Psychonomic Bulletin & Review
https://doi.org/10.3758/s13423-018-1535-5

BRIEF REPORT

A cost of musical training? Sensorimotor flexibility in musical sequence learning

Peter Q. Pfordresher[1] · Karen Chow[2]

Abstract
We report an experiment that tested the flexibility of sensorimotor learning in sequence production. Nonpianists and pianists learned simple melodies by ear under one of two auditory feedback conditions: one with normal pitch mapping (higher pitches to the right) and one with an inverted (reversed) mapping. After learning, both groups played melodies from memory while experiencing each feedback condition. Both groups exhibited sensorimotor learning and produced fewer errors at test while hearing the feedback used during training as opposed to the alternate feedback condition. However, learning was unstable for pianists who learned melodies with an inverted feedback condition, who produced more errors at test than pianists who learned melodies with normal-pitch mapping. Acquiring musical skill may therefore constrain subsequent sensorimotor flexibility.

Keywords Skill acquisition · Sensorimotor learning · Auditory feedback · Musical training · Music performance

In the Austrian courts of 1762, Mozart impressed the nobility by playing the keyboard blindfolded and at times in an inverted position. Although Mozart is an extreme case, it is generally true that expert musicians must develop highly automatized sensorimotor associations so that they may produce music in widely varying contexts. How far does this flexibly extend? In the present experiment, we used a training paradigm to test sensorimotor flexibility among pianists and nonpianists. By having different groups of participants learn melodies on standard or nonstandard pitch/keyboard mapping, we tested whether the skills learned among pianists are of a general nature, extending even to novel sensorimotor regimes, or are *constrained*, exhibiting limits on the situations in which the gains associated with training will manifest.

Several previous studies suggest that experience playing the piano leads to associations between pitch height and spatial locations on a keyboard that may constrain performance in related sensorimotor tasks. For instance, trained musicians are slower at classifying visual or auditory stimuli when target stimuli co-occur with task-irrelevant pitches that contradict standard pitch/space associations. This can occur when high pitches are mapped to vertically low as opposed to high response locations or high pitches are mapped to horizontally left-side as opposed to right-side locations (Cho, Bae, & Proctor, 2012; Lidji, Kolinsky, Lochy, & Morais, 2007; Rusconi, Kwan, Giordano, Umilta, & Butterworth, 2006; Stewart, Verdonschot, Nasralla, & Lanipekun, 2013; Taylor & Witt, 2015). Moreover, the performance of melodies from memory by pianists can be disrupted if pitches are altered to form a pitch sequence whose melodic contour counteracts the planned pattern of finger movements (Pfordresher, 2006).

These effects reflect the fact that the acquisition of musical skills, such as playing the piano, leads to sensorimotor associations that cause the perception of pitch events to elicit motor activity used to produce those same pitches (D'Ausilio, Altenmüller, Olivetti Belardinelli, & Lotze, 2006). Perhaps these learned associations make it difficult for pianists to *recalibrate* when presented with novel associations between pitch and space on a keyboard. However, we know of no studies to date that have given pianists the opportunity to acquire such novel associations in a learning paradigm.

Electronic supplementary material The online version of this article (https://doi.org/10.3758/s13423-018-1535-5) contains supplementary material, which is available to authorized users.

✉ Peter Q. Pfordresher
pqp@buffalo.edu

[1] University at Buffalo, State University of New York, 206-B Park Hall, Buffalo, NY 14226, USA

[2] University at Buffalo, State University of New York, 226 Park Hall, Buffalo, NY 14226, USA

Moreover, acquiring a musical skill relies on and thus may enhance the flexibility of learning, borne out in cognitive transfer and planning (Drake & Palmer, 2000; Palmer & Meyer, 2000). If so, the development of musical skill may enhance the ability of musicians to perform under various sensorimotor relationships between actions and pitches, in contrast to the implications of studies showing stimulus–response conflict.

