nonmusicians' behaviour related to planning and execution.

ANALYSIS OF POOLED DATA FROM EXPERIMENTS 1–3

The purpose of the analysis of pooled data from Experiments 1–3 was twofold. First, this pooled analysis would increase the statistical power to detect an effect of R–E compatibility on nonmusicians' as well as musicians' RTs. Second, with the increased statistical power, we could clarify the issue of whether the apparent equivalence of musicians' and nonmusicians' average RTs is qualified by relatively fast MTs and RDs in musicians. Finding that this is the case would suggest that the anticipation of action effects via auditory imagery does not function to accelerate response planning, but rather to accelerate response execution.

The pooled analyses examined RT, MT, and RD data from the compatible and incompatible conditions from all experiments (see Figure 2). Data from the incompatible-scrambled and incompatible-neutral conditions from Experiment 2a were averaged when pooling, as were data from the incompatible-scrambled and incompatible-reversed conditions from Experiment 2b. Data from the silent condition from Experiment 3 were excluded. Participants with three or more years of regular instrumental experience were classified as musicians ($n = 76$), and the remaining participants were classified as nonmusicians ($n = 58$). RT, MT, and RD data were analysed in

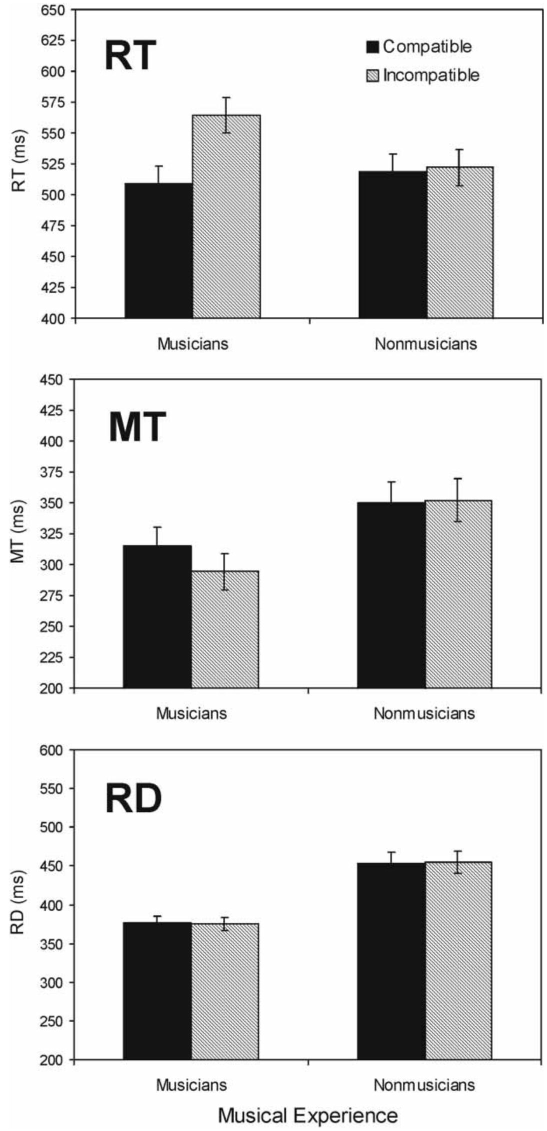

Figure 2. *Musicians' and nonmusicians' RTs, MTs, and RDs in compatible and incompatible conditions averaged across Experiments 1–3. Error bars represent 95% confidence intervals calculated separately for musicians and nonmusicians (see Masson & Loftus, 2003).*

separate 2 × 2 mixed ANOVAs with the within-participant variable R−E compatibility (compatible vs. incompatible) and the between-participant variable musical experience (musicians vs. nonmusicians). Similar results were obtained for the MT and RD, so here we report results for MT + RD (overall response execution time).

