Journal of Experimental Psychology:
Human Perception and Performance
2008, Vol. 34, No. 3, 708–725

0096-1523/08/$12.00 DOI: 10.1037/0096-1523.34.3.708

Auditory Feedback in Music Performance: The Role of Transition-Based Similarity

Peter Q. Pfordresher
University at Buffalo, State University of New York

Past research has suggested that the disruptive effect of altered auditory feedback depends on how structurally similar the sequence of feedback events is to the planned sequence of actions. Three experiments pursued one basis for similarity in musical keyboard performance: matches between sequential transitions in spatial targets for movements and the melodic contour of auditory feedback. Trained pianists and musically untrained persons produced simple tonal melodies on a keyboard while hearing feedback sequences that either matched the planned melody or were contour-preserving variations of that melody. Sequence production was disrupted among pianists when feedback events were serially shifted by one event, similarly for shifts of planned melodies and tonal variations but less so for shifts of atonal variations. Nonpianists were less likely to be disrupted by serial shifts of variations but showed similar disruption to pianists for shifts of the planned melody. Thus, transitional properties and tonal schemata may jointly determine perception–action similarity during musical sequence production, and the tendency to generalize from a planned sequence to variations of it may develop with the acquisition of skill.

Keywords: sequence production, music performance, auditory feedback, melodic contour, similarity

When people produce long, complex sequences typical of music and speech, they simultaneously act and perceive the consequences of their actions. The perceived auditory consequences of actions are commonly referred to as *auditory feedback*. Although fluent production does not appear to depend on the presence of auditory feedback (Finney & Palmer, 2003; Repp, 1999), the disruptive effects of certain alterations to auditory feedback indicate that production does rely on matches between the planned and perceived outcomes of actions. Some past research suggests that the disruptive effect of feedback alterations (particularly those that alter the informational content of auditory feedback—e.g., pitch class) depends on the degree to which the sequence of feedback events is similar to the sequence of planned events (Pfordresher, 2005). The research reported here tests how different transformations of the melody that is performed determine the kinds of feedback alterations that can disrupt production. The focal point of this investigation was the degree to which similarity is defined by event-to-event transitions. In musical keyboard production (the task used here), event transitions constitute changes in response selection that are linked to changes in spatial targets (piano keys), whereas in perception, event transitions refer to changes in pitch across successive tones in a melody.

Portions of these results were presented at the 47th Annual Meeting of the Psychonomic Society, Houston, Texas, November 2006. This material is based on work supported in part by National Science Foundation Grants BCS-0344892 and BCS-0704516 and by a Faculty Research Award from the University of Texas at San Antonio. I thank Bruno Repp for comments on a previous version of this article, and I thank Erik M. Gallemore, Julliann Mejia, and Lilly-Ann Flores for conducting experiments.

Correspondence concerning this article should be addressed to Peter Q. Pfordresher, Department of Psychology, 355 Park Hall, University at Buffalo, Buffalo, NY 14260. E-mail: pqp@buffalo.edu

Altered Auditory Feedback

Early research on the role of auditory feedback explored the effect of alterations that influence perception–action synchrony. For instance, in delayed auditory feedback (Black, 1951; Lee, 1950; first reported in music performance by Havlicek, 1968) a constant time lag is added to the onsets of feedback events, typically leading to asynchronies between actions and feedback events. Some of this research has suggested that fluency of production depends on synchronization of perceived event onsets with actions but not on matches between perception and action with respect to content. For instance, disruption of speech by delayed auditory feedback was still found when feedback was low-pass filtered or converted to an amplitude-modulated square wave tone (P. Howell & Archer, 1984; see also P. Howell, Powell, & Khan, 1983). In both cases, phonetic information was largely removed from auditory feedback, and so disruption should not result because the speaker interprets the (unrelated) delayed feedback as an error. Similarly, in music production Finney (1997) found that synchronized auditory feedback whose pitch information was unrelated to the planned pitch sequence failed to disrupt production (see also Pfordresher, 2005).

However, there is reason to believe that fluency in production is sensitive to feedback content. For instance, when each synchronized feedback event is altered to match a pitch intended for a different sequence position in the past or future, error rates increase significantly relative to production with normal feedback (Pfordresher, 2003a, 2005; Pfordresher & Palmer, 2006; for similar manipulations see Müller, Aschersleben, Esser, & Müsseler, 2000; Stöcker, Sebald, & Hoffman, 2003), although timing of production is not disrupted (Pfordresher, 2003a, 2005). An example of this manipulation, which is used in the current research, is the lag-1 serial shift, in which each keypress triggers a pitch associated with the previous sequence position.

One interpretation of these results, suggested by Pfordresher (2004, 2006), is that disruption occurs because auditory feedback adds activation to events intended for sequence positions other than the current one, which then competes with the activation of the current event. This explanation follows from the assumption that perception and production of sequences draws on the same representation of sequence structure (cf. Hommel, Müsseler, Aschersleben, & Prinz, 2001; MacKay, 1987; Müsseler, 1999; Prinz, 1997). Therefore, when auditory feedback presents a recently produced event (which may have residual activation), that input increases the activation of the action (or actions) associated with that event at a time when such actions ought to receive lower activation than intended for the current position.[1]

However, this proposal also claims that relationships between perception and action exist across multiple timescales, not just between individual events. This proposal stems from the intuition that relative information dominates absolute information in musical sequences. For instance, it is well known that most listeners have a difficult time classifying pitches on the basis of absolute information (Levitin & Rogers, 2005; Takeuchi & Hulse, 1993; Ward, 1999) and that the ability to label absolute pitch may even reflect a specialized genotype (Drayna, Manichaikul, de Lange, Snieder, & Spector, 2001). Although recent evidence does suggest that specific action–pitch associations may be formed during musical training (Lahav, Saltzman, & Schlaug, 2007), it is nevertheless likely that relative information may dominate absolute information when relating a sequence of actions to a sequence of pitch events.

Perception–Action Similarity and Disruption From Altered Content

Recent evidence suggests that serial shifts of synchronized feedback are disruptive because the feedback sequence shares some structural relationship to the planned sequence of pitches but the serial positions of feedback pitches do not match planned serial positions. For instance, whereas serial shifts cause considerable disruption and unrelated sequences do not, as mentioned above, feedback sequences that contain pitches from the planned sequence that are presented in a scrambled serial order cause intermediate levels of disruption (Pfordresher, 2005). This result suggests that both the constituent events (pitch classes) and their global organization (serial order) contribute to similarity between perception and action. Thus, hearing pitches that consistently lag behind (or anticipate) their serial position causes considerable disruption, but hearing pitches for alternate positions that share an inconsistent relationship with the present position reduces disruption, and unrelated sequences do not disrupt.

The current research delves further into what makes a feedback sequence structurally similar to the planned outcomes of actions (for brevity, I refer to this relationship as *perception–action similarity*). Past results suggest that similarity may be a liability in altered auditory feedback paradigms, and this generalization motivated the design of the experiments reported here. Given that serial shifts disrupt production when the identical sequence is misaligned, a feedback sequence that is treated as similar to the planned sequence should disrupt production when it is serially shifted, and a feedback sequence that is dissimilar to the planned sequence should not. Under this assumption, the degree of disruption caused by serial shifts of a feedback sequence reflects its similarity to the planned sequence. The current research harnesses this logic to test a specific basis for perception–action similarity: the idea that event transitions, rather than specific pitches, determine perception–action similarity.

Event Transitions and Perception–Action Similarity

The experiments reported here posed the reverse question to that posed by Pfordresher (2005), who assessed the interfering effect of feedback sequences whose constituent elements matched elements of the planned sequence but were arranged in a scrambled order. By contrast, the present research explores the disruptive effects of feedback sequences that preserve higher order sequential characteristics but differ with respect to their constituent elements.

Transitions between musical events can be characterized with respect to contour or pitch intervals. Melodic contour concerns the pattern of upward and downward pitch motion in melodies, irrespective of the magnitude of pitch separation (interval), whereas pitch interval takes into account the extent of change. Evidence from perception suggests that contour dominates interval in many circumstances. Memory confusions among novel melodies are more immediately influenced by contour (Dowling, 1978; Dowling & Fujitani, 1971), whereas memory for interval information develops after more exposure to a melodic sequence (Dowling & Bartlett, 1981). Furthermore, similarity judgments (Bartlett & Dowling, 1988; Quinn, 1999; Schmuckler, 1999) and melodic accents (Boltz & Jones, 1986; Jones, 1987; Jones & Pfordresher, 1997; Pfordresher, 2003b; Thomassen, 1982) are strongly influenced by contour, possibly more than by pitch interval (cf. Huron & Royal, 1996). The current research tests the degree to which contour determines perception–action similarity. Although it is parsimonious to predict that results for perception–action relationships will mirror those found for perception, recent studies of action–effect associations suggest that binding may be based on absolute pitch information (Drost, Rieger, Brass, Gunter, & Prinz, 2005; Keller & Koch, 2006, in press; Lahav et al., 2007), in contrast to the research described above.

In the experiments reported here, as in their predecessors, participants produced short melodies from memory on a keyboard. Perception–action relationships on the keyboard, in comparison with other musical behaviors, are transparent and, at least on the surface, straightforward. Spatial targets for actions (piano keys) and resulting feedback contents are directly related, such that movement along one dimension of space (left to right) correlates perfectly with pitch height (low to high). Whereas the relationship between actions (movement of fingers and hands) and spatial targets is often complex (e.g., Parncutt, Sloboda, Clarke, Raekallio, & Desain, 1997; Sloboda, Clarke, Parncutt, & Raekallio,

[1] The effects of serial shifts on production, however, suggest more complexity. Serial ordering errors in production with altered auditory feedback tend not to match the position from which altered feedback events originate; in particular, serial shifts from past events tend to increase anticipations, and vice versa (Pfordresher & Palmer, 2006). These results suggest suppression of the positions associated with altered feedback, most likely a result of adaptation to disruptive feedback.

1998), the stimuli used in the experiments reported here simplify these relationships so that transitions between finger movements relate straightforwardly to transitions between pitches.

Figure 1 illustrates perception–action relationships in keyboard performance for a simple melodic segment. As can be seen, the finger sequence has the same transitional properties as pitches in the melody. In this context, contour refers to the change in sign of diatonic scale steps or of transitions in finger selection, whereas interval relates to the separation between the fingers that are selected for action. In general, the hypothesis that perception–action similarity is a function of the match between melodic contour and movement transitions is linked to a broader assumption that relative information (change in spatial targets vs. change in pitch height) supersedes absolute information (finger location in space vs. absolute pitch) in how people relate movement to feedback.

Tonality as a Constraint on Perception–Action Similarity

At the same time, it is well known that relationships among musical pitches are determined by multiple factors beyond pitch height (e.g., Shepard, 1982). Thus, factors beyond the relationship between finger selection and pitch height may determine perception–action similarity in musical sequence production. The role of *tonality* is considered here. In Western music, pitches in melodies typically suggest a specific (diatonic) referent scale to the listener, by virtue of the pitches that are chosen or excluded (usually 7 of the possible 11 pitch classes) as well as the frequency with which pitches and pitch intervals appear in melodies (Krumhansl, 1990, 2000; Smith & Schmuckler, 2004; cf. Butler & Brown, 1984). Such melodies are referred to as *tonal.* By contrast, melodies that include pitches from all 11 possible pitch classes with similar frequency may not suggest an underlying hierarchy and are referred to as *atonal.*

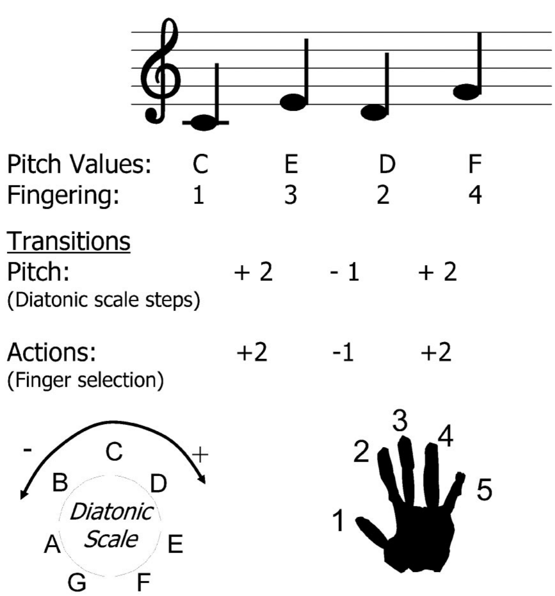

Figure 1. Sample music notation followed by nomenclature for movements and feedback events. Letters indicate pitch class (irrespective of octave). Fingering notation uses 1 = thumb, 2 = index finger, and so forth. Pitch transitions denote pitch class within the diatonic scale (shown as a circle on the bottom), with positive transitions indicating clockwise motion around the pitch circle. Finger transitions are positive for radial to ulnar movement and negative in the opposite direction.

