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ORIGINAL ARTICLE

Generalization of novel sensorimotor associations among pianists and non-pianists: more evidence that musical training effects are constrained

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Abstract

In the process of acquiring musical skills, such as playing the piano, we develop sensorimotor associations between motor movements and perception of pitch. Previous research suggests that these acquired associations are relatively inflexible and show limited generalizability to performance under novel conditions. The current study investigated whether piano training constrains the ability to generalize learning based on an unfamiliar (inverted) pitch mapping, using a transfer-of-training paradigm (Palmer and Meyer in Psychol Sci 11:63–68, 2000). Pianists and non-pianists learned a training melody by ear with normal (higher pitches to the right) or inverted (higher pitches to the left) pitch mapping. After training, participants completed a generalization test in which they listened to and then immediately reproduced four types of melodies that varied in their similarity to the melody used during training and were based on the same, a similar, an inverted, or a different pitch pattern. The feedback mapping during the generalization test matched training. Overall, pianists produced fewer errors and required fewer training trials than non-pianists. However, benefits of training were absent for pianists who trained with inverted feedback when they attempted to reproduce a melody with a different structure than the melody used for training. This suggests that piano experience may constrain one's ability to generalize learning that is based on novel sensorimotor associations.

Introduction

Perhaps the most critical feature of successful learning is the ability to generalize acquired skills beyond the initial task used for training (Poggio & Bizzi, 2004). During motor learning, generalization leads to transfer of training: the ability to learn a new task more rapidly when it shares features with some previously learned task (Schmidt & Lee, 1999). Transfer of learning plays a particularly important role in music performance. The ease with which highly skilled pianists learn new pieces reflects their ability to draw on prior learning. This was illustrated in research by Meyer and Palmer (Meyer & Palmer, 2003; Palmer & Meyer, 2000) that adopted a classic transfer of training paradigm for sequence learning (e.g., Cohen, Ivry, & Keele, 1990; MacKay & Bowman, 1969). In this paradigm, participants repeatedly produce an initial training sequence. With repetitions, performance speed increases, suggesting that learning has occurred. Next, participants switch to a new sequence, which is also performed across several repetitions. When the transfer of learning succeeds, the new sequence is learned more rapidly, with error-free performance being faster at the first repetition of the transfer sequence than for the first performance of the training sequence. Importantly, both motoric and structural factors contribute to the successful transfer of learning in music performance; the similarity between learned and novel sequences in pitch/time patterns, as well as motor movements, affects the transfer of learning.

These results point to an important feature of musical skill acquisition. Although musicians develop fine-grained and precise motor skills, it is equally important that musicians develop associations between motor movements and auditory feedback from their actions, termed sensorimotor associations (Penhune, 2011; Zatorre, Chen, & Penhune, 2007). If music learning only involved motor learning, musicians would show no transfer based on whether the pitch patterns associated with auditory feedback during

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transfer resemble the perceived pitch patterns during training, and would be movement specific. However, previous evidence suggests that pianists are in fact sensitive to training/transfer matches based on pitch patterns. Piano players exhibit high sensitivity to the mapping between pitch and space (e.g., Drost, Rieger, & Prinz, 2007; Keller & Koch, 2008; Lidji, Kolinsky, Lochy, & Morais, 2007; Rusconi, Kwan, Giordano, Umilta, & Butterworth, 2006; Taylor & Witt, 2015). This likely reflects their acquired experience, although it is important to note that non-musicians do show some sensitivity to the conventional mapping of the pitch to space, suggesting that associations between actions and pitch patterns in music may be influenced by implicit musical knowledge (Pfordresher, 2005, 2012, 2019).

The present research used the transfer of learning paradigm to explore how musical training on a particular instrument may constrain the flexibility of forming novel sensorimotor associations between pitch and space. We used music performance on the keyboard as a model system given the one-to-one mapping of the pitch to space that constitutes a major feature of learning to play. Although the vast majority of individuals in a given culture acquire rich implicit knowledge of musical pitch and time structure (e.g., Prince, Stevens, Jones, & Tillmann, 2018; Schultz, Stevens, Keller, & Tillmann, 2013; Tillmann, Bharucha, & Bigand, 2000), fewer individuals have mapped their perception of music to motor planning by learning a musical instrument. For instance, when people learn to play the piano, they acquire associations between spatial locations of keys—the targets of motor planning—and pitch. These associations lead to behavioral and neural changes that reflect enhanced expertise. However, this enhanced expertise may come at a cost. In acquiring associations between motor planning and pitch that are specific to the standard configuration of a keyboard, pianists may become resistant to learning associations that deviate from these norms.