The ANOVA on RTs revealed a significant main effect of R−E compatibility, $F(1, 132) = 18.04$, $p < .001$, $\eta_p^2 = .12$, and a significant interaction between R−E compatibility and musical experience, $F(1, 132) = 14.31$, $p < .001$, $\eta_p^2 = .10$. Follow-up tests examined musicians' and nonmusicians' data separately. For nonmusicians, the R−E compatibility effect was relatively small (3 ms) and not significant, $F(1, 57) < 1$, $\eta_p^2 < .01$. The size of the R−E compatibility effect for the full sample of musicians and nonmusicians ($N = 134$) is Cohen's $f = .39$, meaning that power ($1-\beta$) would be .83 for a sample size of $n = 58$. Thus, statistical power was still not sufficient to detect a weak R−E compatibility effect (if it existed) even in our pooled analysis. For musicians, RTs were on average 55 ms faster in the compatible condition than in the incompatible condition, $F(1, 75) = 29.11$, $p < .001$, $\eta_p^2 = .28$.

A correlation analysis including data from all participants with musical training was run to examine the relationship between the R−E compatibility effect and instrumental experience more closely. A total of 5 "nonmusicians" who possessed 1 or 2 years of musical experience were included in this correlation analysis. Neither the distributions of compatibility effect scores nor the number of years of musical experience deviated significantly from normality (according to the Kolmogorov–Smirnov test). Furthermore, there were no obvious nonlinearities in the relationship between the compatibility effect and years of experience. However, data from 6 participants were classified as outliers (their scores were greater than three times the standard deviation of the residuals) and were excluded from the correlation analysis. The results of this analysis indicated that the magnitude of the R−E compatibility effect grew with increasing amounts of instrumental experience ($r = .30$, $N = 75$, $p < .01$).

Despite the above R−E compatibility effects, musicians' and nonmusicians' RTs were otherwise not significantly different from one another, $F(1, 132) < 1$, $\eta_p^2 < .01$, for the main effect of musical experience. This was the case even in separate one-way ANOVAs on data from the compatible condition, $F(1, 132) < 1$, and the incompatible conditions, $F(1, 132) = 2.19$, $p = .14$. These results suggest that the average amount of time required for response planning did not differ reliably for both groups. However, as can be seen in Figure 2, musicians were faster than nonmusicians when it came to response execution. The reliability of this difference was confirmed in an ANOVA on MT + RD, $F(1, 132) = 8.96$, $p < .01$, $\eta_p^2 = .06$. (R−E compatibility and the interaction of R−E compatibility and musical experience did not affect MT + RD reliably, ps > .2, η_p^2s < .01.) An additional ANOVA revealed that total response time (RT + MT + RD) was also reliably faster in musicians than in nonmusicians, $F(1, 132) = 7.19$, $p < .01$, $\eta_p^2 = .05$. Thus, musicians responded more quickly than nonmusicians, although this difference was not reflected in RTs.

GENERAL DISCUSSION

The role of action−effect anticipation in musical action planning was investigated using an R−E compatibility paradigm that required people with various levels of musical experience to produce short auditory sequences by tapping on vertically aligned response keys. The main finding was that musical experience influenced the degree to which response initiation times were affected by the compatibility between movement trajectories and melodic contours on the "height" dimension. Stronger effects of R−E compatibility on RT were observed in experienced musicians than in individuals with little or no musical training, and, moreover, the magnitude of the R−E compatibility effect grew with increasing amounts of instrumental experience in musicians.

The R–E compatibility effects observed in Experiments 1, 2a, and 2b indicated that responses were selected and initiated more quickly when the mapping between keys and tones was compatible than when it was incompatible: scrambled, reversed, or neutral (i.e., all effect tones had the same pitch). In Experiment 3, response initiation was faster in the compatible condition than in a silent condition in which taps did not trigger tones, while response initiation times in silent and incompatible conditions were commensurate. Taken together, these findings suggest that action planning in musicians was facilitated by compatible key-to-tone mappings, while the various types of incompatible mapping had no discernable effect on planning. The absence of statistically significant costs associated with incompatible mappings is consistent with the results of previous R–E compatibility studies (Kunde et al., 2004; Stöcker et al., 2003) and is reassuring given the pervasiveness of incompatible mappings in the design of musical instruments (e.g., valved brass instruments).