Relatively few past studies address the propensity for nonpianists to acquire nonstandard sensorimotor associations. This leaves open the question of whether individuals prior to musical skill acquisition function as a tabula rasa with respect to possible sensorimotor associations or whether individuals are predisposed to form certain kinds of associations. A few existing studies suggest the latter interpretation. Neuroimaging studies adopting a learning-by-ear paradigm have shown that nonpianists can form audiomotor associations based on musical training within 20 minutes, thus suggesting that standard mapping of pitch to space on a keyboard may be well-suited to sensorimotor learning (Bangert & Altenmüller 2003; Lahav, Saltzman, & Schlaug, 2007; Mutschler et al., 2007). In addition, a study in which nonpianists (who were also musicians) learned melodies on a normal keyboard or one in which the mapping of pitch to space was inverted (high pitch to the left, low pitch to the right) showed an advantage for normal pitch mapping, at least for right-handed participants (Laeng & Park, 1999). This result suggests that the standard right/high left/low space-to-pitch mapping may be well suited to the cerebral dominance of the larger portion of the population (Jäncke, 2002). Finally, it is important to note that nonpianists show patterns of sensitivity similar to pianists, though reduced in magnitude, when presented with alterations of auditory feedback pitch during the production of simple melodies (Pfordresher, 2012).

In the present research, we test the effect of experience on the flexibility of sensorimotor learning in a musical keyboard production task. Pianists and nonpianists learned melodies by ear on a keyboard in which the mapping of pitch to space was normal (left/low, right/high) or inverted (left/high, right/low). In a subsequent test phase, participants performed these melodies from memory while hearing either the feedback they experienced during learning or the alternate pitch mapping. If learning is truly based on sensorimotor associations for the learned sequence, then performance should suffer while experiencing auditory feedback from the alternate pitch mapping, even if that mapping is standard to the keyboard. If, on the other hand, learning is based on motor-specific commands (e.g., if a participant attempts to "tune out" auditory feedback after learning the keyboard sequence), then no effects of pitch mapping at test should be found.

The test phase was also designed to test the stability of learning by placing demands on the performers that were not present during training. According to dynamical systems approaches (e.g., Kelso, 1995), a stable state is resistant to perturbations. Thus, if learning based on normal or inverted pitch mapping is similarly stable, overall performance at test would not differ across training groups. By contrast, if learning based on an inverted pitch mapping is unstable, then performance at test would suffer for that training group in contrast to normal feedback training

Method

Participants

Seventy-eight students (M_{age} = 19 years, % female = 45) from the University at Buffalo participated in exchange for course credit. Those who met the criterion of having at least 3 years of piano experience were categorized as pianists, while those with fewer than 3 years were categorized as nonpianists. 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, $F(1, 74) = 175.22$, $p < .001$, η_p^2, = .70, and on piano lessons, $F(1, 74) = 102.44$, $p < .001$, $\eta_p^2 = .58$, as would be expected, and no effect for total years of experience on some other instrument ($p = .06$). Pianists also had significantly more years of lessons on nonpiano instruments than did nonpianists, though with a smaller effect size, $F(1, 74) = 8.67$, $p = .004$, $\eta_p^2 = .10$.The sample used for this study completed a training phase, described in the next section, in order to demonstrate successful learning of stimulus melodies. Participants were excluded only if it was clear that they could not complete training in enough time to finish the experiment within 60 minutes. Due to the challenge of this task, 45% of the original sample ($N = 143$) could not be included. The attrition rate was higher for nonpianists (54%) than for pianists (32%), and led to differences in sample size across conditions, an issue we address in the Supplementary Materials.

Materials and equipment

Participants learned two stimulus melodies "by ear" using a progressive trial-and-error training phase modeled after Bangert and Altenmüller (2003). Each stimulus melody comprised eight 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, whereas the pitch-to-key mapping was reversed for participants assigned to the inverted trained feedback condition.

Each training trial presented an isochronous piano sequence ranging from three to eight notes in length. The piano

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

Trained feedback/Experience group (*n*)	Piano experience	Piano lessons	Other instrumental experience	Other instrumental lessons
Normal /Pianists (25)	7.86 (3.26)	5.14 (2.19)	5.17 (4.69)	3.17 (1.49)
Inverted/Pianists (14)	9.14 (3.67)	7.43 (4.73)	3.92 (4.55)	2.45 (2.45)
Normal/Nonpianist (16)	0.75 (0.93)	0.56 (0.97)	2.81 (4.10)	0.75 (1.49)
Inverted/Nonpianist (23)	0.58 (1.17)	0.43 (0.84)	3.37 (3.34)	1.03 (1.43)

sequences were prerecorded 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).