A recent paper by two of us provided evidence for this kind of limitation (Pfordresher & Chow, 2019). Pianists and non-pianists learned novel melodies by ear under two mappings of the pitch to space (i.e., the piano key) on a standard keyboard. For half the participants, the mapping was standard, with low pitches to the left and high pitches to the right. For the other half of the participants, the mapping was reversed. This reversed mapping conflicted with the sensorimotor associations acquired by pianists, whereas non-musicians would not have formed the same kind of task-specific associations.[1] Both groups exhibited a similar ability to learn simple melodies based on either mapping, and pianists' learning was at a faster rate than non-pianists regardless of the pitch mapping used during initial learning. However, pianists who learned melodies with the inverted mapping exhibited greater susceptibility to disruption of learning during a later recall when auditory feedback was altered. Thus, learning among pianists was unstable when based on an unfamiliar mapping of the pitch to space on a piano keyboard.

Whereas our previous work addressed the stability of learning for a specific musical piece, it did not address how well participants encoded sensorimotor contingencies in general. In other words, do pianists exhibit learning that is both *unstable* and *inflexible* when learning is based on unfamiliar sensorimotor contingencies? The present research used a transfer of learning paradigm to address the question of flexibility. Following a learning phase based on Pfordresher and Chow, participants went on to a test phase in which they listened to new melodies (not used in training), as well as trained melodies, that they attempted to reproduce immediately thereafter. This paradigm tests whether learning of sensorimotor contingencies—not specific melodies—transfers to novel melodies. We predicted that non-pianists would exhibit similar transfer regardless of whether training was based on a standard or inverted mapping of the pitch. By contrast, we hypothesized that pianists would only show successful transfer when training was based on the standard mapping of the pitch, consistent with the results of Pfordresher and Chow.

Method

Participants

Seventy-seven students (M age = 19 years, 58% female, 9% left-handed) from the University at Buffalo participated in exchange for course credit. All participants completed the training paradigm described in the next sections. The participants we report here represent 71% of a larger sample in which the remaining participants were not able to complete training. Those who met the criterion of having at least three years of piano experience were categorized as pianists ($N = 40$), while those with less than three years were categorized as non-pianists ($N = 37$). Each participant was randomly assigned to a trained feedback condition based on either normal or inverted pitch mapping. Musical background for participants is summarized in Table 1. Analyses of variance yielded main effects of experience group on years of piano experience, $F(1,73) = 170.19$, $p < 0.001$, $\eta^2_p = 0.70$, and on piano lessons, $F(1, 73) = 123.23$, $p < 0.001$, $\eta^2_p = 0.63$, as would be expected, and no effect for total years of experience on some other instrument

[1] It is worth noting that non-musicians in Western cultures typically report explicit knowledge about the mapping of pitch to piano keys. Our focus is not on this kind of explicit awareness, but instead on more implicit features of sensorimotor associations.

Table 1 Means (standard deviations) of years spent on various music-related activities for each group

Trained feedback/experience group (*n*)	Piano experience	Piano lessons	Other instrumental experience	Other instrumental lessons
Normal/Pianists (21)	8.33 (3.65)	6.66 (3.27)	3.90 (5.80)	2.07 (2.99)
Inverted/Pianists (19)	8.05 (3.69)	6.15 (3.55)	6.79 (10.55)	2.92 (5.45)
Normal/Non-pianists (20)	0.45 (0.76)	0.30 (0.57)	4.68 (9.06)	2.53 (3.67)
Inverted/Non-pianists (17)	0.00 (0.00)	0.00 (0.00)	5.35 (5.10)	2.88 (3.12)

($p = 0.89$), or lessons on some other instrument ($p = 0.80$). There were no differences in musical training measures across the feedback training conditions (which was randomly assigned) and musical training measures were consistently distributed across the feedback training conditions and musical experience group (all $p > 0.30$).

Materials and equipment

Participants learned one stimulus melody "by ear" using a progressive trial-and-error training paradigm (cf. Bangert & Altenmüller, 2003; Pfordresher & Chow, 2019). The stimulus melody comprised seven notes from the first five scale degrees of C major, was based on invariant finger-key associations, and was performed with the right hand. Finger patterns associated with melodies were constant for all participants. The pitch-to-key mapping was inverted for participants assigned to the inverted trained feedback condition, such that the keys normally associated with pitches C–D–E–F–G, would produce G–F–E–D–C, respectively.

Each training trial presented an isochronous piano sequence ranging from three to seven notes in length. The piano sequences were pre-recorded on a Roland RD-700 digital keyboard at a tempo of 80 BPM and used a grand piano timbre. Participants performed on the same keyboard and heard feedback through Sony MDR-7506 headphones. FTAP, a Linux-based program, was used to manipulate auditory feedback and record MIDI key presses from participants (Finney, 2001).