Tonality may influence relationships between perception and action by virtue of the schematic knowledge that is involved. Tonal melodies lead the listener to interpret pitches with respect to an internalized hierarchy (e.g., Krumhansl, 1990; Tillmann, Bharucha, & Bigand, 2000). The use of this schematic knowledge may help listeners to interpret melodic gestures that convey tension, relaxation, and closure. By contrast, most listeners do not appear to apply different schematic rules (e.g., tone rows) when processing pitch in atonal melodies (Krumhansl, Sandell, & Sergeant, 1987). Although melodic contour likely determines the perceived similarity of melodies sharing the same tonality, melodies that differ in tonality sound dissimilar even when they share the same contour (Bartlett & Dowling, 1988). There is evidence that memory confusions among melodies are influenced by both contour and tonality (Cuddy, Cohen, & Mewhort, 1981; Dowling, 1978).

With respect to planning of movements, tonality can be considered as a constraint on allowable spatial targets and movement transitions, in that the diatonic scale prioritizes certain pitch classes (piano keys) and intervals (finger transitions) over others. In a more general sense, tonality may determine the kind of pitch alphabet used both to generate auditory sequences and to select spatial targets (cf. Deutsch & Feroe, 1981). Thus, in comparison with contour and interval, tonality represents a more abstract characteristic of musical structure in that it draws on learned schemas that guide perception and (possibly) action. The present experiments tested whether perceptual feedback that forms an atonal sequence is treated as unrelated to planned sequences of actions that would generate a tonal sequence.

The Present Experiments

Three experiments were conducted to test the degree to which transitional information in auditory feedback determines perception–action similarity, focusing in particular on the role of melodic contour. During each trial, participants performed a melody from memory repeatedly while listening to feedback over headphones. Trials began with normal feedback and then changed to an altered feedback condition (or did not, in control trials) until the end of the trial.

A lag-1 serial shift of auditory feedback was used to elicit disruption. Disruption was used to gauge whether a feedback sequence is treated as similar to or different from the planned sequence. This design was predicated on the assumption, described earlier, that a feedback sequence transformation that results in a melody similar to the planned melody will disrupt production if that transformed feedback sequence is serially shifted, whereas sequences treated as dissimilar to the planned sequence will fail to disrupt production whether or not they are serially shifted (cf. Pfordresher, 2005). Consider a feedback sequence formed by randomly selected pitches: Serial shifts of such a sequence would not yield any change to performance because in no case would transitions in the feedback sequence align with the structural transitions of the planned sequence. However, when a structurally similar melody is shifted, disruption may result because transitions in the shifted melody activate certain characteristics of actions planned for other sequence positions.

In all three experiments, participants would hear either *planned melodies* or contour-preserving *variations* as they generated a sequence of keypresses (each planned melody was paired with a single variation across all experiments). Whereas planned melodies are melodies that the participant has learned and attempts to produce, variations are melodies that share the same contour as the planned melody but differ in other respects. Specifically, variations were transformed with respect to absolute pitch (all experiments), pitch intervals (Experiments 2 and 3), or tonality (Experiment 3).[2] Each kind of melody (planned or variation) was presented so that it would either align with the planned pattern of contour changes or be serially shifted with respect to the planned contour. Of course, the presentation of a variation in which the pattern of perceived pitch changes is aligned with the planned actions (i.e., a nonshifted version) could also disrupt production. Such a result would suggest that the kind of transformation used causes disruption and would constitute evidence that alterations of pitch are more disruptive than shifts of transitional patterns, in contrast to predicted results.

If perception–action similarity depends entirely on melodic contour, then serial shifts of all variations used here should cause disruption similar to that found in typical lag-1 serial shifts (Pfordresher, 2003a, 2005; Pfordresher & Palmer, 2006). However, different kinds of transformations could modulate similarity, leading to a reduction or elimination of disruption from serial shifts of certain variations. On the basis of the seminal work of Dowling (1978), I predicted that perception–action similarity would be based on contour and tonality but not interval. Thus, disruption from shifts of altered melodies should be found in Experiments 1 and 2 (exact transpositions and tonal variations, respectively) but not in Experiment 3 (atonal variations). The data of Pfordresher (2005) show that deviations of the feedback sequence from the planned sequence with respect to melodic contour reduce similarity (resulting in reduced disruption).

Each experiment included trained pianists as well as individuals with little or (more commonly) no formal musical training. Pfordresher (2005) found similar patterns of disruption for both groups, suggesting that perception–action similarity follows from a general tendency to relate patterns of planned movements to patterns of change in sound. Thus, it was expected that both groups would yield similar results in the present research. As will be seen, this prediction was not confirmed.

Experiment 1: Exact Transpositions

In Experiment 1 participants performed short, previously unfamiliar melodies from memory while listening to auditory feedback over headphones. Altered auditory feedback conditions could vary with respect to the pitches that made up the feedback melody and/or with respect to its serial alignment with the planned melody's melodic contour. Feedback pitches, which were triggered by each keypress, could form a melody that matched the planned melody or could form a variation in which pitches of the planned melody were transposed by six semitones (e.g., change of key from C major to F-sharp major—note that a change of key is not considered a change in tonality). Planned feedback melodies and variations were each presented with either a normal or serially shifted alignment with actions. Figure 2 illustrates the four auditory feedback conditions in Experiment 1, along with their effects on perception–action relationships, using one of the melodies performed by nonpianists.

I predicted that serial shifts of transpositions would yield the same amount of disruption as serial shifts of normal melodies. This prediction is highly plausible given that people commonly hear musical sequences in different keys with little to no decrement to melody recognition (Dowling, 1978; Dowling & Fujitani, 1971). Furthermore, the ability to label absolute pitch class is rare, as mentioned before. Nevertheless it is important from a theoretical standpoint to establish that links between perception and action in music performance are based on transitions (relative information) rather than endpoints (absolute information). Many theories that address the role of feedback in sequence learning and motor control assume that one-to-one relationships between actions and consequences are strengthened in learning and account for the use of feedback in motor control (e.g., Adams, 1971; Greenwald, 1970; Guenther, Ghosh, & Tourville, 2006; James, 1890; Witney, Vetter, & Wolpert, 2001; Wolpert, Ghahramani, & Jordan, 1995), in contrast to the hypothesis that relative information dominates.

Method

Participants

Pianists. Eight adult pianists (mean age = 28.6, range = 18–48) from the San Antonio, Texas, community participated in exchange for payment. Pianists had 17.1 years of experience playing the piano (range = 6–41) and 9.9 years of private piano training (range = 4–21) on average. None reported having absolute pitch. Six participants reported being right-handed and 1 was left-handed. Two participants were male and 6 were female.

Nonpianists. Twenty-five adult nonpianists (mean age = 19.4, range 18–29) from the University of Texas at San Antonio participated in exchange for course credit in Introductory Psychology. All nonpianists reported having had private piano lessons for 1 year or less ($M = 0.19$). None reported having absolute pitch. Twenty-three participants reported being right-handed, 1 was left-handed, and 1 was ambidextrous. Fifteen participants were male and 10 were female.

Materials

All planned melodies were monophonic and performed with the right hand. However, different melodies were used for each group in order to maintain approximately the same level of difficulty. Earlier research using the same methods has revealed similar overall error rates for each group under these conditions (Pfordresher, 2005). Moreover, it was feared that too few errors (the primary measure of disruption) would be generated by pianists performing the simplified melodies designed for nonpianists.

Pianists. Four melodies served as stimulus materials for pianists (for details, see Pfordresher, 2003a). Examples of melodies are shown in Figure 3. Two melodies (shown in Figure 3) were notated in a binary meter (2/4 time signature), and two were

[2] It is important to note that alterations of tonality necessarily cause deviations from the planned melody with respect to pitch interval.

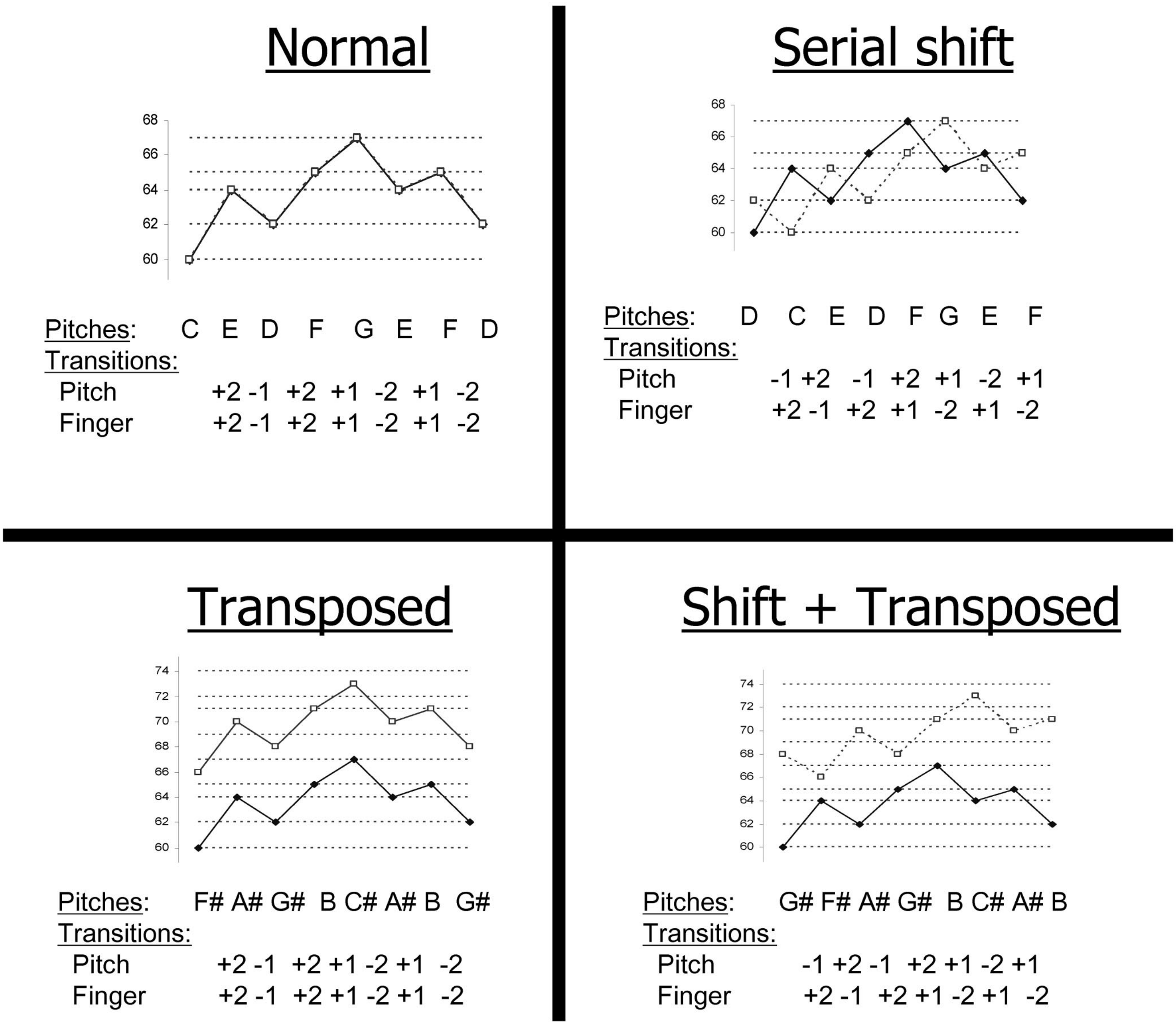

Figure 2. Examples of conditions in Experiment 1, depicting one of the sequences used for nonpianists. In each plot, the abscissa is time and the ordinate is pitch height (as MIDI note number). Solid lines with filled squares indicate the planned sequence of pitches (related to actions), dotted lines with open squares indicate feedback pitches, and horizontal dashed lines highlight pitch classes from the C major scale. Pitch and fingering transitions under each plot use the nomenclature illustrated in Figure 1; pitch names refer to the feedback sequence. Feedback pitches for shifted melodies are displayed for one of many repeating cycles following the first cycle; thus, the first feedback pitch is mapped to the final keypress from the preceding cycle.

