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Musical training and the role of auditory feedback during performance

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Recent research has shown that music training enhances music-related sensorimotor associations, such as the relationship between a key press on the keyboard and its associated musical pitch (auditory feedback). Such results suggest that the role of auditory feedback in performance may be based on learned associations that are task specific. Here, results from various studies will be presented that suggest that the real state of affairs is more complex. Several recent studies have shown similar effects of altered auditory feedback during piano performance for pianists and individuals with no piano training. Other recent research suggests dramatic differences between pianists and nonmusicians concerning the influence of auditory feedback on melody switching that suggest greater influence of auditory feedback among nonmusicians than pianists. Taken together, results suggest that musical training refines preexisting sensorimotor associations.

Keywords: auditory feedback; musical expertise; sensorimotor coordination; sequence production

Introduction

The performing musician is, in a sense, also a member of the audience insofar as he or she perceives the music being performed in the form of auditory feedback. A compelling question thus concerns the role of auditory feedback for the performer. Whereas earlier accounts proposed that performers use auditory feedback for error monitoring,[1–3] more recent data suggest a limited role for auditory feedback.[4–6] Existing data from the domain of music performance suggest that performers are sensitive both to the way in which auditory feedback is coordinated with actions in terms of the timing of pitch onsets, and to the way that action sequences are coordinated with pitch patterns.[7–11]

Most studies concerning the role of auditory feedback have adopted the altered auditory feedback (AAF) paradigm, in which participants produce an action sequence although hearing auditory feedback that differs from what one would usually expect. Effects of such alterations on the planning and execution of musical sequences can be used to determine how and to what degree performers rely on auditory feedback. In my lab, we address the role of auditory feedback in music performance among both musically trained and untrained populations, by incorporating simplified melodies and forms of music notation that are easily learnable by nonmusicians.[9] In addition to the AAF paradigm, other paradigms can also be used to assess the role of auditory feedback during music performance, which are discussed here.

In this paper, I consider how musical expertise influences the role of auditory feedback during music performance. Music performance offers an excellent context in which to explore questions related to expertise, given large individual differences. Furthermore, despite such large-scale differences in expertise, most humans possess elaborate implicit knowledge of the rules that guide musical pattern formation.[12,13] As such, I review here the results of several recent studies in which participants of varying musical experience produce short musical sequences on a keyboard, in experiments designed to test the kind of associations that these participants

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have between their actions and resulting pitches. I focus specifically on associations with respect to pitch content, rather than synchronization between actions and sounds (as in traditional delayed auditory feedback), because pitch-based associations are most likely to be shaped by experience.

Three views of the learning process

Before discussing experimental effects of training on the role of auditory feedback during performance, I first consider three canonical hypotheses concerning the relationship one might expect, based on long-standing trends in research on perception and action.

Hypothesis 1: strict associationism

The first hypothesis follows from a standard associationist view, first articulated in psychology in the "serial chaining" hypothesis of William James,[14] and expanded on in the "closed loop" theory of motor learning.[15] According to this view, the novice has no associations between actions and pitches before training. Over the course of training, these associations form and become solidified. Thus, whereas an