The training phase consisting of nine types of training subsequences that were designed to facilitate progressive learning of a 7-note *Training Melody* by ear (see "Procedure" for more details). During training, each participant experienced either normal or inverted pitch mapping of auditory feedback. The progression of training subsequences is shown in Fig. 1. As can be seen, the progression of subsequences is designed to guide participants through subsequences of different lengths in a way that promotes additive learning of melody structure (Mishra, 2002).

Following the training phase, participants listened to and then reproduced four *Transfer Melodies* while experiencing the same auditory feedback mapping used during training. Notations of the four conditions are shown in Fig. 2. One

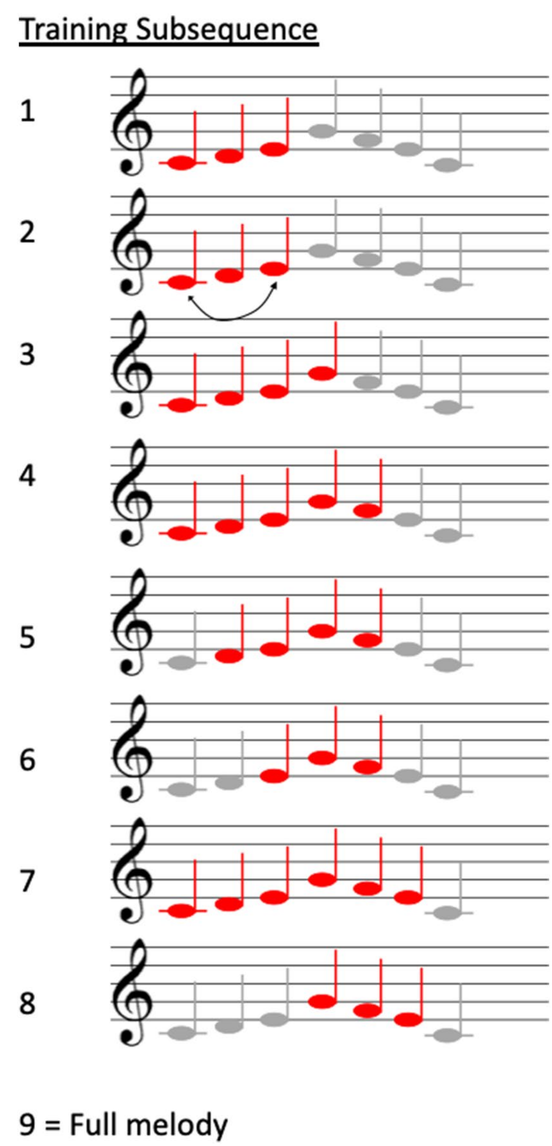

Fig. 1 Progression of subsequences in the training phase. Each notation illustrates the subsequence from the stimulus melody via red highlighting, with other (unperformed) pitch events shown in grey. The second subsequence comprised reverse ordering of the first three pitch events

