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Sensorimotor mechanisms in music performance: actions that go partially wrong

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Even expert musicians make errors occasionally, and overt responses that are correct may be accompanied by partial-error behavior that can be indicative of online error detection processes. We compare pianists' production of correct pitches, pitch errors, and partial errors (correct pitches with incorrect force or duration) by examining events prior to errors. Errors tended to be produced with slower durations and softer intensities (associated with force reduction) than correct events. In addition, pre-error events tended to have durations and intensities that fell between those of errors and correct responses, presumably due to response competition with upcoming errors that resulted in partial-error outcomes. These findings support the inference that partial information about upcoming (planned) sequence events is used to guide current responses, consistent with cascade models of activation during sequence production.

Keywords: conflict monitoring; mismatch detection; executive control; partial errors

Introduction

Even the best musicians make errors occasionally: tones whose sensory outcomes do not resemble the performers' expected or intended tones. Errors can arise from many sources, including inattention, lack of skill, or reading failures; we focus here on the occasional unambiguous pitch error when a pianist strikes the wrong key, which can arise even in well-practiced performance. Studies of piano performance indicate a 2–3% error rate in performance of familiar pieces that have been practiced for many hours,[1] similar to error rates reported in other well-learned tasks.[2] One intriguing finding across many domains is that error outcomes resemble events intended for elsewhere in a sequence: for example, a sightreading error that slips the eye because the error fits well within the musical context,[3] or an exchange of order between neighboring elements of an action sequence.[4]

Several studies suggest that performance errors influence the production of surrounding events. The altered force or timing with which those surrounding events are produced has led them to be termed "partial errors," which have been defined in simple response tasks as error tendencies (such as a faulty timing or response force) that do not result in a full-fledged inaccurate response (such as pressing the wrong key).[5] These partial errors are particularly interesting because they are often accompanied by electromyographic or electroencephalographic signals prior to their production that indicate some awareness that an error has been planned prior to its execution.[6,7] Explanations of how errors and partial errors arise, and what they reveal about real-time processing mechanisms, fall into two primary camps. One explanation is that error detection is the product of a mismatch comparator,[7,8] in which a representation of a correct response is compared with a representation of an actual response. Sufficient mismatch between these representations triggers the comparator to generate an error signal, which is thought to generate an error-related negativity that often precedes the error outcome.[6,7] An alternate explanation is the conflict monitoring hypothesis,[9] in which two or more events prepared for execution are compared; the comparison reflects the degree of conflict between these events, which generates a larger signal, the greater the conflict.

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Possible functions of an error-related negativity include immediate error correction (within-trial), as have been reported for fast error corrections[10] and for partial (inhibited) errors.[5] Only the error mismatch theory is consistent with the immediate error correction function. Another possible function is strategic adjustments between trials, as seen in post-error slowing[10] or in conflict adaptation.[11] The conflict monitoring theories are most consistent with this function. Unfortunately, the timing of the event-related negativity (ERN) is not always consistent with post-error slowing or error correction,[6,12] and larger ERN amplitudes have sometimes been noted for lower conflict than for higher conflict conditions.[13]

Several researchers have proposed that errors and, to some extent, partial errors arise from mismatches to a predictive sensorimotor consequence;[6,8] as a response unfolds, the predicted sensory outcome of the action is compared with the actual sensory input. This predicted outcome is thought to include stimulus features and kinesthetic properties, and deviations from the predictions are used to correct movements. Similar internal prediction models have been proposed for motor control tasks,[14] and for visual and kinesthetic feedback in aimed movements.[15] Most of these tasks entail single arm or hand movements, in which the sensory consequences do not overlap with preceding or successive outcomes that are typical of the relatively fast tone sequences that musicians must execute.

We describe a study of the occasional errors that arise in piano performance, typified by production of very fast series of individual hand and finger movements whose sensory/kinesthetic properties overlap in time. Music performance provides an excellent ground for testing the adaptive nature of the brain in response to occasional pitch errors that arise when fingers strike the wrong keys. We test whether information associated with error outcomes is used for online corrections, and we examine the events preceding errors for signs of partial errors that have been reported in piano performance.[16,17] Pianists performed two-part musical pieces at fast tempi after producing a note-perfect performance of the pieces at a slower tempo. The musical contexts in which pianists performed were examined for their influence on the types of errors that occurred.

Method

Participants and materials

Twenty-four adult pianists from the Montreal community participated in the study; all participants had at least seven years of piano training ($M = 16.2$ years). Every participant reported playing the instrument regularly; none reported any hearing problems. They performed eight novel pieces, composed in 4/4 meter and consisting of 33 isochronous sixteenth notes in two parts (one part controlled by each hand). Half of the pieces were in a major key and half were in a minor key, and all conformed to conventions of Western polyphonic music.

Design and procedure

Each participant performed four musical pieces twice per block in each of four experimental blocks ($4 \times 2 \times 4$), with the musical notation in view. Two pieces were performed at a medium tempo (225 ms per sixteenth-note interonset interval [IOI]), and the other two at a fast tempo (187.5 ms per sixteenth-note IOI). Each piece was performed twice at one of the two experimental tempi within each trial. The ordering of pieces and assignment of tempo to piece were counterbalanced across subjects.