notated in a ternary meter (3/4 signature). Only results from the binary melodies, which are more similar in structure to the melodies performed by nonpianists, are reported here, and thus only these melodies are displayed in Figure 3.[3] One melody for each meter condition was in the key of G major, and the other was in C major. Melodies did not contain repeating melodic patterns so that performers would not rely on stereotyped motor movements, and none of the melodies included repeated pitches on successive events. Although minor changes in hand position were required, none of the melodies required participants to move fingers over the thumb, a more difficult maneuver than other finger transitions (cf. Parncutt et al., 1997) that complicates the relationship between fingering and spatial location of targets for action. All melodies were isochronous, comprised 12 notes, and were performed with

[3] Results from trials with ternary meters were highly similar to those from trials with binary meters, one exception being that more individual differences in the pattern of results were found among trials with ternary meters in Experiment 2.

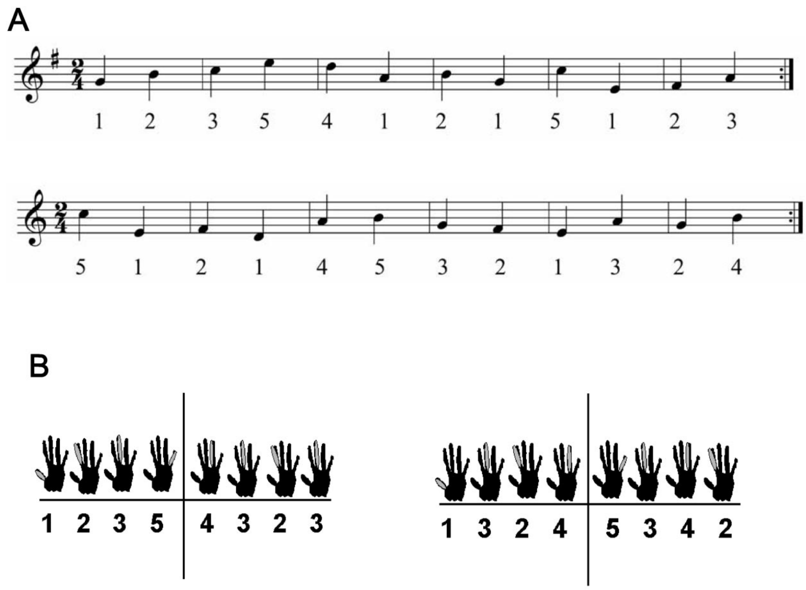

Figure 3. Examples of notation used for melodies memorized and performed by pianists (A) and nonpianists (B). Numbers indicate prescribed fingering for the right hand (1 = thumb). Two additional melodies (not shown) for nonpianists comprised inversions of the melodies shown here (5 becomes 1, 4 becomes 2, etc.)

the right hand only. Pianists read each melody from standard music notation during memorization and then performed each melody from memory during the experiment.

Nonpianists. Four different melodies served as stimulus materials for nonpianists (used also in Pfordresher, 2005). Each melody comprised 8 events and was created so that mapping between fingers and piano keys was invariant. The melodies were created to vary with respect to starting pitch (C4 or G4) as well as the shape of the contour (see examples in Figure 3B). They were displayed as a row of numbers that corresponded to finger–key combinations rather than standard music notation. On the keyboard, numbers 1–5 were arranged in a row above the corresponding piano keys, with arrows pointing to the requisite piano key. Thus, for each melody, 1 indicated that the thumb should press the C4 key, 2 indicated that the index finger should press the D4 key, and so on.

Conditions

Four feedback conditions resulted from crossing the factors feedback pitch and serial shift. Conditions thus comprised normal feedback, serially shifted feedback (including pitches from the planned melody), the variation (which was an exact transposition of the planned melody), and the serially shifted variation (see Figure 2). Each participant performed 10 repetitions of each feedback condition with two of the four melodies, resulting in 80 trials per session. Pianists performed one binary meter melody in the key of C major or G major and one ternary melody in the alternate key. Nonpianists performed one smooth-contour melody that began on C4 or G4 and one alternating-contour melody that started on the alternate pitch. Trials were blocked first by melody and then by repetition. Participants thus cycled through one repetition of all four feedback conditions before going on to the next repetition of each condition. The order of feedback conditions varied randomly within each melody block, except that the normal feedback condition was always the first trial experienced after learning a new melody (i.e., at the beginning of the session and after Trial 40). The following additional factors were counterbalanced in a Latin square design that yielded four order conditions: the set of two melodies used, order of the melodies, and ordering of conditions.

Apparatus

Pianists performed on a Roland RD-700 weighted-key digital piano positioned on a keyboard stand at a height similar to that found in standard acoustic pianos. Nonpianists performed on a FATAR CMK 49 unweighted keyboard held on the lap. The rationale behind varying the physical task conditions was to equate the comfort of the task across groups. Pianists are used to playing on a weighted piano, and so I wished to mimic the comfort of the standard performance context for them. Nonpianists are not used to such contexts, and so I tried to make the task motorically and posturally easier for them.

Both groups listened to auditory feedback over Sony MDR-7500 professional headphones at a comfortable listening level. Presentation of auditory feedback and MIDI data acquisition were implemented by the program FTAP (Finney, 2001). The piano timbre originated from Program 1 (Standard Concert Piano 1) of the RD-700.

Procedure

At the beginning of a session, participants practiced the first melody with immediate feedback until it was memorized and performed without errors, after which the music notation was removed. Nonpianists were given additional instructions regarding the correct hand position for piano performance, as well as an explanation of the notation. Then participants performed the first melody with a lag-1 serial shift at a comfortable self-selected rate for two repetitions. After this familiarization with altered auditory feedback, participants performed at least one practice trial using the lag-1 serial shift. Then the participant completed all experimental trials for the first half of the session (40 trials in all). A brief break occurred between the two blocks, during which participants completed a questionnaire regarding musical experience. The participant then learned the second melody and performed one practice trial with lag-1 feedback before completing the second half of the session.

On each trial, participants performed the melody at a self-selected moderate tempo, repeatedly and without pausing between repetitions. Participants were instructed to adopt a legato (connected) playing style and to avoid correcting any pitch errors. Trials were divided into two phases. During the first phase of a trial auditory feedback was always normal. During the second phase, which followed immediately after the first, auditory feedback would either remain normal or change to one of the three altered feedback conditions. Phases were defined by counts of keypresses. The length of each phase was slightly different for pianists versus nonpianists. Phase 1 for pianists lasted for 12 keypresses (one repetition of the stimulus) but lasted for 16 keypresses (two repetitions) for nonpianists; Phase 2 lasted for another 24 keypresses for pianists (three repetitions) but lasted another 32 keypresses (four repetitions) for nonpianists. Slightly shorter trials were used for pianists because their melodies took longer to memorize. That is, different trial lengths allowed for the best use of the 1-hr experimental time slot.

During all experimental feedback conditions (including normal), each keystroke triggered a preselected feedback pitch. This technique does not differentiate between correct and incorrect keypresses—either one triggers the same pitch—and error analyses were adapted to this constraint (as described below). During trials that included a lag-1 alteration, the first pitch of the sequence was repeated twice upon introduction of altered feedback in the second phase of the trial.

Data Analysis

Errors in production were detected with software that compared produced pitches with those that would occur in a correct performance (Large, 1993; Palmer & van de Sande, 1993, 1995). The proportion of trials with any error (number of trials with an error/number of trials for a given participant and condition) functioned as the measure of disruption (as in Pfordresher & Palmer, 2006). This measure was used rather than others (e.g., measures of timing, error rates within each trial) for two reasons. First, past research has found that feedback alterations of the sort used here yield negligible effects on measures of produced timing (Pfordresher, 2003a, 2005; Pfordresher & Palmer, 2006). Analyses of tempo carried out for all three experiments reported here likewise failed to uncover any effects of feedback condition on tempo or any reliable relationships between tempo and error proportions. Second, because all auditory feedback was presented as a fixed sequence of pitches, errors that alter the serial ordering of events (such as deletions and additions) may alter the sequential relationship between actions and feedback. For instance, the production of an additional event during a normal feedback condition would cause the feedback sequence to be like a lag-1 sequence. The use of proportion of trials with any error as a measure of disruption guards against this problem by incorporating information only about the very first error in a trial (i.e., its presence vs. absence). Any trials on which participants made errors during the initial (normal feedback) phase that altered the serial order of events (e.g., deletions, additions) were likewise discarded. This conservative procedure resulted in the removal of 8% of all trials for pianists and 31% of all trials for nonpianists, with data from all three experiments reported here pooled.[4]

Close inspection of the data across experiments revealed consistent deviations from normality (which can be seen in box plots; see Figures 4, 6, and 7). Nonparametric statistical analyses (Wilcoxon matched-pairs signed ranks tests; e.g., D. C. Howell, 2002, pp. 713–717) are therefore reported, although parametric analyses led to similar conclusions. A series of planned contrasts was carried out separately for pianists and nonpianists. First, both lag-1 serial shift conditions combined (including conditions with feedback that presented planned melodies or variations) were contrasted with both nonshifted conditions combined, and both variation conditions combined (including nonshifted and shifted presentations) were contrasted with both planned melody conditions combined. These contrasts amount to main effects of serial shift and feedback pitch; a Bonferroni correction ($\alpha = .025$) was used to control familywise error rate for these contrasts. Second, each altered feedback condition was contrasted with the normal feedback conditions to measure its disruptive effect; these contrasts used $\alpha = .017$ owing to the inclusion of the normal feedback condition in all three contrasts. Finally, a contrast between the two serially shifted conditions was carried out as an additional test of how the variation influenced the disruptive effect of serial shifts, using $\alpha = .025$ because each mean was used in a second contrast.

Results

Mean proportions of trials in error are shown as box plots in Figure 4 for pianists (4A) and nonpianists (4B). Serial shifts increased error proportions for pianists, $T(14) = 0$, $p < .001$. Variations elevated error rates slightly overall, but this difference fell short of significance given the correction applied to α ($p = .041$) and is primarily attributable to the errors elicited by the serially shifted variation condition. Furthermore, significant increases in error proportions, relative to normal feedback, resulted from serial shifts of the planned melody, $T(7) = 0$, $p < .017$, and serial shifts of variations, $T(7) = 0$, $p < .017$, but not the no-shift variation condition ($p > .100$). Likewise, there was no difference between the shift and shift + variation conditions given the α

[4] The fact that more trials were thrown out for nonpianists than for pianists, as well as differences in error proportions (discussed later), suggests that the attempt to equate task difficulty across groups was not successful here as it was in Pfordresher (2005). However, these differences across groups may arise in part because of the particular error measure that was used. Differences across groups for error rates (number of errors in a trial/number of sequence events) were smaller (5% error rate for nonpianists and 3% for pianists, averaged across experiments), though this difference was statistically significant ($p < .05$).