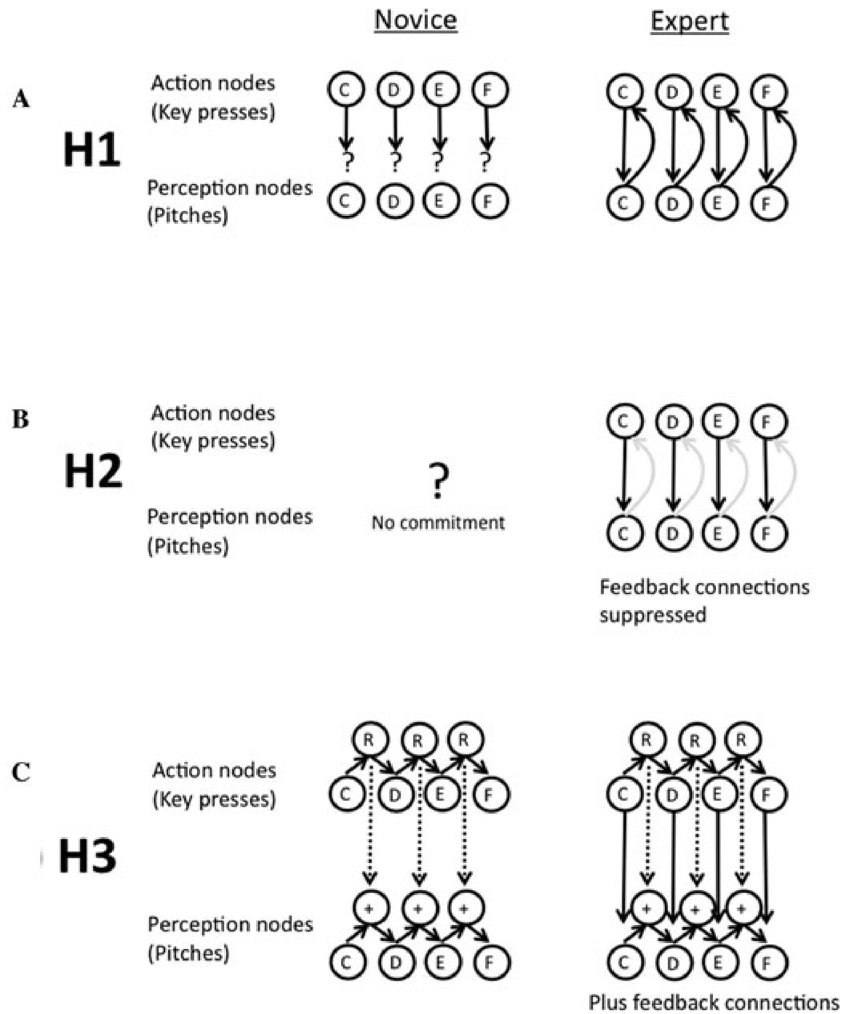

Figure 1. Three hypotheses concerning the influence of musical training (novice vs. expert) on neural associations between action plans and auditory feedback. Planned actions (key presses) are represented as nodes (circles) with the intended key press denoted by the letter name of the pitch associated with that key. Perception nodes denote the perceived pitch category. Solid arrows indicate zero-order associations between planned action and perceived events; dotted lines indicate first-order associations. Question marks indicate absent associations, and gray bars indicate suppressed associations. Text has further details.

expert should be sensitive to relationships between actions and auditory feedback, a novice should not. Figure 1A illustrates such an architecture, adopting the framework of a neural network in which action "nodes" that represent target key presses may be associated with perceptual "nodes" that represent pitch events. Before training, action nodes are not systematically associated with perceptual nodes. Training leads to bidirectional connections, such that perceptual feedback confirms planned actions when feedback is appropriate (the "perceptual trace" in closed-loop theory). This approach predicts sensitivity to alterations of auditory feedback among experts but not among novices.

Hypothesis 2: motor schema formation

A second hypothesis follows from the framework of motor programming and schema theory,[16] as well as problems in relating a strict associationist view to skilled performance.[17] According to this view, experts develop internalized schemas that allow them to perform without the use of feedback. In Figure 1B, this prediction for experts is represented by a set of unidirectional perception action connections leading from planning nodes to feedback nodes, whereas feedback connections to planning are suppressed. Indeed, the ability to ignore potentially interfering auditory events is critical for expert performers, who often have to perform in ensembles in which sounds made by other musicians may cause interference. This approach does not make an explicit commitment to the kind of connections that may exist among novices. However, it is clear that any sensitivity to auditory feedback would be restricted to novices.