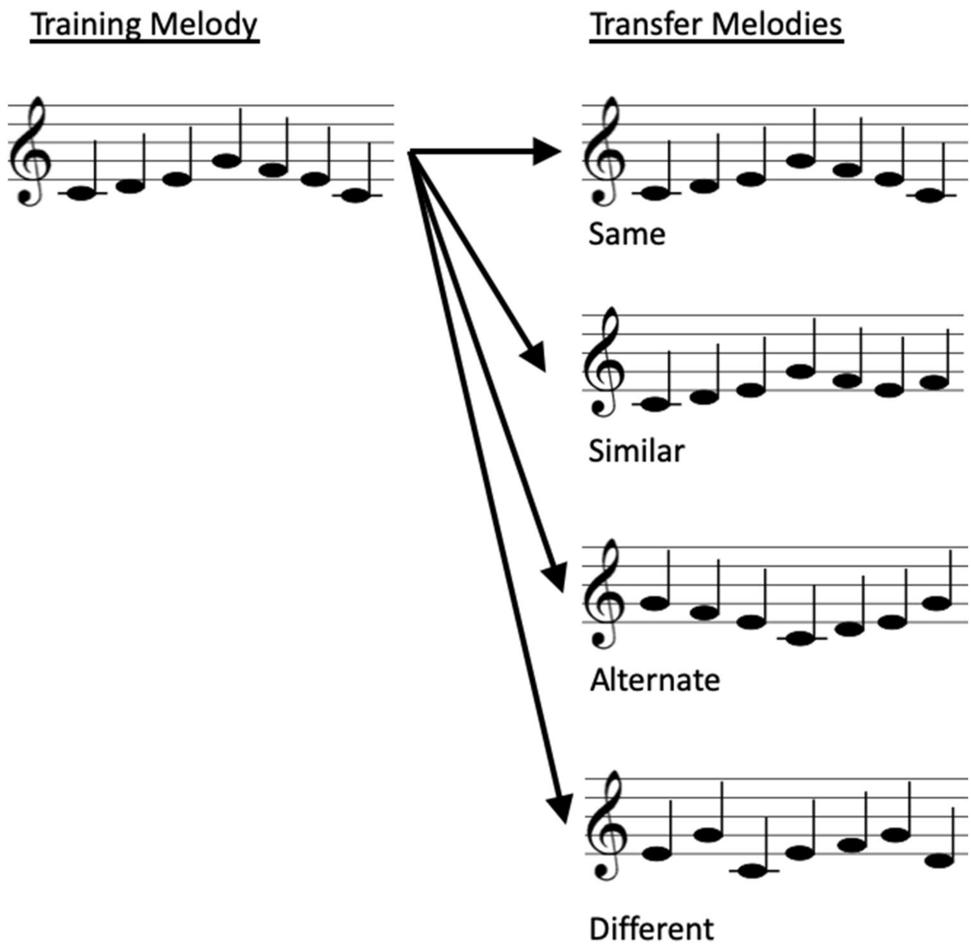

Fig. 2 Notation illustrating the training melody and the four different transfer melodies

melody (*Same Transfer*) was identical to the training melody. The second type (*Similar Transfer*) differed from the training melody only in the pitch of one note. The *Alternate Transfer* melody presented participants with the pitch contents that would result from the alternate auditory feedback, leading to an inversion of the pitch. Finally, the *Different Transfer* melody comprised different pitch events at every serial position, leading to a melody with a distinct melodic contour but the same tonal center as the training melody.

Procedure

All participants were randomly assigned to either the normal or inverted feedback condition during training. After answering questions related to their music background, they were seated in front of the keyboard with the music stand blocking their view of their right hand. The experimenter placed the participant's right-hand fingers on the white keys from C4-G4 and informed participants that they did not need to move their hand to play any of the melodies.

Participants then completed the *Training Phase* introduced in the previous section. On each trial, participants would listen to a subsequence and then attempt to reproduce it by pressing keys in the way that caused auditory feedback to match the target sequence. The time participants had to replicate the subsequence was cued by a single drumbeat sound, which initiated the response period, and then two successive drumbeats that signaled the end of the response period. Trials were repeated if the participant made any pitch errors or if the tempo was outside the range of 68 to 109 BPM. Two consecutive correct trials were necessary to progress to the next trial, and two incorrect trials led to a repetition of the previous trial.[2]

After completing all training subsequences shown in Fig. 1, as well as the full training melody, participants' learning of the training melody was further verified using a listening test in which the participant listened to the performed melody as well as a lure (a melody differing with respect to one pitch) and reported which one was learned in

[2] In Pfordresher & Chow (2019) only one successful trial was needed to progress. However, that study was limited by a high attrition rate (only 45% of recruited participants could complete the procedure). We reasoned that more repetitions of each progressive melody would facilitate memory consolidation. In support of this prediction, participant retention was much higher in this study (77%).

the training phase. Then participants were asked to perform the melody from memory and had to reproduce the melody correctly to go on to the test phase. Participants who failed either the listening test or performing from memory did not continue to the next phase.

During the *Test Phase*, participants performed a series of transfer melodies by ear after a single presentation. At the start of each trial, participants listened to one of the transfer melodies (see the previous section). Following a response cue (a drum beat), the participant attempted to reproduce the melody as accurately as possible. There were 16 test phase trials, organized into 4 successive blocks that each included a different ordering of the 4 transfer melodies. The order of conditions within each cycle varied according to a Latin Square. There were 4 different orderings of these cycles, counterbalanced across participants. These variations in order were used to circumvent any tendency for transfer performance to vary based on the serial position of the condition. Participants experienced the same mapping of auditory feedback during test phase trials as they had experienced during the training phase.

Data Analysis

Analyses focused on the accuracy of reproduction during training and test. Although we also analyzed timing (production rate and timing variability), these results were less robust than accuracy and, more importantly, less germane to the main question of interest. Qualitatively speaking, the pattern of results for measures of timing mirrored those for accuracy, which we report here.

The data were analyzed using Analyses of Variance (ANOVA) for all participants, followed by analyses that focus on patterns of results within each training group (pianists versus non-pianists). Comparisons within these groups were theoretically based, given that the primary question for this research is whether musical training leads to differences in sensorimotor integration.