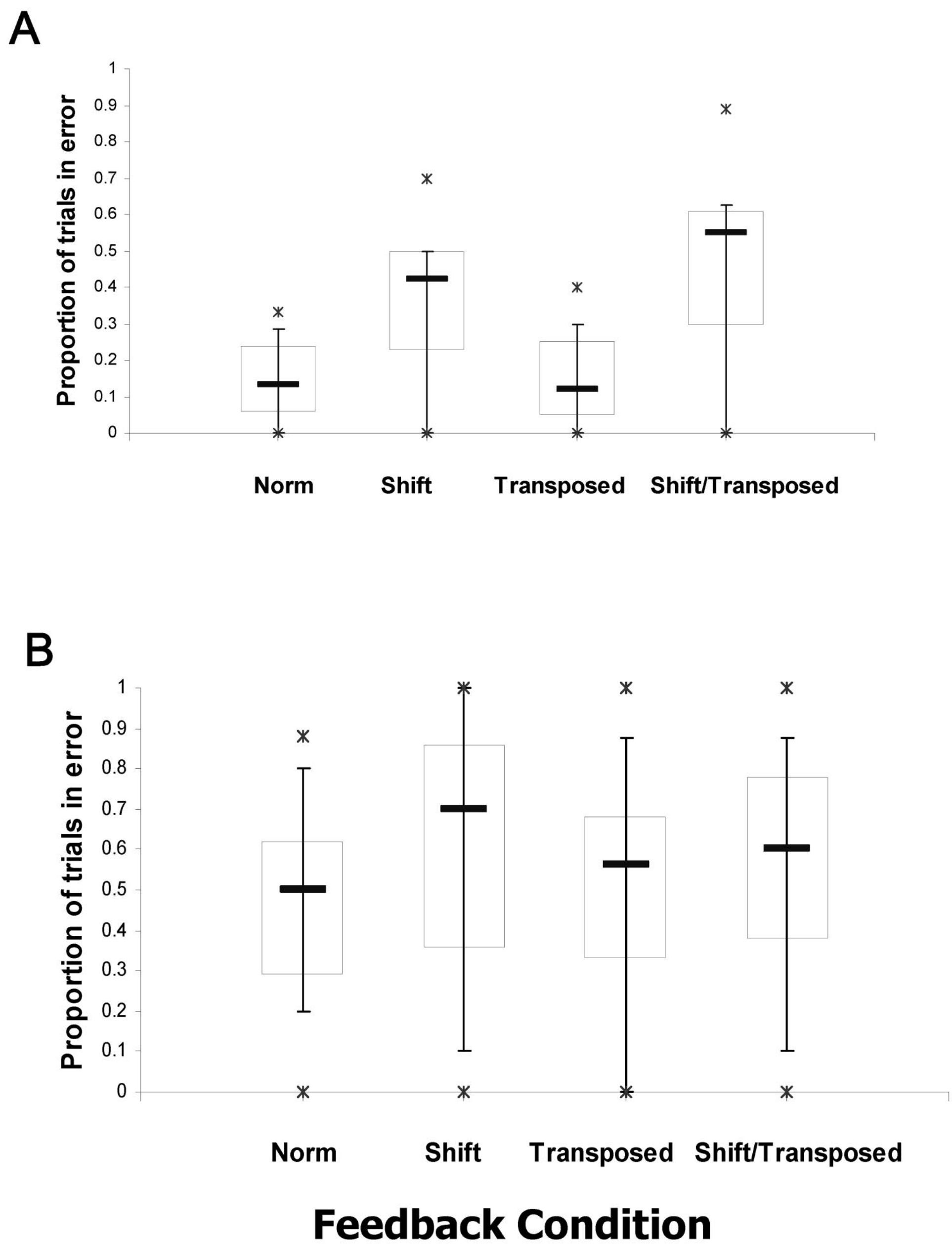

Figure 4. Box plots representing distributions for proportions of all trials with any error from Experiment 1 for pianists (A) and nonpianists (B). Horizontal lines within boxes display medians, box boundaries highlight the interquartile range, whiskers display the 90th and 10th percentile ranks, and asterisks signify extreme values.

correction ($p = .029$), although somewhat higher error rates were observed in the shift + variation condition.

Nonpianists, by contrast, were disrupted by shifts of the planned melodies but not by shifted variations. As with pianists, serial shifts elevated errors relative to both no-shift conditions, $T(75) = 952.5$, $p < .017$, but transpositions of feedback melodies did not increase errors relative to planned melodies ($p > .100$). Serial shifts of the planned melody increased errors relative to normal feedback, $T(37) = 174.5$, $p < .017$, but the contrast between normal feedback and shift + transposed melodies fell short of significance ($p = .033$). No-shift variations did not elevate error rates ($p > .100$), and the serial shift and the shift + transposed conditions did not differ ($p > .100$). Nonpianists also yielded substantially higher error proportions than did pianists, contrary to expectations based on previous research with the same stimuli (Pfordresher, 2005). This difference may reflect the dependent measure that was used in the current study (see footnote 4).

As mentioned earlier, it was predicted that both groups would yield similar patterns of disruption. The fact that the groups differed somewhat in their responses therefore renders the use of different stimuli for each group problematic. For instance, slight changes of hand position required by the pianists' melodies may have encouraged the formation of a more abstract sequence representation during memorization. In order to address the possible contribution of materials to the results, several additional pianists ($n = 4$) were run in a follow-up study in which they experienced the same conditions and materials as did the nonpianists in Experiment 1. Pianists in the follow-up study also rated the difficulty of each trial after the trial was over (on a scale of 1 to 100), to guard against the possibility that these easy melodies would generate few errors when performed by pianists. The results of this study mirrored those of the pianists in Experiment 1. Serial shifts increased error proportions, $T(15) = 5.0$, $p < .001$, relative to normal feedback (median for normal = 0, median for shifted = 0.30), but variations did not ($p > .10$). Most important, shift + variation conditions significantly increased errors, as for pianists but not nonpianists in Experiment 1, $T(8) = 0$, $p < .01$. Furthermore, difficulty ratings, analyzed via a two-way analysis of variance, revealed only a main effect of serial shift, $F(1, 3) = 20.06$, $p < .05$, with higher ratings of difficulty for serially shifted ($M = 43.6$) than for unshifted ($M = 30.6$) feedback sequences.

Discussion

The results for trained pianists support the hypothesis that similarity between planned action sequences and perceived sequences arises from the relationship between movement transitions and transitions between perceived events, rather than the relationship between the spatial location of an individual action (a keypress) and the resulting event. When participants heard serially shifted feedback, for which the pitch associated with the previous planned action was presented, errors increased, as found in previous research (Pfordresher, 2003a, 2005; Pfordresher & Palmer, 2006). More important, disruption was also found for pianists when the feedback sequences did not present any planned pitch but instead represented transpositions of the produced sequence that were then serially shifted. In such cases, disruption results from the fact that auditory feedback presents pitch transitions that match previously planned transitions in finger movements. For nonpianists, however, the disruptive effect in this condition was smaller and not significant. Furthermore, no disruption in either group resulted when auditory feedback sequences were merely transposed. Such conditions result in participants hearing unexpected pitch feedback that nevertheless matches planned actions with respect to movement transitions.

Results for pianists match common intuitions about the nature of musical sequences. Processing of pitch sequences appears to be dominated by relational information in most individuals, as mentioned earlier. Experiment 2 was therefore designed to provide a stronger test of the idea that people derive similarity between planned action sequences and auditory feedback from patterns of transitions rather than absolute information by incorporating *tonal variations*.

Experiment 2

Experiment 2 was designed to apply the current understanding of how melodic similarity is determined in perception to the way in which an auditory sequence may be treated as similar to a concurrent action sequence. Past research on music perception, mentioned earlier, suggests that melodic contour (direction of pitch changes) supersedes interval information in tasks that assess the similarity of unfamiliar melodies. In other words, two melodies that share the same patterns of ups and downs in pitch (contour) but differ with respect to the degree of change between successive pitches (interval) will be treated as similar. On the basis of this work, I hypothesized that auditory sequences would be treated as similar to the planned action sequence if the melodic contour of the melody matches the pattern of finger transitions even if the intervallic separation between adjacent pitches in the auditory sequence does not match the spatial separation between adjacent keypresses on the keyboard. In other words, the hypothesis was that performers process similarity with respect to the direction but not the magnitude of changes, given that both planned and perceived sequences are tonal.

This hypothesis was tested by employing melodic variations like those used in previous research on memory for perceived sequences (e.g., Dowling, 1978). Tonal variations were set in major keys, like planned sequences, though the key differed so that feedback pitches would not match individual planned pitches (as in the transposed feedback melodies of Experiment 1). Most important, tonal variations followed the same pattern of pitch motion as in the planned melody. As in Experiment 1, melodic variations were presented as nonshifted or shifted feedback melodies, such that the contour pattern could directly match each successive planned movement trajectory (lag 0) or be presented such that each pitch change in the feedback melody matched the previous planned movement trajectory (lag 1). Examples of these conditions are shown in Figure 5. It was predicted that disruption would result from lag-1 shifts of melodic contour but not when the feedback melodic contour matched movement trajectories (lag 0). Moreover, the presence of equivalent disruption from lag-1 shifts of variations or planned melodies would verify the hypothesized similarity of feedback melodies to planned sequences based on melodic contour.

Method

Participants

Pianists. Fifteen adult pianists from the San Antonio, Texas, community who had not participated in Experiment 1 participated in exchange for pay. Owing to an oversight, the demographic information from one pianist was lost. The remaining participants were, on average, 21.9 years old (range = 17–30) and had 10.9 years of training (range = 6–20) and 14.6 years of experience (range = 8–35; note that the participant reporting 35 years of training did not report age) on the piano. None reported having absolute pitch. Five were male and 10 were female. Thirteen reported being right-handed and 2 were left-handed.

Nonpianists. Twenty-three adult nonpianists (mean age = 19.8, range 18–25) from the University of Texas at San Antonio who had not participated in Experiment 1 participated in exchange for course credit in Introductory Psychology. No participant reported having experience or training on the piano or having absolute pitch. Nineteen participants reported being right-handed and 4 were left-handed. Eleven participants were male and 12 were female.

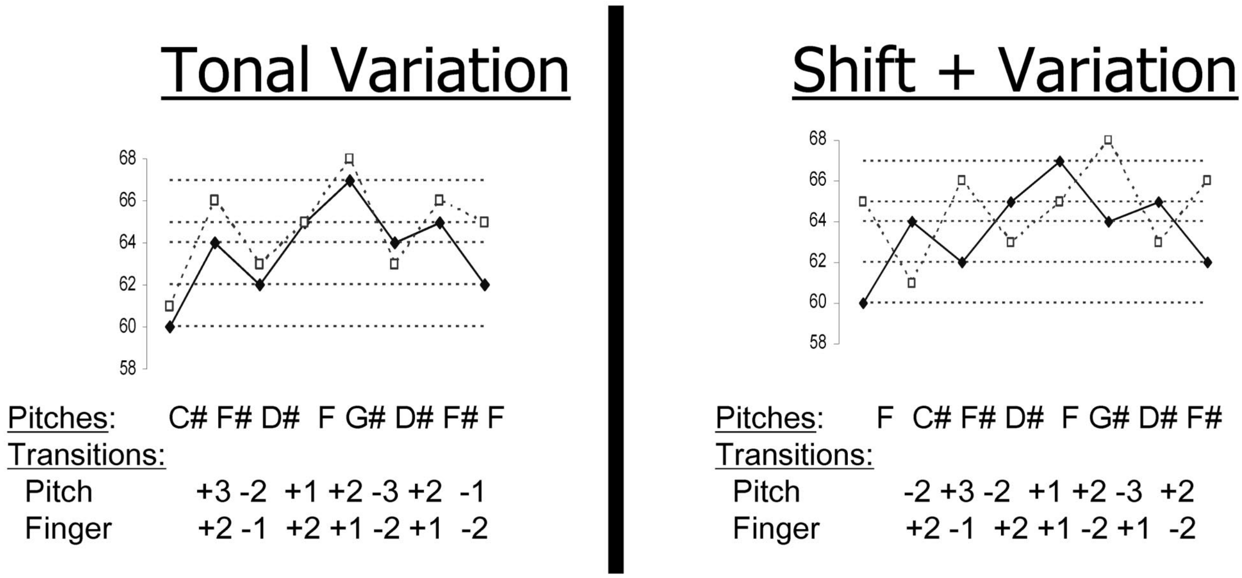

Figure 5. Examples of new conditions in Experiment 2, shown as in Figure 2.