Hypothesis 3: hierarchical shared representations

A third hypothesis adopts a more hierarchical view, inspired by evidence that motor planning adopts higher order retrieval structures.[8,18–20] In keeping with other views of action planning,[21] the hierarchy proposed here is based on transitions among events in a sequence, as opposed to dominance hierarchies that have been used to characterize musical schemas.[13,22,23] In Figure 1C, a two-level hierarchy is shown for action in which movements from C to F are linked by nodes that encode movement transitions between action nodes. In Figure 1C these higher order transitional nodes encode rightward movement between adjacent key presses, though other transitions are possible. Commensurate transitional associations among perception nodes are represented as upwards pitch motion. According to this perspective, the novice is sensitive to certain aspects of perception/action relationships, but only those aspects that are general to a wide range of behaviors. Thus, with respect to the piano, the novice may be sensitive to the mapping between movement transitions on the keyboard and concurrent patterns of pitch motion, though not to specific pitch class–piano key relationships. With training, one retains these general-purpose associations although building more refined associations with music-specific characteristics of auditory feedback.

Results from different experimental paradigms

Here, I consider relevant data concerning the effect of musical training on the role of auditory feedback during performance. All paradigms summarized here concern associations between produced action and concurrent sequences of musical pitches (auditory feedback). However, these paradigms differ with respect to how such associations are manifested. My division of results across paradigms is done in part because each paradigm, on the surface, appears to support a different hypothesis described above.

Effects of sensorimotor associations on subsequent unimodal processing

Various studies have examined how the action pitch associations formed in musical training influence the subsequent planning of actions or the processing of pitch information. What is common across these paradigms is that the researcher measures how binding across modalities (perception and action) affect subsequent processing of one modality on its own. Moreover, a common theme across these studies is that results tend to support the associationist view (hypothesis 1) given above.

Keller and Koch[24] explored how musical training influenced sensitivity to perception/action associations with respect to the initial planning of motor sequences. They incorporated a proto-musical task in which participants tapped sequences on vertically arranged metal plates. The authors varied the vertical mapping of actions to pitch height, such that the mapping could be compatible or incompatible. Sequences were only three taps long and the authors were not concerned with effects of these alterations on production of the three taps. They were instead interested in how quickly participants could prepare a subsequent movement sequence based on the action/effect contingencies they experienced in a block of trials. Musicians' performance deteriorated when the mapping was incompatible. By contrast, nonmusicians seemed to be insensitive to the mapping, in keeping with hypothesis 1.

Further support for hypothesis 1 has been found in neuroimaging studies that have investigated how musical training may lead to motor associations during the perception of musical pitch. In one study, Bangert and Altenmüller[25] used slow-moving frequencies in the electroencephalography (EEG) signal to identify brain areas that reflect audiomotor associations after training. In their task, nonmusicians were trained to produce musical sequences, although hearing auditory feedback that was either mapped appropriately with keys on a keyboard, or had an unpredictable mapping. Though both novice groups were able to learn musical sequences, subsequent perceptual responses of the brain included motor activity (in the inferior frontal gyrus) only for the group that had experienced reliable mapping between actions and pitch. In a related fMRI study by Lahav *et al.*,[26] novices likewise learned to play musical sequences (with normal mapping of pitch), and then afterwards listened to the melodies they had learned to play or melodies comprising different pitch classes. Similar to Bangert and Altenmüller, Lahav *et al.* found that training led to activations in the inferior frontal gyrus, only when participants heard the melodies they had learned to play.

Taken together, these effects are in agreement with the associationist hypothesis 1. It is furthermore significant that these results may reflect associations that are localized at the inferior frontal gyrus, given the proposal that this area of the brain plays a role in the mirroring of perception and action.[27]

Disruptive effects of AAF during performance

Now we turn to the way in which pianists and nonmusicians respond to AAF when feedback pitches are altered but feedback events are presented in synchrony with key presses. The primary difference between the AAF paradigm and the paradigms discussed in the previous section is that for AAF tasks, one is interested in the effect of altered feedback on ongoing production. As such, the AAF paradigm speaks to the effects of sensorimotor coordination on concurrent production, whereas paradigms discussed earlier reflect generalization of sensorimotor coordination to subsequent processing.