Participants completed eight training trials that were designed to teach participants two stimulus melodies, presented in Trials 5 and 8. The progression of training trials is shown in Table 2. The first two trials consisted of three-note melodies that oriented participants to the pitch mapping, although the very first trial comprised the first three notes of Stimulus Melody 1. Next, participants completed two trials comprising subsequences (Notes 1–4, followed by Notes 5–8) of the first stimulus melody that was to be performed in the test phase. Next participants completed Stimulus Melody 1, followed by two trials with subsequences of the second stimulus melody, and finally Stimulus Melody 2.

Procedure

All participants were randomly assigned to either the normal or inverted trained feedback condition. 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 in order 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 sequence and then attempt to reproduce it by matching auditory feedback to the target sequence. The time participants had to replicate the sequence was cued by a single drumbeat sound, which initiated this period, and then two successive drumbeats that signaled the end of the response period. The presentation of a new sequence on the next trial was a cue to participants that they performed correctly. Trials were repeated if the participant made any pitch errors or if the tempo was outside the range of 68 to 109 BPM. Successful reproduction led to a more challenging successive trial. After completing all eight training trials error free, participants completed a memory test to ensure that they could perform each stimulus melody from memory without errors.

During the *test phase*, participants performed both stimulus melodies from memory on different trials. At the start of each trial, participants listened to one of the two melodies. Following a response cue (a drumbeat), they performed the melody repeatedly for approximately nine repetitions (72 key presses), without pausing between repetitions. Within each trial, auditory feedback would switch from one feedback condition to another after every 24 key presses (three error-free repetitions). Participants experienced normal pitch mapping, inverted pitch mapping, or silence during each of these within-trial segments. The stimulus melody alternated on every other trial, and participants completed six trials in all, with the ordering of trial segments (feedback presentation) varying across trials according to a Latin square.

Results

Training phase

We first address the difficulty of training across the four participant groups using the number of trials needed for completion (see Fig. 1). The minimum number of trials possible is eight (cf. Table 2). On average, nonpianists required more training trials to reach criterion ($M = 30.08$, $SD = 20.44$) than did pianists ($M = 15.67$, $SD = 8.64$), $F(1, 74) = 14.99$, $p < .001$, $\eta_p^2 = .17$, although there was a large amount of variability within groups and many nonpianists exhibited rapid learning. More important, there was no effect of trained feedback condition ($p = .92$), and no interaction ($p = .83$).

Test phase

Errors in test phase were computed from an algorithm that compares the produced sequence to the intended sequence (Large, 1993; Palmer & van de Sande, 1993, 1995).[1] Mean error rates across trial segments (feedback conditions) were analyzed using a 2 (piano experience: pianist, nonpianist) × 2 (trained feedback: normal, inverted) × 2 (test feedback: normal, inverted) mixed-design ANOVA, with piano experience and trained feedback as between-subjects factors and test feedback as a within-subjects factor (see Fig. 2). We

---

[1] Analyses of timing are reported in the Supplementary Materials.

Table 2 Sequences used in training phase for normal and inverted feedback conditions

Training trial	Trial type	Normal feedback	Inverted feedback	Key press
1	Orientation	c-d-e	e-d-c	c-d-e
2	Orientation	e-d-c	c-d-e	e-d-c
3	Sub-sequence	c-d-e-g	g-f-e-c	c-d-e-g
4	Sub-sequence	f-e-d-e	d-e-f-e	f-e-d-e
5	Melody 1	c-d-e-g-f-e-d-e	g-f-e-c-d-e-f-e	c-d-e-g-f-e-d-e
6	Sub-sequence	g-e-f-d	c-e-d-f	g-e-f-d
7	Sub-sequence	c-d-e-f	g-f-e-d	c-d-e-f
8	Melody 2	g-e-f-d-c-d-e-f	c-e-d-f-g-f-e-d	g-e-f-d-c-d-e-f

simplified these analyses by dropping the silent feedback condition (see Supplementary Materials for results including this condition). There was a significant main effect of piano experience, $F(1, 74) = 13.88$, $p < .001$, $\eta_p^2 = .16$, a significant Piano Experience × Trained Feedback interaction, $F(1, 74) = 6.04$, $p = .002$, $\eta_p^2 = .08$, and a significant Trained Feedback × Test Feedback interaction, $F(2, 148) = 22.77$, $p < .001$, $\eta_p^2 = .24$.