Materials, Conditions, and Procedure

The stimulus materials, conditions, and procedure were identical to those of Experiment 1 except that transposed melodies (lag 0 and lag 1) were replaced with tonal variations. Tonal variations were created by increasing or decreasing at random each pitch in the melody to the nearest possible scale step. The melody that resulted from these altered intervals was then examined to make sure that it sounded dissimilar to the original melody yet still sounded tonal. Then every pitch in the melody was shifted up or down one semitone so that feedback pitches generally did not match pitches in the planned melodies.

Results

Disruption was measured through the proportion of trials with any error, as in Experiment 1. Mean proportions of trials in error are shown in Figure 6 for pianists (6A) and nonpianists (6B). Three participants from the nonpianist group and 1 participant from the pianist group were discarded because errors in the normal feedback condition exceeded those in all altered feedback conditions. Their exclusion did not change any reported results qualitatively.

Results were analyzed as in Experiment 1. For pianists, conditions with serial shifts caused more errors than those without serial shifts, $T(20) = 36.5$, $p < .017$, but conditions with tonal variations did not increase errors above trials with planned melodies ($p > .100$). Errors increased relative to normal feedback conditions when participants heard serial shifts of the planned melody, $T(10) = 3.0$, $p < .017$, or serially shifted variations, $T(12) = 11.0$, $p < .017$. Nonshifted tonal variations increased errors slightly but not significantly given the correction of α ($p = .034$), and the two serially shifted conditions did not differ from each other ($p > .100$).

Nonpianists likewise generated more errors in conditions with serial shifts than in those without, $T(74) = 628.0$, $p < .001$, but not in conditions with variations compared with planned melodies ($p = .078$). Relative to normal feedback, serial shifts of planned melodies increased errors, $T(47) = 169.0$, $p < .001$, as did serially shifted tonal variations, $T(49) = 215.0$, $p < .001$. Nonshifted variations increased errors slightly, but this difference fell short of significance given the correction of α ($p = .026$). The two serially shifted conditions did not differ from each other ($p > .100$).

Discussion

The results of Experiment 2 further confirm that performers determined the similarity of feedback sequences to planned action sequences on the basis of patterns of transitions rather than absolute values. Furthermore, Experiment 2 suggests that coarse-grained information about the direction of change across auditory feedback events dominates more fine-grained information about the magnitude of change. At the same time, slight disruption from the no-shift variations suggests some sensitivity to differences between planned melodies and variations.

Experiment 2 showed greater concordance between pianists and nonpianists than did Experiment 1, in that serially shifted tonal variations disrupted both groups whereas serially shifted transpositions disrupted only pianists in Experiment 1. However, it is important to note that variations also caused slightly greater disruption for nonpianists in Experiment 2 than in Experiment 1. Whereas the contrast between nonshifted transpositions and normal feedback for nonpianists did not approach significance in Experiment 1, the comparable contrast would have been significant in Experiment 2 given a more liberal criterion for α. As mentioned in the introduction, disruption from altered feedback melodies that share the planned melody's contour likely reflects a response to the type of transformation used (e.g., alterations of intervals). In this context, disruption from shifted variations among nonpianists probably reflects the sum of modest increases to error rates brought about by altered intervals and the shifted melodic contour, rather than the shifted contour on its own.

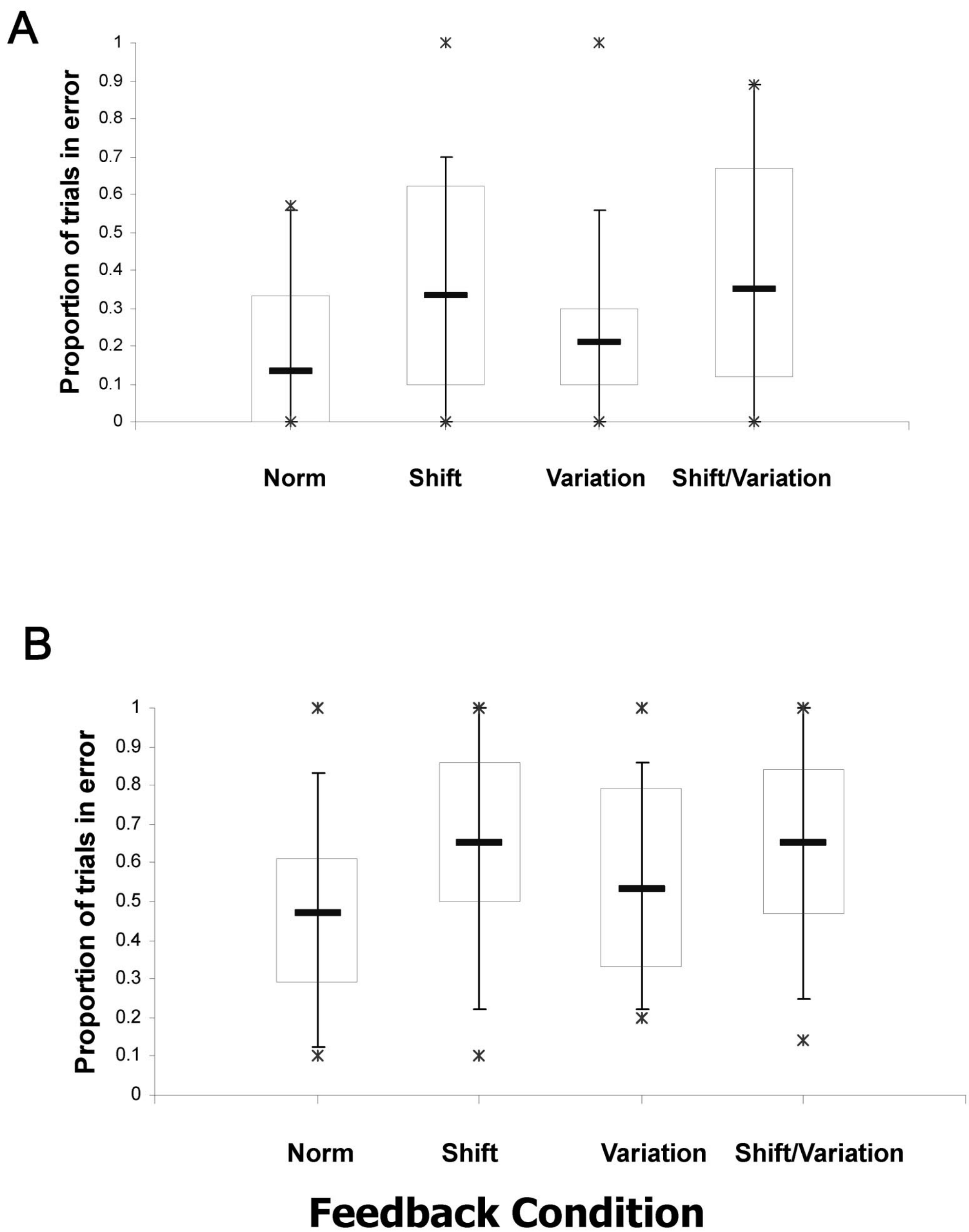

Figure 6. Box plots representing distributions for proportions of all trials with any error from Experiment 2 (tonal variations) for pianists (A) and nonpianists (B). Horizontal lines within boxes display medians, box boundaries highlight the interquartile range, whiskers display the 90th and 10th percentile ranks, and asterisks signify extreme values.

Results from Experiments 1 and 2 could be taken to suggest that perception–action similarity may be based solely on directional information and that no music-specific information (such as pitch class) contributes. This seems unlikely, both in light of the finding that nonpianists (who presumably have stored less music-specific information about perception and action) may not base perception–action similarity on transitional information and in light of other research (discussed earlier) suggesting that alterations to tonality (not addressed by Experiment 2) cause melodies with the same contour to sound dissimilar. Experiment 3 tested the role of tonality by replacing tonal variations with atonal variations.

Experiment 3

Atonal variations maintain the pattern of pitch changes in planned melodies but are unconstrained with respect to pitch class and the allowable intervals between pitch classes (e.g., the interval C-sharp–G deviates from the diatonic context of C major but is allowable in an atonal context). As a result, atonal variations lack the "tuneful" quality of planned melodies for most listeners. If performers base perception–action similarity solely on directional information (in pitch space and physical space), then atonal variations should yield the same pattern of results as was found for tonal variations. However, it is possible that performers will be sensitive to the kind of pitch alphabet that is used. Research in music perception indicates that tonal music and atonal music inhabit different conceptual categories for listeners, and that the way in which pitches are processed and remembered is influenced strongly by whether pitches are interpreted within a tonal framework (e.g., Krumhansl, 1979). On the basis of this research, it is possible that atonal variations will be treated as separate from the representation of the sequence used to guide planning of actions, resulting in a lack of interference from serial shifts, much like the failure of unrelated pitch sequences to disrupt production (Finney, 1997; Pfordresher, 2005).

Method

Participants

Pianists. Fourteen adult pianists (mean age = 26.0, range = 17–49) from the San Antonio, Texas, community who had not participated in the other experiments participated in exchange for pay. They had 9.8 years of training (range = 5–15) and 17.4 years of experience (range = 9–42) playing the piano, on average. One pianist reported having absolute pitch. Twelve reported being right handed and 2 were left handed. Five were male and 9 were female.

Nonpianists. Twenty-two adult nonpianists (mean age = 22.8, range 18–36) from the University of Texas at San Antonio who had not participated in the other experiments participated in exchange for course credit in Introductory Psychology. Nonpianists had 0.05 years of private piano training (max = 1) and 0.25 years of experience playing the piano (max = 4) on average (the individual who reported having 4 years of experience reported no years of training). None reported having absolute pitch. Owing to an experimental oversight, handedness information was not collected. Nine participants were male and 13 were female.

Materials, Conditions, and Procedure

The stimulus materials, conditions, and procedure were identical to those of Experiment 2 except that tonal variations (lag 0 and lag 1) were replaced with atonal variations. Atonal variations were created in the same way as tonal variations, except that changed intervals were not assimilated to the nearest diatonic scale step and could instead match any of the 12 pitch classes in the chromatic scale. Atonal variations were then listened to by the author to confirm that they did sound atonal. As an additional test, pitch classes within atonal variations were correlated with the tone profile found in Krumhansl and Kessler (1982). For the purposes of this analysis, I allowed the "tonic" to vary in order to establish the best fit. In every case, the correlation with the tone profile was weaker for the atonal variation than for the stimulus from which it was created (mean r for original melodies, .60; for atonal variations, .39), and this difference was significant (paired t test, $p <$ .01). By contrast, tonal variations from Experiment 2 were marginally better correlated with the tone profile ($r = .65$, $p > .05$).