Our additional finding that R–E compatibility did not affect the time taken to complete responses once they were initiated suggests that the benefits of compatible movement-effect representations did not extend from action planning to action execution. This may be due to the specific requirements of our task. In particular, the brevity and rapidity of responses may have led to movements being fully preplanned (at least by musicians; see below) and then controlled in an open-loop fashion (see Schmidt & Lee, 1999). In a recent study that employed a "nonspeeded" variant of the current paradigm, Keller and Koch (2006) found that R–E compatibility affected the timing accuracy of each tap when musically trained participants were required to produce sequential responses at a regular tempo rather than as quickly as possible.

The influence of R–E compatibility on planning in the current study can be explained in terms of endogenous response priming by anticipated action-effects (see Kunde et al., 2004). On this account, representations of movement trajectories and auditory-effect pitch contours are activated simultaneously during response planning (under conditions when movements reliably produce sounds). Such concurrent activation could be expected to occur automatically if representations of movements and their auditory effects were to some degree integrated in memory (cf. Prinz, 1990; Hommel et al., 2001), presumably as a consequence of the cross-modal association and serial chaining/chunking processes that facilitate sequence learning (see, e.g., Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Stöcker et al., 2003).

In accordance with the Kunde et al. (2004) model, we assume that similarity-based priming accelerates the activation of these integrated movement and auditory-effect representations when they are compatible with one another, thus leading to a reduction in the time taken to reach the activation threshold for triggering an appropriate motor programme. The endogenous nature of this cross-modal priming can account for the observed influence of musical experience on the magnitude of the R–E compatibility effect. Specifically, the increase in auditory imagery vividness that accompanies musical training strengthens the activation of anticipatory auditory-effect representations, thereby heightening the degree to which these representations can prime appropriate motor responses.

The above account does not postulate that action–effect anticipation accelerates planning in general, as the process of generating images is time consuming (see, e.g., Crowder, 1989; MacKay, 1992). This may be the reason why RTs were even somewhat numerically larger, on average, for musicians than for nonmusicians in our study (although this difference was not reliable). Instead of benefiting planning per se, the advantages of action–effect anticipation appear to be deferred until action execution. This was suggested by the finding that response execution times (MTs + RDs) were shorter for musicians than for nonmusicians. Thus, the extra time required to generate auditory images during movement preparation was compensated for by accelerated movement execution. The fact that the total responses times (RTs + MTs +

RDs) were shorter for musicians than for nonmusicians indicates that this compensation was complete. It may be the case that auditory imagery assisted musicians in fully preplanning their responses, while nonmusicians planned their responses in a more incremental fashion. This skill-based difference may reflect a stronger tendency in musicians than in nonmusicians to represent sequential action–effect tones as melodic chunks rather than isolated events.

In conclusion, the results of the current study provide evidence for the role of action–effect anticipation in planning sequences of movements with music-like auditory effects, and that musical experience modulates this anticipation. Specifically, representations of forthcoming sounds seem to make an increasingly potent contribution to planning as one gains experience playing a musical instrument. This change in potency may reflect strengthening activation for auditory-effect representations due to the development of auditory imagery skills. More generally, the ability to engage in imagery (visual, auditory, or motor) may also constrain the endogenous activation of representations based on cross-modal movement–effect associations in domains other than music. Thus, whereas action–effect anticipation processes have been shown to be effective in discrete, single key-press responses (e.g., Kunde et al., 2004) and in vocal responses (Koch & Kunde, 2002) in musically untrained participants, it is possible that the planning and execution of more complex sequential skills requires trained imagery to benefit from R–E compatibility. This possibility needs to be further investigated in future studies.

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