To date, several studies have addressed the effects of AAF for pitch.[7,9,11,28,29] In general, the most disruptive alteration to pitch is the *serial shift* of pitch, in which feedback events originate from serial positions at a constant lag (or lead) relative to the current position. For instance, in the lag-1 serial shift (results of which I report here), every key press generates the pitch associated with the immediately preceding key press. Note that disruption from this condition would necessarily reflect action pitch-based associations, given that sounds are always synchronized with key presses.

The effects of serially shifted AAF have been explored among pianists and nonmusicians. Figure 2A shows error rates (which typically reflect disruption from alterations to pitch) among a group of participants with no musical training, as well as a group of participants with at least six years of private piano lessons. The data shown here are pooled across five experiments from a previously published paper.[9] Both groups performed single-voice melodies with the right hand, although pianists performed 12-note melodies that required changes in hand position, and nonmusicians performed 8-note melodies with fixed finger–key relationships. Melodies were varied to match difficulty to skill level; the success of this matching is reflected in similar error rates for the normal feedback condition. Both groups made more errors during serially shifted AAF than during normal feedback. Thus nonmusicians, as well as pianists, were disrupted by alterations to pitch. At the same time, pianists made significantly more errors when hearing serially shifted feedback than nonmusicians. Figure 2B illustrates the change in the amount of disruption from serial shifts when treating musical training on a continuum. As can be seen, increase in the years of training are associated with greater disruption from serial shifts among individuals reporting at least one year of private piano lessons.

Two important implications arise from these results. First, nonmusicians do experience disruption when hearing altered feedback pitches. This result is critical because it suggests that sensorimotor associations during music performance may not be due

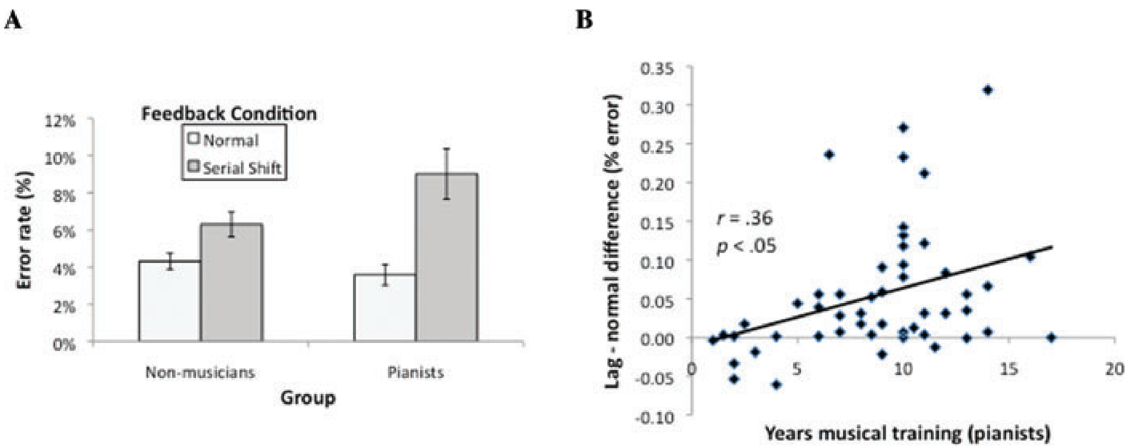

Figure 2. (A) Mean error rates for the sequencing of pitch events during piano performance as a function of auditory feedback condition and musical training. Error bars represent one standard error of the mean. (B) Scatterplot relating years of total musical training on any instrument to the disruptive effect of serial shifts on error rates (difference in error rates across serially shifted and normal feedback conditions) among pianists.

simply to learned task-specific associations. That is, nonmusicians may transfer other kinds of associations to the novel task of performing a melody on the piano. Further support for this idea comes from recent evidence that nonmusicians may have associations between spatial location and pitch (the SMARC effect, Ref. 30). Moreover, recent fMRI data suggests that the brain's responses to serially shifted auditory feedback are not localized in the inferior frontal gyrus, but instead involve a network of centers including the cerebellum, thalamus, and the anterior cingulate cortex.[31] These areas are typically associated with error monitoring[32] and the use of internal models during production.[33]