Results

Training phase

As in Pfordresher and Chow (2019), we analyzed the learning rate using the number of trials it took participants to complete the training phase.[3] The minimum number of trials necessary was 18 because participants needed to complete each trial error-free twice. Figure 3 displays the number of

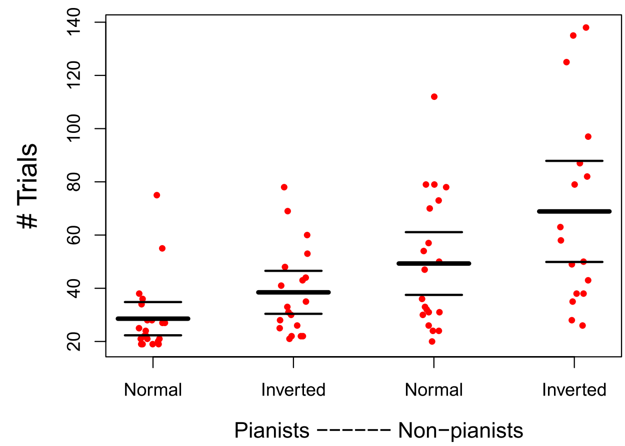

Fig. 3 Strip chart (with jitter) of the total number of trials needed to complete the training phase for each participant, with superimposed horizontal lines showing means surrounded by 95% confidence intervals

Table 2 Means (standard deviations) for number of trials during training as a function of subsequence number (Fig. 1) and as a function of musical training and feedback during training

Subsequence	Pianists		Non-Pianists	
	Normal	Inverted	Normal	Inverted
1	2.48 (1.97)	5.32 (2.60)	4.05 (4.38)	10.71 (9.59)
2	2.67 (2.06)	2.95 (1.35)	4.20 (3.81)	6.88 (6.09)
3	3.00 (2.37)	3.47 (2.09)	5.15 (4.40)	8.12 (6.61)
4	4.19 (3.74)	6.21 (5.48)	8.90 (8.90)	12.06 (9.69)
5	4.24 (3.33)	6.74 (6.35)	7.45 (5.95)	8.59 (5.66)
6	2.90 (1.81)	3.79 (2.84)	4.35 (2.46)	5.65 (4.69)
7	2.62 (1.02)	3.26 (1.73)	4.70 (3.18)	6.12 (5.98)
8	2.57 (0.98)	2.74 (1.28)	4.65 (3.31)	5.18 (4.56)
9 (full melody)	2.90 (1.26)	3.00 (1.60)	4.85 (2.87)	4.59 (2.43)

trials to complete learning as a function of piano experience group and training feedback. There was a significant main effect of experience, $F(1, 73) = 20.94$, $p < 0.001$, $\eta^2_p = 0.22$. Non-pianists required significantly more training trials than pianists to complete the training successfully, as in Pfordresher and Chow (2019). There was also a significant but much smaller effect of training feedback, $F(1, 73) = 6.93$, $p = 0.001$, $\eta^2_p = 0.09$. Participants who trained with inverted feedback required more training trials than those who trained with normal feedback. Although the interaction effect was not significant ($p = 0.38$), planned follow-up analyses of the training effect within each group suggested that the effect of training feedback on a number of training trials was only significant for pianists, $t(38) = 2.05$, $p = 0.047$, and not significant among non-pianists ($p = 0.065$).

Table 2 presents a closer look at the learning rate within each subsequence of training. A general trend that can be

[3] The pattern of results reported here remained the same when Log-transforming these data to better approximate a normal distribution.

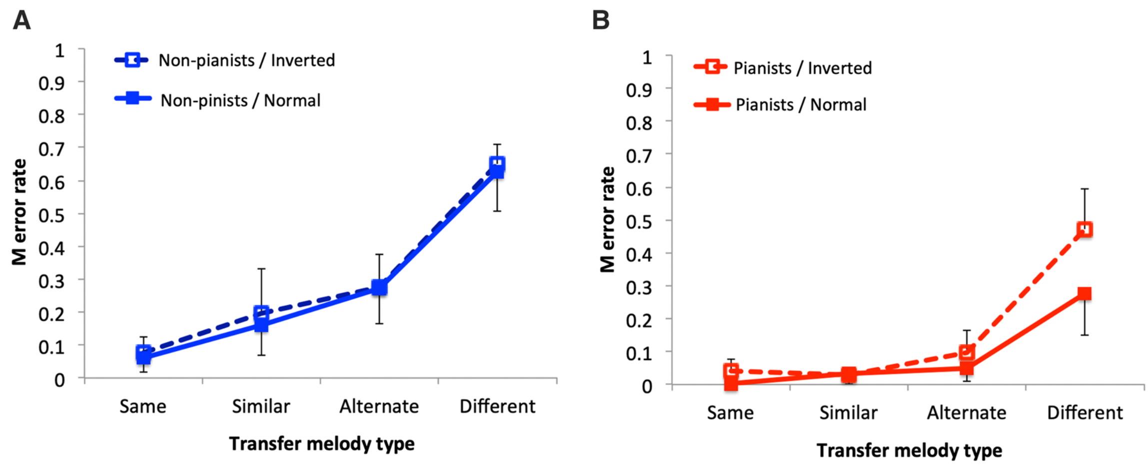

Fig. 4 Error rates at transfer for non-pianists (**a**) and pianists (**b**). Error bars represent 95% confidence intervals