Results

Results were analyzed as in Experiments 1and 2 and are shown in Figure 7. The data from 4 nonpianists who made more errors in the normal feedback condition than in all other conditions were removed; the elimination of their data did not change the results qualitatively. Among pianists, conditions with serial shifts caused more errors than those without serial shifts, $T(26) = 21.0$, $p <$ .001, but conditions with atonal variations did not raise errors above conditions in which planned melodies were presented ($p =$ .052). Errors increased relative to normal feedback conditions when participants heard serial shifts of planned melodies, $T(13) = 0$, $p < .001$, or serially shifted atonal variations, $T(13) = 5.0$, $p <$ .01, but not nonshifted atonal variations ($p > .10$). In contrast to Experiments 1 and 2, the two serially shifted conditions differed from each other, with fewer errors resulting from serially shifted variations than from serial shifts of planned melodies $T(10) = 0$, $p < .01$.

Nonpianists likewise generated more errors in conditions with serial shifts than without, $T(66) = 466.5$, $p < .001$, and in contrast to Experiments 1 and 2, conditions with atonal variations resulted in fewer errors than conditions in which planned melodies were presented, $T(63) = 659.0$, $p < .010$. Serially shifted atonal variations were slightly less disruptive than serial shifts of planned melodies for nonpianists in Experiment 3, in contrast to other experiments, $T(59) = 606.0$, $p < .02$. Whereas serial shifts of planned melodies elevated errors relative to normal feedback conditions, $T(32) = 77.0$, $p < .001$, serially shifted atonal variations and nonshifted atonal variations both failed to increase errors ($p >$ .10 for each). Not surprisingly, serial shifts of planned melodies caused more errors than serial shifts of atonal variations, $T(31) =$ 88.0, $p < .001$.

Discussion

The results of Experiment 3 differed from those of Experiments 1 and 2 in that both groups showed a tendency to treat atonal variations as dissimilar to the planned sequence. This result was clearest among nonpianists, who showed no disruption from shifted atonal variations. It is true that nonpianists were also not disrupted (to a significant degree) by shifts of transposed melodies in Experiment 1. However, no difference between the two shift conditions was found in that experiment, demonstrating greater similarity in responses to shifted planned melodies and variations than was found in Experiment 3. Thus, it seems appropriate to conclude that nonpianists only weakly generalize from the planned melody to variants of it and that this weak tendency vanishes completely when the feedback melody is an atonal variant of a planned tonal melody. By contrast, pianists show a strong tendency to generalize on the basis of contour, given the results of Experiments 1 and 2, but this strong tendency is weakened (though not absent) when the feedback melody is an atonal variant of a planned tonal melody. Although pianists experienced disruption from serial shifts of both planned melodies and atonal variations in Experiment 3, disruption was reduced in conditions with atonal variations.

Pooled Results Across Experiments

In the present experiments disruption was used to probe how various transformations of a feedback sequence affect its similarity

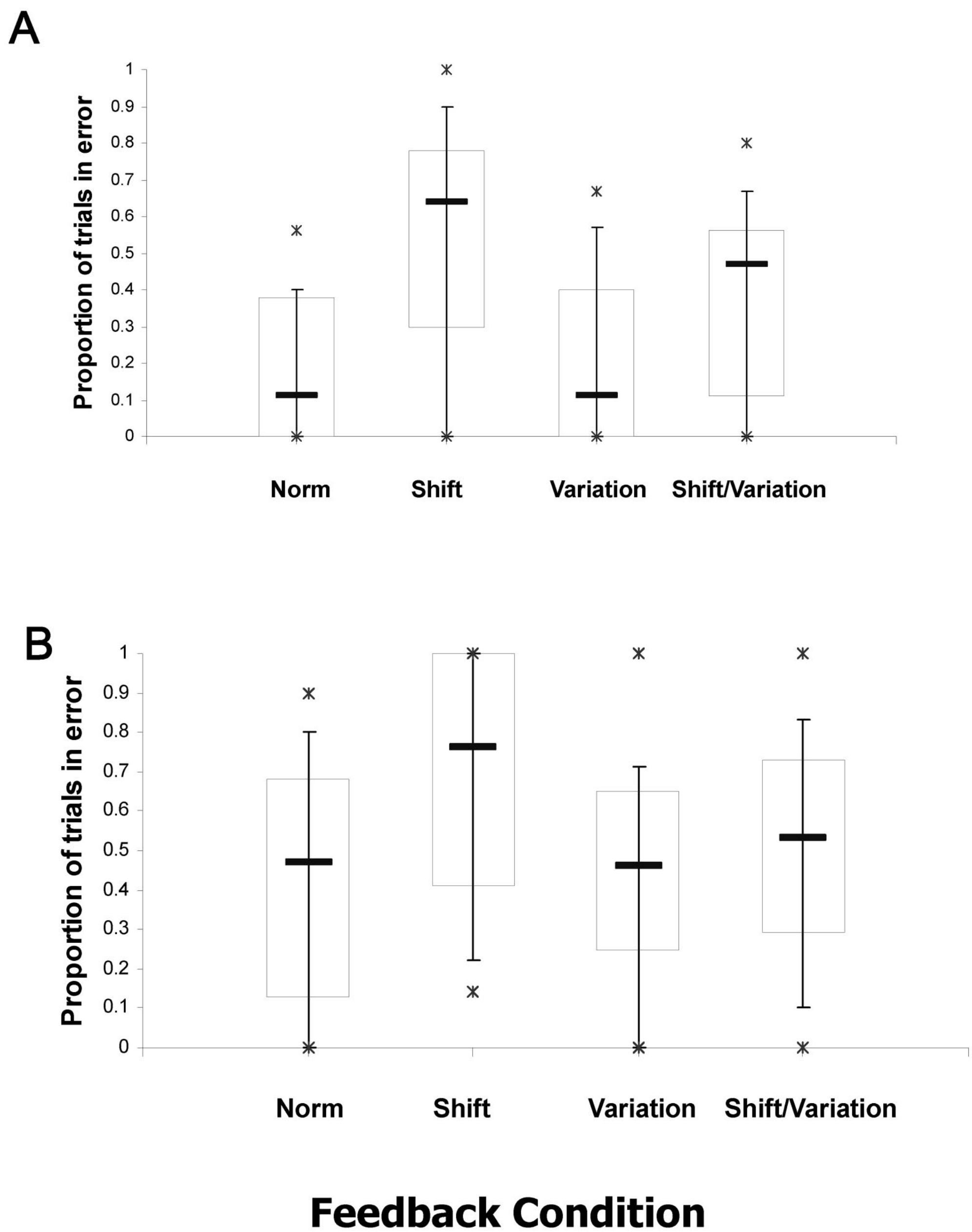

Figure 7. Box plots representing distributions for proportions of all trials with any error from Experiment 3 (atonal variations) for pianists (A) and nonpianists (B). Horizontal lines within boxes display medians, box boundaries highlight the interquartile range, whiskers display the 90th and 10th percentile ranks, and asterisks signify extreme values.

to the sequence that one plans to produce via a series of actions. The specific logic was that disruption from serial shifts of a particular feedback sequence indicates that the feedback sequence is treated as similar to the produced sequence (cf. Pfordresher, 2005). In other words, we expected that participants' responses to altered feedback would reflect generalization from the planned melody to variations, contingent on the similarity of the variation to the planned melody. A final analysis addressed the degree of generalization from planned sequences to variations across groups and experiments directly. A metric of generalization was based on the design of Experiments 1–3:

$$\text{generalization} = \frac{\%\ \text{s-var} - \%\ \text{var}}{\%\ \text{shift}}, \qquad (1)$$

where *s-var* refers to serially shifted variations (which could be exact transpositions, tonal variations, or atonal variations), *var* refers to nonshifted variations, *shift* refers to serially shifted sequences with normal feedback pitches, and percent signs denote the signed change in error proportions for these conditions relative to conditions with normal feedback (*norm*). For instance, for the shift + variation conditions, disruption relative to normal feedback is calculated as

$$\%\text{s-var} = [p(\text{error})_{\text{s-var}} - p(\text{error})_{\text{norm}}]/p(\text{error})_{\text{norm}}. \quad (2)$$

Relative disruption is thus a variant of the Weber fraction that uses signed rather than absolute differences.

Generalization scores express the disruptive effect of shifted variations relative to the disruptive effect of shifted planned melodies, correcting for possible disruption caused by the transformation that generates the variation. Disruption from the unshifted variation suggests that the performer responds to the fact that the melody he or she hears is a different melody. By contrast, lag-1 disruption suggests that the performer responds to the fact that the serial pattern structure is displaced. When the shifted variation causes disruption that is equivalent to the shifted planned melody, the implication is that the performer treats the variation as similar. Generalization scores of 1 indicate perfect generalization, scores greater than 1 indicate compounding effects of the transformation and serial shifts, and scores between 0 and 1 indicate some loss of generalization due to transformation (with 0 indicating no generalization). Negative values, which were less frequent than positive values (25% of all scores), typically resulted from fewer errors occurring in the serial shifted variation conditions than in normal conditions (leading to %s-var < 0). All but one of the negative generalization scores were obtained from nonpianists.

Figure 8 shows distributions of generalization scores for different groups of participants. Deviations from normality in some groups suggest that the mode is most representative of central tendency. Discussion of these results thus focuses on modal responses, although nonparametric analyses (median tests) are also reported. Three participants' scores (3% of the data) were three standard deviations or more greater than the mean for all participants ($M = 0.92$, $SD = 4.11$). These scores were not included in Figure 8 in order to use more informative bin widths, although they were included in the analyses (for which the influence of outliers is negligible). Likewise, the plots (but not the analyses) exclude the data from 1 participant whose generalization score was lower than -6.

Figure 8A shows distributions of generalization scores for pianists. As can be seen, the highest generalization scores were obtained in Experiments 1 and 2, with modal scores greater than 1, though a secondary peak at 0 emerged from a few participants who did not generalize. Experiment 3, by contrast, yielded lower generalization, with a mode less than 1. Note also that the elevated left tail at the negative extreme for Experiment 2 (a deviation from normality that affected means) reflects the fact that a minority of participants were more disrupted by nonshifted tonal variations than by any serial shifts (cf. extreme scores in Figure 6). A median test on all generalization scores for pianists (including those not shown in Figure 8A) revealed a significant effect of Experiment, $\chi(2) = 7.71$, $p < .05$. Experiment 1 ($Mdn = 1.70$) and Experiment 2 ($Mdn = 1.68$) generated more scores above the overall median (1.38) than did Experiment 3 ($Mdn = 0.93$). Figure 8B shows distributions of generalization scores for nonpianists. Nonpianists did not show the same ordering of generalization with experiment (median test nonsignificant). Generalization scores were lower in general for nonpianists than for pianists, which can be seen in Figure 8C, suggesting that little generalization occurred. This result confirms the observation, stated earlier, that nonpianists in Experiment 2 did not treat tonal variations as fully similar to planned melodies. A median test revealed a significant difference between groups, $\chi(1) = 12.73$, $p < .01$, with scores from pianists ($Mdn = 1.38$) more often exceeding the overall median (0.65) than scores from nonpianists ($Mdn = 0.21$).

Generalization scores offer a useful summary statistic, but the combination of three relative difference scores leads to some ambiguity concerning how each relative difference contributes to generalization. Closer examination of relative difference scores indicated that the significant effects were primarily influenced by %s-var and %shift but not by %var. Consider the significant influence of experiment found for pianists: %s-var scores were highest in Experiment 1 ($Mdn = 2.10$) and lower in Experiments 2 and 3 ($Mdn = 0.60$ and 0.58, respectively), $\chi(2) = 10.86$, $p < .01$. The similarity in generalization for Experiments 1 and 2 (not evident in %s-var scores) resulted from %shift scores, which were also reduced in Experiment 2 relative to Experiment 1 for pianists. Differences in %shift across experiments were not significant for pianists, however. With respect to the difference in generalization between pianists and nonpianists, both %s-var and %shift were higher for pianists than for nonpianists: For %svar, $\chi(1) = 13.01$, $p < .01$; for %shift, $\chi(1) = 5.45$, $p < .05$. The significant difference in generalization thus results from a larger difference across groups for %s-var than for %shift.