The second important implication is that sensitivity to AAF, though present among novices, may be enhanced during skill acquisition. The fact that pianists experience more disruption than nonmusicians may reflect the fact that pianists are sensitive to a broader range of hierarchical levels when relating actions to sound than are nonpianists, in keeping with hypothesis 3 (see Fig. 1C). In support of this view, we have found that pianists are also more sensitive to random alterations of feedback pitch than are nonmusicians, who show no disruption from this manipulation.[9] In addition, pianists are disrupted by serial shifts of a melody that is a melodic variation of the melody they play, suggesting generalization. Nonmusicians are not.[11]

Taken together, these results support the hierarchical perspective of hypothesis 3 described above. Both pianists and nonmusicians are disrupted by AAF, although the basis for disruption among nonmusicians may be different than among trained pianists.

Melody switching

The third research paradigm described here combines characteristics of both paradigms described earlier. In this paradigm, participants learn two different melodies and on each trial perform one of them although hearing either normal feedback—the melody they are playing—or feedback from the other melody they learned, referred to as alternate feedback. While playing and experiencing one of these feedback conditions, participants hear a randomly positioned auditory response cue (a single tone). This cue may signal participants to switch from the melody they are playing to the alternate melody, or to continue their current melody depending on the timbre.

We recently reported results for a group of 10 nonpianists, some of whom had modest amounts of musical training on instruments other than the piano.[28] Surprisingly, nonmusicians showed no effect of auditory feedback during trials in which the response cue signaled a switch, but did show a feedback effect during trials in which the response cue was irrelevant. In such trials, nonmusicians paused after hearing the irrelevant cue (leading to a lengthened interonset interval) although experiencing alternate auditory feedback, but not when they heard

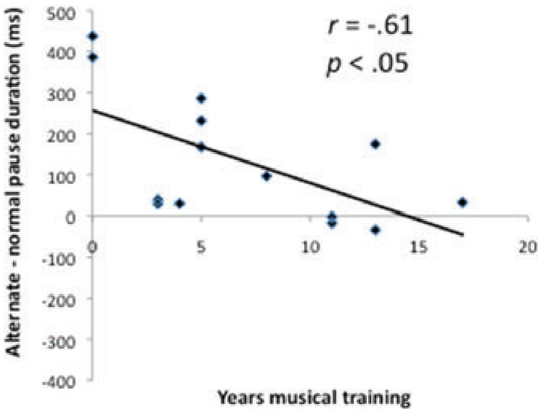

Figure 3. Scatterplot relating years of total musical training (abscissa) to the effect of hearing alternate feedback on the duration of a pause that follows an irrelevant response cue (the ordinate) in a melody-switching task.

feedback from the performed melody. These results suggested that participants had difficulty withholding a switch response when auditory feedback activated pitch events associated with the switch.

We also collected data from five pianists (not reported in the original paper). Surprisingly, pianists did not show any effects of cue type or auditory feedback. Furthermore, the effect of alternate feedback diminished as a function of musical experience, as shown in Figure 3 (which includes the sample from the published paper plus the additional pianists). Whereas alternate feedback leads to long pauses after the irrelevant response cue for nonmusicians (even greater than 400 ms), more musically trained participants are better able to withhold the switching response even with alternate auditory feedback. This is initially puzzling as the result seems to support hypothesis 2. In fact, the effect of training on the role of auditory feedback appears to be the exact opposite of what we have found for the effects of AAF (see Fig. 3), and is clearly distinct from the effects of auditory feedback on subsequent unimodal processing.