seen here is a sharp improvement in learning rate from subsequence 5 to subsequence 6, at which point the participant has had exposure to all but the final two notes and starts to review subsequences learned earlier. An ANOVA that included the within-subjects factor subsequence in addition to experience and training feedback yielded a significant main effect of subsequence, $F(8, 584) = 10.94$, $p < 0.001$, $\eta^2_p = 0.13$, along with main effects of training feedback and experience, as noted earlier. There was also a subsequence × training feedback interaction, $F(8, 584) = 2.73$, $p = 0.007$, $\eta^2_p = 0.036$. The interaction reflected the fact that participants who trained with inverted feedback required more training trials for subsequences 1–5, and then used a similar number of training trials as those who trained with normal feedback for the remaining subsequences. There were no interactions associated with a piano experience.

Test phase

We analyzed success at transfer using the proportion of produced pitch errors for each transfer condition, aggregating across the four repetitions of each condition during the transfer phase.[4] Although other studies of transfer have focused on timing (e.g., Palmer & Meyer, 2000), those studies involved speeded performance based on music notation. By contrast, the present procedure emphasized imitative reproduction of an auditorily presented target. Measures of performance timing (mean inter-onset interval and timing variability) mirrored the results reported here.

There was a significant main effect of experience, $F(1, 73) = 42.05$, $p < 0.001$, $\eta^2_p = 0.37$, and transfer melody, $F(3, 219) = 141.03$, $p < 0.001$, $\eta^2_p = 0.66$, and a significant experience x transfer melody interaction, $F(3, 219) = 7.68$, $p < 0.001$, $\eta^2_p = 0.10$. Whereas all participants produced similar error rates when the transfer melody matched the training melody, non-pianists produced more errors when generalizing to novel melodies in transfer, particularly when the transfer melody had a distinct structure (the different melody condition). Figure 4 illustrates this effect in the context of a 3-way interaction involving training feedback, although no effects involving training feedback were significant in the omnibus ANOVA.

Planned follow-up ANOVAs focused on the interaction of training feedback and transfer melody within each experience group, and revealed different effects of training feedback that are apparent in Fig. 4. For non-pianists (Fig. 4A), there was a significant effect of transfer melody, $F(3, 105) = 82.71$, $p < 0.001$, $\eta^2_p = 0.70$, but no main effect of training feedback ($p = 0.67$) and no interaction ($p = 0.98$). Pairwise contrasts on the main effect of transfer melody (using the Bonferroni correction) indicated lowest error rates in the same melody condition, followed by the similar and alternate conditions (which did not differ from each other) and highest error rates for the different melody condition. Non-pianists thus exhibited difficulty at transfer in proportion with the similarity of transfer to training melody with respect to melodic structure, but also exhibited sensorimotor flexibility insofar as the effect of transfer melody showed no influence of pitch mapping established during training.

Pianists, in contrast (Fig. 4B), yielded significant main effects of training feedback $F(1, 38) = 5.8$, $p = 0.021$, $\eta^2_p = 0.13$, transfer melody, $F(3, 114) = 60.08$, $p < 0.001$, $\eta^2_p = 0.61$, and a training feedback x transfer melody interaction, $F(3, 114) = 4.24$, $p = 0.007$, $\eta^2_p = 0.10$. Pairwise

[4] The pattern of results reported here remained the same when analyzing the arc-sine square root transform of the data, yielding a closer approximation to the normal distribution.