General Discussion

The experiments reported here were designed to explore the conditions under which a performer treats a sequence of feedback events as similar to the sequence that is anticipated to result from a series of actions. The altered auditory feedback paradigm was incorporated, the logic being that feedback sequences similar to the planned sequence would disrupt production when they were serially displaced relative to actions. One important characteristic of these experiments is that a performer would make fewer errors if he or she treated a variation as dissimilar from the planned melody. This design thus constitutes a strong test of similarity.

Possible determinants of similarity were drawn from past results concerning how different aspects of musical structure influence perception and memory. As in perceptual research, the current results suggest a dominant influence of contour and tonality over interval relationships and absolute pitch for pianists. Nonpianists, by contrast, were less likely to be disrupted when the shifted melody was a variant of the planned melody and thus appear less likely to treat nonidentical sequences as similar. Results from these experiments have implications for the bases of similarity between sequences of feedback events and sequences of planned actions, as well as the way in which musical skill modulates these similarity relationships.

The current results suggest that for pianists, melodic contour—the pattern of upward and downward pitch motion in a melody—constitutes a major determinant of perception–action similarity. In all experiments, pianists' errors increased both when the exact melody they planned to produce was serially shifted and when a contour-matched variation was serially shifted. The disruptive

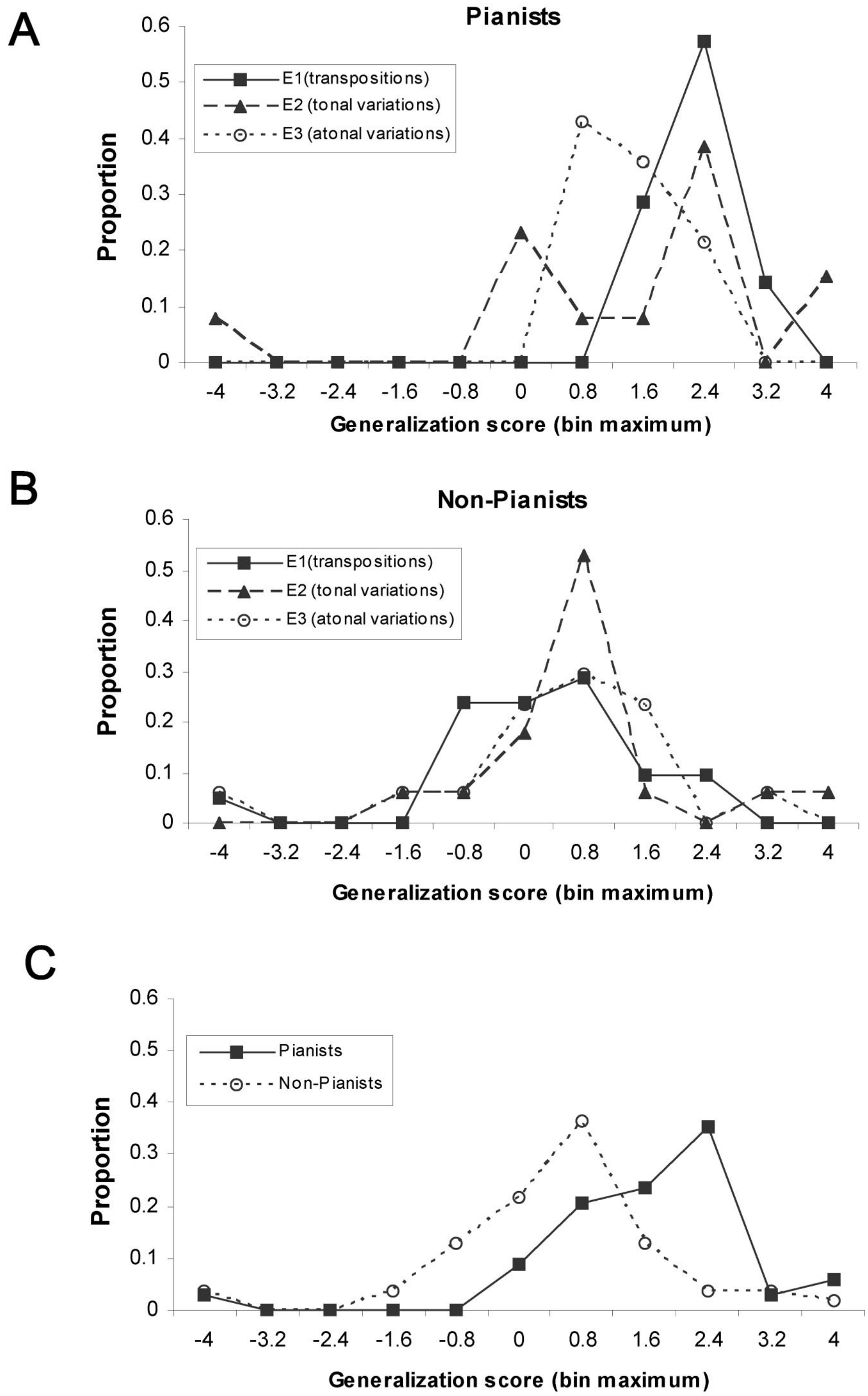

Figure 8. Distributions of generalization scores across participants. Individual panels show distributions for all pianists by experiment (A), distributions for all nonpianists by experiment (B), and distributions across experiments by musical training (C). E = experiment.

effect of serial shifts therefore reflects the fact that auditory feedback presents pitch motion that matches planned movement transitions between other serial positions. Note that the disruptive effect of serial shifts does not simply result from hearing a melodic contour that conflicts with executed movements, given the fact that scrambled pitch sequences cause less disruption than serial shifts (Pfordresher, 2005). The experiments reported here therefore suggest that pianists relate actions to their consequences primarily on the basis of directional information.

Each experiment was designed to test whether a certain kind of melodic transformation reduces perception–action similarity when contour is preserved. Pianists showed no evidence of differentiating produced melodies from exact transpositions, which preserve all relational information but differ with respect to absolute pitch. The fact that pianists did not distinguish these melodies offers support for the prominence of relational information in perception–action similarity. Although this result may not seem surprising, it is worth noting that nonpianists did not generalize in a similar way (as discussed later). Similar to exact transpositions, serial shifts of contour-matched tonal variations also yielded disruption similar to that caused by serial shifts of the planned melody. Tonal variations differ from produced melodies with respect to pitch intervals, thereby altering the mapping between perception and action with respect to the magnitude (but not direction) of change. Thus, the direction of movement transitions, more so than the distance between spatial targets, influences perception–action similarity. At the same time, the salience of movement transitions is probably limited by interval size, in that very large pitch changes are likely to be both perceived and planned as if they were two separate sequences (e.g., Bregman, 1990; Palmer & van de Sande, 1993, 1995).

More individual differences were found in the effects of tonal variations than were found with exact transpositions (see Figure 6A). A few pianists were more disrupted by nonshifted tonal variations than by either shifted tonal variations or serial shifts of the planned melody. This result suggests that some pianists may base perception–action similarity in part on the magnitude of transitions rather than directional information, though the modal response is clearly based on direction.

Pianists responded differently when variations were atonal. Although serial shifts of these feedback melodies did disrupt production, disruption was reduced in magnitude relative to serial shifts of the planned melody, a finding borne out by generalization scores. Contour and tonality appear to have the strongest influence on perception–action similarity. The reduction of disruption from atonal variations is important because it suggests that perception–action similarity is not based exclusively on directional information in melodic contour. Were this the case, effects of altered feedback in piano performance would be no different from well-known effects of response–effect compatibility observed in much simpler tasks (e.g., Elsner & Hommel, 2001; Keller & Koch, 2006, in press; Kunde, 2001; Stöcker et al., 2003). Rather, the influence of tonality verifies that perception–action similarity also relies on schematic information. Research in music perception has shown that tonal and atonal melodies are highly distinguishable (e.g., Bartlett & Dowling, 1988). An influential model of music memory suggests that listeners draw on different pitch alphabets in order to conceptualize tonal or atonal melodies (Deutsch & Feroe, 1981). Beyond individual pitches, tonality may also be determined by (and may determine) transitional information in the form of pitch intervals. With respect to performance, the distinction between tonal and atonal melodies may regulate the kinds of movement transitions that are allowable. Thus, pianists may be able to "tune out" atonal variations, more so than transpositions or tonal variations, on the basis of the fact that the feedback melodies did not present pitch transitions that mapped onto allowable movement transitions. At the same time, the fact that disruption did occur when atonal variations were shifted suggests that the dominant influence of directional information prevented pianists from disregarding the relationships between planned movements and atonal variations.

Nonpianists, in contrast to pianists, apparently did not treat any variations as similar to planned melodies. This tendency allowed nonpianists to experience less disruption from altered feedback than did pianists when the effects of all altered feedback conditions are considered. At the same time, it is clear that nonpianists were sensitive to perception–action similarity based on pitch information, given that they were disrupted by serial shifts of the planned melody. Thus, differences between groups are unlikely to result strictly from action–effect associations solidified through long-term musical training. Instead, it appears as though nonpianists conceptualize perception–action relationships in a more specific way, focusing on individual pitch events, than do pianists, who focus on more abstract transitional information. By contrast, nonpianists may form short-term action–effect associations during the experiment but do not generalize these associations to other kinds of sequences that might result from a similar pattern of movements. This interpretation fits a long-standing idea that the planning of action sequences becomes more abstract with skill acquisition (Fitts & Posner, 1967) and also resembles a transition from absolute to relative pitch processing that may occur during development (Saffran & Griepentrog, 2001). At the same time, this result conflicts with past research from music perception suggesting that untrained listeners rely more on contour, as opposed to pitch class, when recognizing atonal melodies (Dowling, 1978).[5]

The differences between pianists and nonpianists found in the current study contrast with other recent results that show similar patterns of disruption across both groups (Pfordresher, 2005). This difference was particularly surprising in light of the fact that the more obviously recursive melodies performed by nonpianists should have encouraged a greater use of relational information in memory (cf. Boltz & Jones, 1986). In Pfordresher (2005), both pianists and nonpianists were disrupted by lag-1 serial shifts of unaltered melodies (as in the current experiments), were not disrupted when keypresses triggered random pitches, and demonstrated intermediate levels of disruption (viz. error rates) when the pitches of the feedback melody were presented in a scrambled order. The important distinction between current and previous experiments concerns the aspects of similarity that were manipulated. Pfordresher (2005) manipulated event order and pitch class in ways that resulted in feedback melodies with melodic contours that were unrelated to the planned sequence of movement transitions (which did not cause disruption). Such manipulations constitute coarse-grained and perceptually salient manipulations of similarity. By contrast, the current experiments focused on more fine-grained aspects of similarity that follow from music theoretical descriptions of melodic structure. Thus, whereas coarse-grained aspects of similarity (e.g., event order) may cut across all levels of musical skill, the use of more detailed aspects of structure that relate actions to perceived consequences may develop with experience.

The current research focused explicitly on patterns of disruption in production tasks to determine similarity. A more common practice incorporates ratings of perceived similarity, which could be collected following performances with different feedback conditions (as in Pfordresher, 2005, Experiment 5). Such ratings were not incorporated into the design of the current experiments for two reasons. First, the primary focus here was the influence of perception–action similarity on the fluency of production, rather than its effect on perception. Second, there already exists an extensive literature on the way in

[5] I thank an anonymous reviewer for pointing out this discrepancy.

which contour, interval, and scale influence perceived similarity (e.g., Bartlett & Dowling, 1988).