Not surprisingly, pianists made fewer errors overall than nonpianists did, leading to the significant main effect of piano experience. However, this advantage was qualified by the significant interaction of piano experience with trained feedback. Post hoc Tukey's HSD contrasts ($\alpha = .05$) revealed significantly lower error rates between musicians who trained with normal pitch mapping ($M_{\text{error rate}} = 2\%$, $SD = 3.3\%$) and every other group, including pianists who trained with inverted pitch ($M_{\text{error rate}} = 5.1\%$, $SD = 4.4\%$). By contrast, pianists who trained with inverted pitch mapping, despite rapidly learning sequences, produced errors during the test phase at a rate that did not differ significantly from participants who had almost no experience performing the piano (M for nonpianists who trained with inverted pitch = 5.7%, $SD = 3.5\%$; M for nonpianists who trained with normal pitch = 6%, $SD = 3.3\%$).

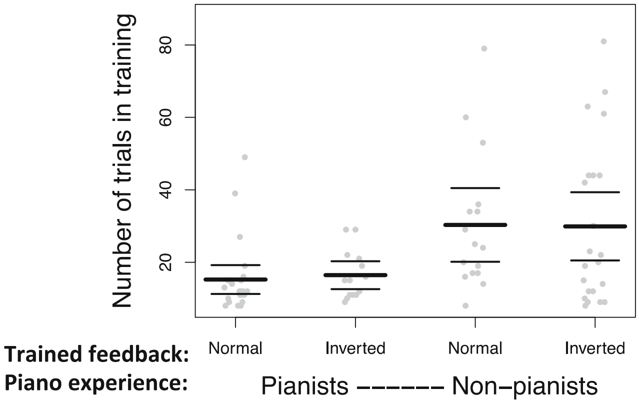

Fig. 1 Strip chart (with jitter) of the total number of trials per participant by piano experience and training feedback, with superimposed horizontal lines showing means surrounded by 95% confidence intervals

The Trained Feedback × Test Feedback interaction was further explored using a contrast analysis designed to address whether participants performed more accurately while experiencing the feedback condition used in training. For pianists who trained with inverted feedback, this analysis addresses whether recalibration to the new sensorimotor mapping was successful. For each participant, we subtracted the mean error rate for normal feedback trials from the mean error rate for inverted feedback trials. This difference is positive if performance is more accurate (i.e., a lower error rate) during the normal feedback trials, and negative if performance is more accurate during inverted feedback trials. A two-way ANOVA on these factors only yielded a main effect of trained feedback, $F(1, 74) = 24.06$, $p < .001$, $\eta_p^2 = .25$, but no main effect of piano experience ($p = .25$) and no interaction ($p = .30$), as shown in Fig. 3. The mean contrast score across participants who were trained with normal pitch mapping was positive ($M = .013$, $SD = .023$) and significantly greater than zero, $t(40) = 3.66$, $p < .001$, whereas the mean contrast for participants who were trained with inverted pitch mapping was negative ($M = -.013$, $SD = .026$) and significantly less than zero, $t(36) = -3.01$, $p = .005$. These results support the presence of sensorimotor learning for both training groups as a function of trained feedback.

Individual differences

Our division of participants into two discrete groups masks potentially informative differences within groups that result from years of piano experience. As shown in Fig. 4, piano experience significantly correlated with errors in the test phase for those participants who had been trained with normal auditory feedback, $r(39) = .46$, $p < .01$, but not for participants who had been trained with inverted feedback, $r(35) = 0$.

Discussion

This experiment documents how task-specific sensorimotor associations influence the flexibility of sensorimotor learning

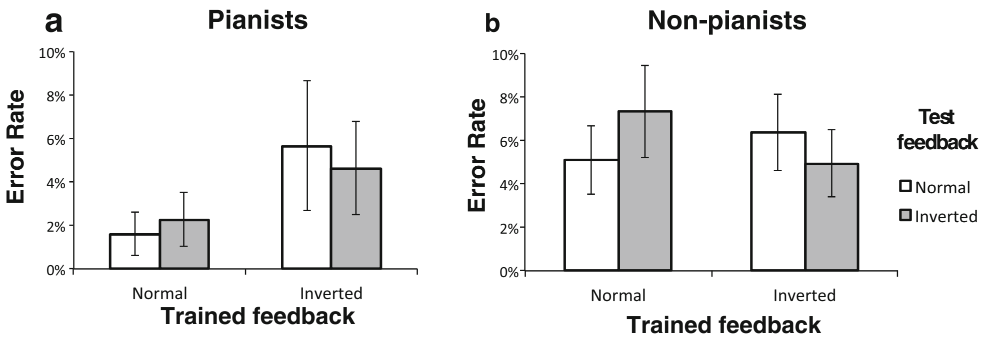

Fig. 2 Mean error rates across all experimental conditions in the test phase. Separate panels are used to display date from pianists (**a**) and nonpianists (**b**). Error bars reflect 95% confidence intervals