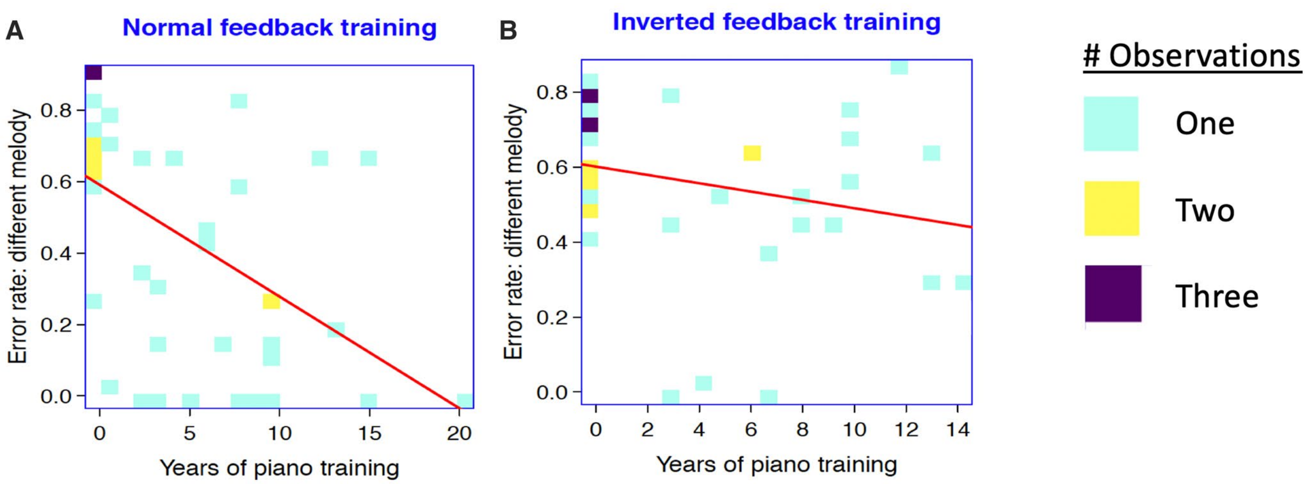

Fig. 5 Scatterplots illustrating the relationship between total years of piano experience (*X*) and mean error rates (*Y*) for different melody transfer conditions among participants who trained with normal (**a**) or inverted (**b**) feedback. Color differences account for the number of overlapping data points (see legend)

contrasts on the main effect of transfer melody (using the Bonferroni correction) revealed a different pattern than was found for non-pianists; error rates in the different transfer melody condition were significantly higher than the other three conditions, which did not differ from each other. Pianists thus exhibited greater facility overall in generalizing from same to similar and alternate transfer melodies than non-pianists.

The training feedback × transfer melody interaction among pianists was further analyzed with orthogonal post-hoc pairwise comparisons between trained feedback conditions within each transfer melody condition. Significant contrasts were found for the same ($p = 0.016$) and different ($p = 0.024$) melody conditions. In both cases, pianists who trained with inverted feedback made more errors than those who trained with normal feedback. It is important to note that whereas there were no errors made in the same transfer melody condition by pianists who trained with normal feedback, the proportion of errors made by pianists who trained with inverted feedback in this condition ($M = 0.04$) is within the range of errors often found among skilled pianists (e.g., Palmer & Pfordresher, 2003). Therefore, this result suggests that pianists who trained with inverted feedback exhibited greater difficulty learning a distinct melody than those who trained with normal feedback, thus exhibiting constraints to their generalization ability.

As in Pfordresher and Chow (2019) we conducted regression analyses to address how auditory feedback during training influenced performance by virtue of accumulated years of training, as opposed to categorizing participants into dichotomous groups. We focused on error rates at test while performing different transfer melodies, as this condition yielded the most dramatic differences as a function of both musical training (treated dichotomously) and training feedback. Figure 5a shows the relationship between years of musical training on the piano and errors at the test for those participants who trained with normal pitch mapping. As might be expected, participants with more piano training produced fewer errors than those with fewer years of training, $r(40) = -0.52$, $p < 0.001$. This reflects the way in which musical training facilitates generalization through the transfer of learning, as documented elsewhere (e.g., Palmer & Meyer, 2000). In contrast, years of musical training did not significantly correlate with errors while performing different transfer melodies for those participants who trained with inverted pitch mapping, $r(34) = -0.24$, $p = 0.156$, nor did years of experience on non-piano instruments correlate with errors for either feedback training group ($p > 0.25$ in both cases). Thus, similar to Pfordresher and Chow (2019), pianists failed to benefit from their accumulated experience after learning melodies based on this novel feedback mapping, even though they were highly effective at learning the initial melody based on this feedback. The present data suggest that pianists have a limited ability to generalize learning based on this novel mapping, and therefore exhibit generalization comparable to that exhibited by individuals with little to no experience playing the piano.

Discussion

Whereas a sensorimotor skill like music performance primarily causes enhancements in the flexibility, dexterity, and generalizability of motor planning, these improvements in performance may be constrained in ways that reflect encoding of the sensorimotor system in which these behaviors occur. Specifically, motor learning may enhance efficiency by prioritizing certain sensorimotor associations that are reinforced during learning. As a result, subsequent learning that explicitly counteracts the learned sensorimotor system may face constraints unlike those seen among individuals who have not undergone sensorimotor learning. Similar interference effects have been found in perceptual "over-learning" paradigms (Shibata et al., 2017). We focus on piano performance and the sensorimotor system based on mapping of the pitch to space on a standard keyboard.