One aspect of the procedure may have influenced the salience of variations. Each trial began with normal feedback and then changed suddenly to the altered feedback condition (on relevant trials). Trials were constructed in this way so as to counteract our primary hypothesis, which was that relational (trajectory) information supersedes absolute (pitch) information in determining perception–action similarity. This was a particular concern for exact transpositions in Experiment 1. A procedure that presented the altered feedback condition throughout the trial might have resulted in many participants not noticing the fact that the feedback melody differed from the planned melody. Incorporating the transition from normal to altered feedback served to maximize the probability that people would treat the transposition as dissimilar. The procedure is somewhat more problematic for Experiment 3. Previous research has shown that atonal melodies sound more dissimilar to a preceding tonal melody than do tonal melodies to a preceding atonal melody (Bartlett & Dowling, 1988). Thus, participants might have treated atonal variations as less dissimilar to the planned melody if the atonal melody had been presented for the entire trial. In order to address this issue, a follow-up study was conducted with 21 nonpianists, in which auditory feedback conditions were present throughout the trial (as in Pfordresher, 2005, Experiment 4). Although serial shifts of the planned melody were less disruptive in this study than in Experiment 3, error frequencies for nonshifted and shifted variation conditions were indistinguishable from those found for nonpianists in Experiment 3.

One potential limitation of the present research is that pianists and nonpianists produced different melodies, with pianists' melodies being longer and more complex than those produced by nonpianists. This decision was based in part on a pragmatic concern: Sequences needed to be difficult enough to elicit errors but not so difficult as to be unplayable. In addition, past research had shown very similar effects of altered feedback when pianists and nonpianists played these different melodies. In the current experiments, however, unexpected differences emerged. Thus, an obvious question emerges as to whether the difference in stimuli, rather than acquired skill, accounts for differing results. Specifically, the more difficult melodies could have elicited increases in error rates more effectively overall. By this account, the failure of shifted variations to disrupt nonpianists may have occurred because the melodies were easier to begin with, leaving nonpianists less vulnerable to disruption. This alternative explanation seems unlikely on two accounts. First, the follow-up study to Experiment 1 revealed highly similar results for pianists for both sets of melodies. Second, nonpianists were generally more error prone than pianists. Thus, although produced sequences varied in difficulty (it should also be noted that pianists took more time to memorize their melodies than did nonpianists, thereby verifying the difference in difficulty of the materials), the accuracy with which these sequences were retrieved from memory was overall best predicted by skill. An additional limitation of the design is that melodic contour was visually represented in the music notation given to pianists but not in the notation given to nonpianists. However, the fact that both groups performed from memory, and in view of the keyboard, suggests that for both groups the dominant association with sounds would have been visual and motoric information from finger movements (also representative of contour) rather than notation.

Taken together, these results suggest that the acquisition of musical skill elicits changes in the way actions are related to resulting pitches. Inexperienced performers relate action to perception in a highly specific way, with action–perception similarity depending not only on transitions but also possibly on links between absolute pitch and the spatial locations of movement targets (i.e., piano keys). With experience performers tend to generalize such that planned action sequences are associated with sequences of outcomes that span beyond the specific sequence one plans to produce. Generalizations are primarily based on the relationship between directional information in feedback (i.e., pitch motion), along with the kind of schema from which feedback events are sampled.

References

Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior, 3,* 111–149.

Bartlett, J. C., & Dowling, W. J. (1988). Scale structure and similarity of melodies. *Music Perception, 5,* 285–314.

Black, J. W. (1951). The effect of delayed side-tone upon vocal rate and intensity. *Journal of Speech and Hearing Disorders, 16,* 56–60.

Boltz, M., & Jones, M. R. (1986). Does rule recursion make melodies easier to reproduce? If not, what does? *Cognitive Psychology, 18,* 389–431.

Bregman, A. S. (1990). *Auditory scene analysis.* Cambridge, MA: MIT Press.

Butler, D., & Brown, H. (1984). Tonal structure versus function: Studies of the recognition of harmonic motion. *Music Perception, 2,* 6–24.

Cuddy, L. L., Cohen, A. J., & Mewhort, D. J. K. (1981). Perception of structure in short melodic sequences. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 869–883.

Deutsch, D., & Feroe, J. (1981). The internal representation of pitch sequences in tonal music. *Psychological Review, 88,* 503–522.

Dowling, W. J. (1978). Scale and contour: Two components of a theory of memory for melodies. *Psychological Review, 85,* 341–354.

Dowling, W. J., & Bartlett, J. C. (1981). The importance of interval information in long-term memory for melodies. *Psychomusicology, 1,* 30–49.

Dowling, W. J., & Fujitani, D. S. (1971). Contour, interval, and pitch recognition in memory for melodies. *Journal of the Acoustical Society of America, 49,* 524–531.

Drayna, D., Manichaikul, A., de Lange, M., Snieder, H., & Spector, T. (2001, March 9). Genetic correlates of musical pitch recognition in humans. *Science, 291,* 1969–1972.

Drost, U., Rieger, M., Brass, M., Gunter, T., & Prinz, W. (2005). Action–effect coupling in pianists. *Psychological Research, 69,* 233–241.

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 229–240.

Finney, S. A. (1997). Auditory feedback and musical keyboard performance. *Music Perception, 15,* 153–174.

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

Finney, S. A., & Palmer, C. (2003). Auditory feedback and memory for music performance: Sound evidence for an encoding effect. *Memory & Cognition, 31,* 51–64.

Fitts, P. M., & Posner, M. I. (1967). *Human performance.* Belmont, CA: Brooks/Cole.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review, 77,* 73–99.

Guenther, F. H., Ghosh, S. S., & Tourville, J. A. (2006). Neural modeling and imaging of the cortical interactions underlying syllable production. *Brain and Language, 96,* 280–301.

Havlicek, L. (1968). Effects of delayed auditory feedback on musical performance. *Journal of Research in Music Education, 16,* 308–318.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences, 24,* 849–937.

Howell, D. C. (2002). *Statistics for the behavioral sciences* (5th ed.). Pacific Grove, CA: Duxbury.

Howell, P., & Archer, A. (1984). Susceptibility to the effects of delayed auditory feedback. *Perception & Psychophysics, 36,* 296–302.

Howell, P., Powell, D. J., & Khan, I. (1983). Amplitude contour of the delayed signal and interference in delayed auditory feedback tasks. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 772–784.

Huron, D., & Royal, M. (1996). What is melodic accent? Converging evidence from musical practice. *Music Perception, 13,* 489–516.

James, W. (1890). *Principles of psychology* (Vol. 2). New York: Holt.

Jones, M. R. (1987). Dynamic pattern structure in music: Recent theory and research. *Perception & Psychophysics, 41,* 621–634.

Jones, M. R., & Pfordresher, P. Q. (1997). Tracking melodic events using joint accent structure. *Canadian Journal of Experimental Psychology, 51,* 271–291.

Keller, P., & Koch, I. (2006). The planning and execution of short auditory sequences. *Psychonomic Bulletin & Review, 13,* 711–716.

Keller, P. & Koch, I. (in press). Action planning in sequential skills: Relations to music performance. *Quarterly Journal of Experimental Psychology*.

Krumhansl, C. L. (1979). The psychological representation of musical pitch in a tonal context. *Cognitive Psychology, 11,* 346–374.

Krumhansl, C. L. (1990). *Cognitive foundations of musical pitch.* New York: Oxford University Press.

Krumhansl, C. L. (2000). Rhythm and pitch in music cognition. *Psychological Bulletin, 126,* 159–179.

Krumhansl, C. L., & Kessler, E. J. (1982). Tracing the dynamic changes in perceived tonal organization in a spatial representation of musical keys. *Psychological Review, 89,* 334–368.

Krumhansl, C. L., Sandell, G. L., & Sergeant, D. C. (1987). The perception of tone hierarchies and mirror forms in twelve-tone serial music. *Music Perception, 5,* 31–78.

Kunde, W. (2001). Response–effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 387–394.

Lahav, A., Saltzman, E., & Schlaug, G. (2007). Action representation of sound: Audiomotor recognition network while listening to newly acquired actions. *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.

Lee, B. S. (1950). Effects of delayed speech feedback. *Journal of the Acoustical Society of America, 22,* 824–826.

Levitin, D. J., & Rogers, S. E. (2005). Absolute pitch: Perception, coding, and controversies. *Trends in Cognitive Sciences, 9,* 26–33.

MacKay, D. G. (1987). *The organization of perception and action.* New York: Springer-Verlag.

Müller, K., Aschersleben, G., Esser, K. H., & Müsseler, J. (2000). Effects of delayed auditory feedback on speech: Just a problem of displaced rhythm? In P. Desain & L. Windsor (Eds.), *Rhythm perception and production* (pp. 249–262). Lisse, the Netherlands: Swets & Zeitlinger.

Müsseler, J. (1999). How independent from action control is perception? An event coding account for more equally-ranked crosstalks. In G. Aschersleben, T. Bachmann, & J. Müsseler (Eds.), *Cognitive contributions to the perception of spatial and temporal events* (pp. 121–148). Amsterdam: Elsevier.

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 skilled music performance. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 947–962.

Parncutt, R., Sloboda, J. A., Clarke, E. F., Raekallio, M., & Desain, P. (1997). An ergonomic model of keyboard fingering for melodic fragments. *Music Perception, 14,* 341–382.

Pfordresher, P. Q. (2003a). Auditory feedback in music performance: Evidence for a dissociation of sequencing and timing. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 949–964.

Pfordresher, P. Q. (2003b). The role of melodic and rhythmic accents in musical structure. *Music Perception, 20,* 431–464.

Pfordresher, P. Q. (2004). Can altered auditory information affect planning? Evidence from music performance. *Stammering Research, 1,* 51–53.

Pfordresher, P. Q. (2005). Auditory feedback in music performance: The role of melodic structure and musical skill. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 1331–1345.

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

Pfordresher, P. Q., & Palmer, C. (2006). Effects of hearing the past, present, or future during music performance. *Perception & Psychophysics, 68,* 362–376.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9,* 129–154.

Quinn, I. (1999). The combinatorial model of pitch contour. *Music Perception, 16,* 439–456.

Repp, B. H. (1999). Effects of auditory feedback deprivation on expressive piano performance. *Music Perception, 16,* 409–438.

Saffran, J. R., & Griepentrog, G. J. (2001). Absolute pitch in infant auditory learning: Evidence for developmental reorganization. *Developmental Psychology, 37,* 74–85.

Schmuckler, M. A. (1999). Testing models of melodic contour similarity. *Music Perception, 16,* 295–326.

Shepard, R. N. (1982). Structural representations of musical pitch. In D. Deutsch (Ed.), *The psychology of music* (pp. 344–390). San Diego, CA: Academic Press.

Sloboda, J. A., Clarke, E. F., Parncutt, R., & Raekallio, M. (1998). Determinants of finger choice in piano sight-reading. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 185–203.

Smith, N. A., & Schmuckler, M. A. (2004). The perception of tonal structure through the differentiation and organization of pitches. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 268–286.

Stöcker, C., Sebald, A., & Hoffman, J. (2003). The influence of response–effect compatibility in a serial reaction time task. *Quarterly Journal of Experimental Psychology, 56A,* 685–703.

Takeuchi, A. H., & Hulse, S. H. (1993). Absolute pitch. *Psychological Bulletin, 113,* 345–361.

Thomassen, J. M. (1982). Melodic accent: Experiments and a tentative model. *Journal of the Acoustical Society of America, 71,* 1596–1605.

Tillmann, B., Bharucha, J. J., & Bigand, E. (2000). Implicit learning of tonality: A self-organizing approach. *Psychological Review, 107,* 885–913.

Ward, W. D. (1999). Absolute pitch. In D. Deutsch (Ed.), *The psychology of music* (2nd ed., pp. 265–298). San Diego, CA: Academic Press.

Witney, A. G., Vetter, P., & Wolpert, D. M. (2001). The influence of previous experience on predictive motor control. *NeuroReport, 12,* 649–653.

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995, September 29). An internal model for sensorimotor integration. *Science, 29,* 1882–1884.

Received November 6, 2006
Revision received July 30, 2007
Accepted August 15, 2007 ■