in the context of music performance. Both nonpianists and experienced pianists demonstrated some ability to learn melodic sequences based on either a standard or inverted mapping of pitch to space. Pianists learned melodies more rapidly than did nonpianists, regardless of the pitch mapping they experienced, thus exhibiting an advantage based on their experience. However, the apparent flexibility among pianists during training did not always persevere through the more challenging test phase. At test, pianists who learned sequences with inverted pitch mapping generated significantly more errors than did pianists who learned sequences with normal pitch mapping. Nonpianists, though generating more errors on average than pianists (as would be expected), did not exhibit any difference in accuracy based on the feedback mapping used during training. Thus, learning based on an unusual sensorimotor regime was unstable for pianists, leading to performance at test that did not reflect the sensorimotor experience of this group.

Two features of the present experiment are critical. First, all learning was based on audiomotor associations. At no point were participants presented with a visual representation of melodies, which may induce associations between pitch and space, particularly for pianists. Thus, we found more effective flexibility in this study than a similar study by Laeng and Park (1999), in which pianists and nonpianists (who could read music) exhibited difficulty learning melodies based on the same inverted mapping used here, but in a learning paradigm that relied on standard music notation. The second critical feature is the use of auditory feedback manipulations in the test phase. The fact that feedback manipulations affected performance counters the possibility that learning may have been based simply on encoding finger movements and not on sensorimotor associations. If that had been the case, then no effect of altered auditory feedback would have emerged.

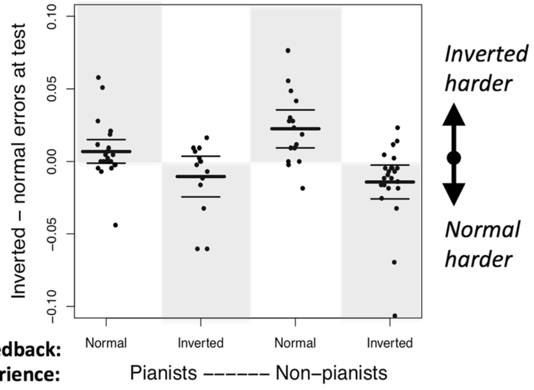

Fig. 3 Strip chart (with jitter) of differences between mean error rates during inverted feedback trials and normal feedback trials in the test phase for each participant, with superimposed horizontal lines showing means surrounded by 95% confidence intervals. Positive scores indicate that participants performed more accurately in normal than inverted feedback, and negative scores indicate that participants performed more accurately in inverted than normal. Shaded gray areas highlight the sign of differences that would be anticipated if participants have consolidated the sensorimotor pitch mapping used during training

It is important to note that the constraining effect of piano experience on sensorimotor learning found here was not apparent during training. Both groups of pianists completed the training phase after a similar number of trials, and analyses of errors during these phases revealed no differences across these groups. It was only when pianists had to recall previous melodies during trials in which auditory feedback could be altered that the limitations of this learning emerged. At the same time, effects of different feedback conditions did suggest that many pianists who experienced inverted trained feedback recalibrated their sensorimotor associations even in the brief training period we gave them. Thus, in a span of several minutes, the kind of pitch mapping these pianists had experienced for years functioned as a disruptive form of altered auditory feedback. Were we to extend training over several days, as in other similar studies (e.g., Bangert & Altenmüller 2003), then this kind of plasticity would likely be more apparent. Thus, although we find that piano experience is a constraining factor in learning sensorimotor associations, this constraint may not be rigid.