Whereas Pfordresher and Chow (2019) addressed the stability of motor learning, the present study addressed the generalizability of motor learning and how that may be constrained by acquired sensorimotor associations. Pianists and non-pianists learned a melody by ear in a training phase and then attempted to reproduce several melodies by ear in a transfer phase that varied with respect to their similarity to the training phase melody. Importantly, and in contrast to our earlier study, the mapping of auditory feedback remained constant throughout the entire study. Ideal performance in the transfer phase, therefore, would result if participants did not simply learn the sequence of motor movements used to perform the training melody, but instead acquired broader knowledge about the sensorimotor system used during training.

Pianists in general exhibited strong sensorimotor learning abilities. They progressed through training rapidly, relative to non-pianists, and performed nearly error-free in most transfer conditions. However, sensorimotor constraints on their generalization ability were apparent when the transfer melody was highly distinct from the training melody. In this condition, pianists who experienced inverted mapping exhibited significantly poorer performance than pianists who experienced normal mapping of the pitch. In this respect, pianists' limited generalization when learning involved a diversion from their acquired sensorimotor experience suggests a kind of constraint or "cost" associated with musical training, which accompanies the considerable benefits also associated with this acquired skill. By contrast, although non-pianists performed more poorly than pianists in general, they exhibited no differences at the test as a function of auditory feedback during training. Thus, as in Pfordresher and Chow (2019), non-pianists exhibited a relatively greater level of sensorimotor flexibility than pianists.

The present results complement other results from the literature on sensorimotor associations formed during music learning (for reviews, see Herholz & Zatorre, 2012; Novembre & Keller, 2014; Zatorre et al., 2007) in suggesting that musical training results in long-term consolidation of associations between action and perception. These associations can affect performance on basic motor tasks, occasionally leading to interference effects for musicians when movement patterns conflict with these associations. For instance, pianists experience interference when the direction of a movement conflicts with pitch motion implied by an accompanying melodic pattern (Taylor & Witt, 2015). Similar to these studies, the present data suggest that musical training may benefit performance when sensorimotor contingencies match associations formed in learning while diminishing performance for situations in which these contingencies are disrupted.

As in our previous study, we used a more liberal criterion for classification as pianist: 3 years, as opposed to the more dominant standard in the literature which is 6 years of private lessons (Zhang, Susino, McPherson, & Schubert, 2020). The rationale for this classification is that the present research program focuses primarily on the formation of sensorimotor associations, which form rapidly and early in musical training (cf. Bangert & Altenmüller 2003; Herholz & Zatorre, 2012; Lahav, Saltzman, & Schlaug, 2007), as opposed to expert qualities of performance. Nevertheless, the regression analyses shown in Fig. 5 suggest that similar, or even larger, effects of trained feedback may result if we used a more conservative and standard criterion. Moreover, the result of sensorimotor learning among non-pianists in the present study suggests that these rapidly formed associations may be based on flexible contingencies, in contrast with more strongly solidified associations formed over the long term.

There were some differences in the present study from our previous work that warrant consideration. First, unlike what was found by Pfordresher and Chow (2019), the type of feedback during training influenced learning rate in the current study, particularly for subsequences practiced early in training. Participants required significantly more learning trials when experiencing inverted feedback than when experiencing normal feedback, although this difference was small relative to the effect of musical training and was only significant within pianists. Nevertheless, it is important to consider whether effects at transfer for pianists may be due simply to the level of difficulty evident during training. In this context, it is important to note that an effect based only on the learning rate should be found across all transfer conditions. In contrast, the effect of training feedback was specific to only one transfer condition: the different transfer melody. A second difference from our previous work was that only one melody was used during training. This was an important constraint because learning multiple melodies during training (as in Pfordresher & Chow, 2019) would have required generalization across melodies both during training and during transfer. Although the use of one melody is limiting, previous similar studies on the role of auditory feedback have yielded consistent effects across different melodies that are matched with respect to complexity (for a review, see Pfordresher, 2019).

A larger issue that ties into the present research has to do with the general malleability of the sensorimotor system prior to motor learning. In other words, are we effectively "blank slates" when we learn a novel task like playing the piano? Although the present data are largely consistent with such a view it is important to consider an important caveat. Although an inverted pitch mapping deviates from what is typical for a piano, it still preserves the kind of sensorimotor contingencies that characterize most of daily life: The mapping of the pitch to space is directionally consistent, proportional, and temporally synchronous. All of these factors may promote motor learning (Pfordresher, 2019). Future tests of the "blank slate" view should involve deviations from these principles to explore the limits of sensorimotor flexibility among non-pianists.

Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest.

Ethical standards All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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