Resolving a puzzle

The results provided here are puzzling in that each paradigm seems to support a different hypothesis regarding the effects of learning on sensorimotor associations. It is of course unlikely that all three learning mechanisms operate in parallel. The most plausible resolution would involve an approach that modifies one of the existing hypotheses. I here propose that a modification of hypothesis 3 (hierarchical shared representations) holds the greatest promise. Hypothesis 3 is the only candidate that suggests that all individuals are sensitive to perception/action relationships during music performance, based on general principles of sensorimotor coordination, with the nature of these associations being modified through experience.

Hypothesis 3 clearly accounts for the effects of AAF, but why do results from other paradigms differ? A particularly informative feature of the paradigms presented here has to do with whether the effects of auditory feedback emerge in generalizations from one performance context to a subsequent task or not. Such generalization is present when one examines the influence of auditory feedback on subsequent unimodal processing, or the effects of auditory feedback on the ability to switch from one melody to another within a trial. Results from these paradigms suggest *qualitative* differences across training groups. When one assesses the effect of altered feedback on concurrent production, the qualitative effects on performance (a significant increase in error rates) is there for both untrained and trained performers, even though disruption varies in magnitude (a quantitative, rather than qualitative, difference).

Thus, the effects of AAF on concurrent production may reflect basic properties of the perception/action system. Specifically, the effects of altered feedback may be based primarily on one's sensitivity to the degree of coordination between patterns of movement through space, and any pattern of perceptual events that coincides with these movement patterns. Given this interpretation it is not surprising that disruption from alterations of pitch during music performance are based primarily on how the pitch contour pattern is related to the pattern of movements during production, more so than whether the performer does or does not hear the specific pitch that is associated with a single key.[9,11]

By contrast, tasks that reveal differences across pianists and nonmusicians may reflect the way in which musical training enhances one's hierarchical representation of music, beyond levels summarized in Figure 1C. Earlier research concerning music perception suggested that musically trained individuals might have more refined hierarchical representations for pitch[34] and for timing.[23] Furthermore, in transfer of learning tests that involve music performance, pianists have been found to generalize across sequences based on abstract structural characteristics.[35,36] Thus it is possible that pianists may differ from nonmusicians with respect to their tendency to generalize relationships in one trial to a subsequent trial.

However, the melody-switching paradigm is different in that "alternate" feedback is not disruptive. In fact, in that study all melodies comprised the same metrical structure. Given the lack of disruption in this task, the challenge becomes evaluating the response cue, which is facilitated by ignoring auditory feedback. Here is where one aspect of hypothesis 2 emerges. When feedback is coordinated with respect to metrical pattern, pianists are able to focus on the task-switching component. Pianists are good at this and so any influence of alternate feedback is diluted by their enhanced ability to generalize from one sequence to the other when switching. Because of their enhanced memory capacity, pianists can have access to two sequences at the same time, and readily switch between the two. Nonmusicians, however, may have difficulty sustaining two sequence representations in memory, and so the effect of alternate feedback is more apparent.

Conclusion: toward a new model of learning

These results suggest a new framework for understanding the way in which enhanced music performance skill influences sensorimotor associations associated with that skill. First, with training, musicians build sensitivity to action-effect relationships across multiple hierarchical scales. Nonmusicians begin with sensitivity to coarse-grained and easily generalizable aspects of perception/action coordination, specifically the way in which spatial transitions on the keyboard map on to changes in pitch height. With skill, these associations may spread to both lower and higher levels. This leads to both costs and benefits. Whereas switching between two melodies may become an easier task, given the richer action hierarchies one has stored, a greater tendency to be disrupted by incompatible relationships may emerge.

Results reported here come exclusively from paradigms that involve piano performance, and thus our focus on perception/action relationships has been on relationships between patterns of movement in space (the keyboard) and variations in pitch. For performance on other instruments, and in singing, such spatial mapping is either indirect (as in the trumpet) or absent (the voice). Nevertheless, we suspect that similar kinds of mappings will emerge in these contexts, although the parameters may vary (for example, laryngeal tension may substitute spatial movement). For the present, this claim remains a hypothesis for the future.

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Conflicts of interest

The author declares no conflicts of interest.

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