One important result we found had to do with flexibility of learning among nonpianists. This group had minimal formal musical training, even given the fact that they passed the difficult training regime, and thus provides a useful gauge of what kind of sensorimotor associations exist at the beginning of musical training. As discussed before, studies on stimulus–

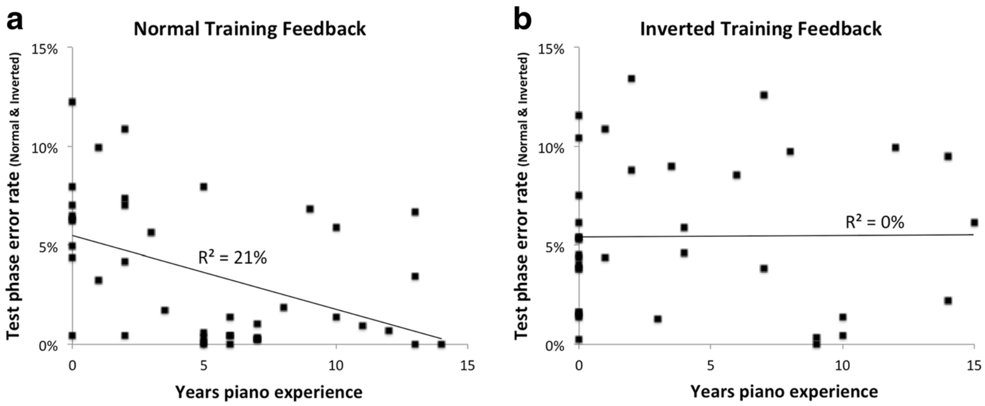

Fig. 4 Scatterplots illustrating the relationship between total years of piano experience (*x*-axis) and mean error rates across all test-phase trials with normal or inverted pitch feedback (*y*-axis), for participants who trained with normal pitch mapping (**a**) or inverted pitch mapping (**b**)

response compatibility effects based on associations of pitch height with space are mixed concerning whether non-pianists associate rightward locations with high-pitches, as is the case with pianists (Lidji et al., 2007; Rusconi et al., 2006; Taylor & Witt, 2015). Here, however, we demonstrate that nonpianists can be trained for either kind of association, thus suggesting high plasticity with respect to these kinds of associations. It is worth noting, however, that both feedback-training conditions here involved a completely proportional mapping of pitch to space, and thus both regimes are likely to be easily learned based on sensorimotor associations that extend, in general, across motor skills. For instance, a mapping of pitch to space where movements to the right did not lead to a consistently higher or a consistently lower pitch would likely lead to poor learning, even among nonpianists.

The results of this study have implications for sensorimotor learning across multiple instruments and domains beyond music. For example, how are different pitch mappings mentally represented in a musician who plays a piano, violin, and clarinet, each of which has a different pitch–space orientation (cf. Lachmair et al., 2017)? Further investigation is needed to examine what other aspects of one's musical or nonmusical experience contribute to the formation of pitch–space relations that might affect motor execution. If prior task-specific experiences constrain one's ability to adapt to a new mapping system, then perhaps the bigger question to ask is how one should improve the design of a sensorimotor training system in order to facilitate pitch–space plasticity. Because the current study used a relatively simple trial-and-error learning regime, using a short training session, there is the possibility that one could observe more accurate performances to inverted feedback given a more rigorous training session and over a longer period of time, similar to that used in longitudinal studies on piano practice (Bangert & Altenmüller 2003; Herholz, Coffey, Pantev, & Zatorre, 2016). Future research should also assess the strength and persistence of learned feedback beyond that of the immediate test phase, to determine the extent to which the change is relatively permanent (Salmoni, Schmidt, & Walter, 1984). Understanding the effects of increased task-specific experiences on executing novel auditory–motor pairings imparts our awareness of the lasting effects of training on long-term learning. In a broader context, the present results bear some similarity to constraints on learning seen in adults who struggle to acquire a new language, having consolidated the sensorimotor contingencies of languages learned early in life (e.g., Kuhl, 2004). The interplay between plasticity and constraint found here thus might be representative of processes in sensorimotor learning across domains.

Acknowledgements This research was supported in part by NSF grant BCS-1256964. We thank Kathryn Toffolo and Catherine Moore for help with data collection. We thank Emma Greenspon, Tim Pruitt, and two anonymous reviewers for helpful comments on previous versions of this manuscript. Correspondence concerning this article may be sent to pqp@buffalo.edu.

References

Bangert, M., & Altenmüller, E. O. (2003). Mapping perception to action in piano practice: A longitudinal DC-EEG study. *BMC Neuroscience, 4*, 26. doi:https://doi.org/10.1186/1471-2202-4-26

Cho, Y. S., Bae, G. Y., & Proctor, R. W. (2012). Referential coding contributes to the horizontal SMARC effect. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 726–734.

D'Ausilio, A., Altenmüller, E., Olivetti Belardinelli, M., & Lotze, M. (2006). Cross-modal plasticity of the motor cortex while listening to a rehearsed musical piece. *European Journal of Neuroscience, 24*, 955–958.

Drake, C., & Palmer, C. (2000). Skill acquisition in music performance: Relations between planning and temporal control. *Cognition, 74*, 1–32.

Finney, S. A. (2001). FTAP: A Linux-based program for tapping and music experiments. *Behavior Research Methods Instruments & Computers, 33*, 65–72.

Herholz, S. C., Coffey, E. B. J., Pantev, C., & Zatorre, R. J. (2016). Dissociation of neural networks for predisposition and for training-related plasticity in auditory-motor learning. *Cerebral Cortex, 26*, 3125–3134.

Jäncke, L. (2002). The case of a left-handed pianists playing a reversed keyboard: A challenge for the neuroscience of music. *NeuroReport, 13*, 1579–1583.

Kelso, J. A. S. (1995). Dynamical patterns: The self-organization of brain and behavior. Cambridge, MA: MIT Press.

Kuhl, P. K. (2004). Early language acquisition: Cracking the speech code. *Nature Reviews Neuroscience, 5*, 831–843.

Lachmair, M., Cress, U., Fissler, T., Kurek, S., Leininger, J., & Nuerk, H.-C. (2017). Music-space associations are grounded, embodied and situated: Examination of cello experts and non-musicians in a standard tone discrimination task. *Psychological Research*. Advance online publication. doi:https://doi.org/10.1007/s00426-017-0898-y

Laeng, B., & Park, A. (1999). Handedness effect on playing a reversed or normal keyboard. *Laterality, 4*, 363–377.

Lahav, A., Saltzman, E., & Schlaug, G. (2007). Action representation of sound: Audiomotor recognition network while listening to newly acquired actions. *The Journal of Neuroscience, 27*, 308–314.

Large, E. W. (1993). Dynamic programming for the analysis of serial behaviors. *Behavior Research Methods, Instruments, & Computers, 25*, 238–241.

Lidji, P., Kolinsky, R., Lochy, A., & Morais, J. (2007). Spatial associations for musical stimuli: A piano in the head? *Journal of Experimental Psychology: Human Perception and Performance, 33*, 1189–1207.

Mutschler, I., Schulze-Bonhage, A., Glauche, V., Demandt, E., Speck, O., & Ball, T. (2007). A rapid sound-action association effect in human insular cortex. *PLOS ONE, 2*, e259.

Palmer, C., & Meyer, R. K. (2000). Conceptual and motor learning in music performance. *Psychological Science, 11*, 63–68.

Palmer, C., & van de Sande, C. (1993). Units of knowledge in music performance. *Journal of Experimental Psychology: Learning Memory and Cognition, 19*, 457–470.

Palmer, C., & van de Sande, C. (1995). Range of planning in music performance. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 947–962.

Pfordresher, P. Q. (2006). Coordination of perception and action in music performance. *Advances in Cognitive Psychology: Special Issue: Music performance, 2*, 183–198.

Pfordresher, P. Q. (2012). Musical training and the role of auditory feedback during performance. *Annals of the New York Academy of Sciences, 1252*, 171–178.

Rusconi, E., Kwan, B., Giordano, B. L., Umilta, C., & Butterworth, B. (2006). Spatial representation of pitch height: The SMARC effect. *Cognition, 99*, 113–129.

Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: A review and critical reappraisal. *Psychological Bulletin, 95*, 355–386.

Stewart, L., Verdonschot, R. G., Nasralla, P., & Lanipekun, J. (2013). Action–perception coupling in pianists: Learned mappings or spatial musical association of response codes (SMARC) effect? *The Quarterly Journal of Experimental Psychology, 66*, 37–50.

Taylor, J. E., & Witt, J. K. (2015). Listening to music primes space: Pianists, but not novices, simulate heard actions. *Psychological Research, 79*, 175–182.