At the start of the session, participants practiced each piece until an error-free performance was achieved at a slow tempo (429 ms per sixteenth-note IOI). This criterion ensured that errors that occurred at faster tempi were not due to sight-reading failures, errors of perception, or incorrect learning of the musical pieces. Pianists were instructed to perform at the tempo indicated by the metronome throughout the trial and to perform without correcting any errors. Additional (unrelated) pieces were performed either before or after the performances of the pieces evaluated in the study.

Errors in pitch accuracy were identified by computer comparison of pianists' performances with the information in the notated musical score.[18,19] Although pianists were instructed at the beginning of the session not to stop and correct any errors that they produced, they occasionally corrected some of the errors and thus the error was interrupted and could not be coded unambiguously. These correction errors were excluded from all analyses (less than 1.2% of total errors).

Results

The mean pitch error rate across all performances was 0.12 (mean error rate in medium tempo performance = 0.092; fast performance = 0.144). Pitch errors were first compared with correct tones in terms of their duration, measured by IOIs (shown in Fig. 1). To evaluate influences of errors on the performance of events that preceded them, correct tones were divided into two groups for analysis. The first group consisted of every correct event that was produced immediately before an error, referred to as pre-error tones, and the second group consisted of every correct event that was not followed by an error, referred to as correct tones. IOIs were determined from the onset of a particular pitch event to the onset of the subsequent pitch that was produced by the same hand of the pianist.

A repeated measures analysis of variance (ANOVA) on the mean event IOIs in each performance by tempo and event type indicated a significant main effect of tempo, $F(1, 23) = 367.68$, $P < 0.001$. As expected, event IOIs in the medium condition ($M = 227$ ms) were significantly greater than event IOIs in the fast condition ($M = 195$ ms) and closely matched the prescribed tempi of 225 ms IOI in the medium condition and 187.5 ms IOI in the fast condition. Also, there was a significant effect of event type on produced IOI, $F(2, 46) = 3.25$, $P < 0.05$, and no interaction of tempo with event type. *Post hoc* comparisons (Tukey HSD = 5.22, $\alpha = 0.05$) indicated that mean IOIs of errors were significantly greater than IOIs of correct tones, but mean IOIs of pre-errors did not differ significantly from those of correct tones or error tones. Thus, the accuracy of performance pitches influenced the relative length of time that the pitches were sounded, from fastest (correct) performance to slowest (errorful) performance. Pitch errors were performed less accurately in time relative to the metronome tempo than were correct events.

We further analyzed whether error tones differed from correctly performed tones in terms of the intensity with which they were produced. Figure 2 shows mean intensities of correctly performed tones, pitch errors, and pre-error correct tones. The repeated measures ANOVA on event intensities by tempo and event type indicated a significant main effect of tempo, $F(1, 23) = 6.44$,

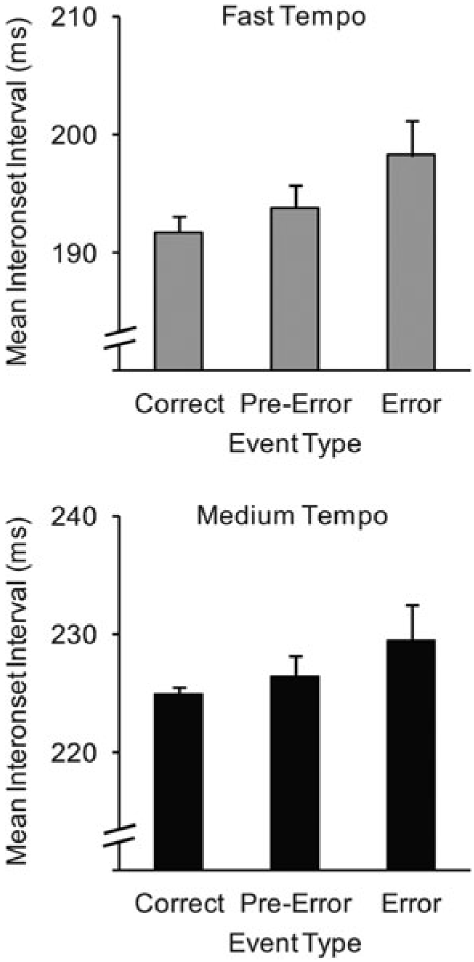

Figure 1. Mean IOIs of correctly performed pitches that were not immediately followed by an error, correct pitches produced one tone before errors, and pitch errors. Fast tempo condition on top; medium tempo condition on bottom.

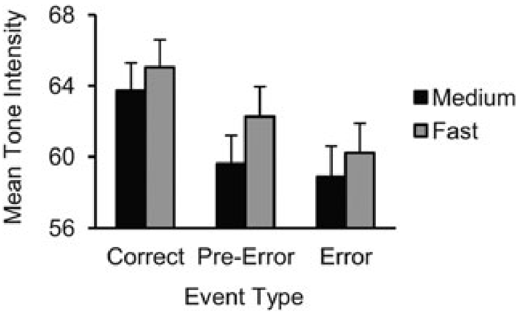

Figure 2. Mean intensities (MIDI velocity values) of correctly performed pitches that were not immediately followed by an error, correct pitches produced immediately before an error, and pitch errors for the medium- and fast-tempo conditions.

Figure 3. One of the notated stimulus pieces with predicted metrical accent strengths according to a 4-tier metrical grid. Events aligned with higher tiers are more strongly accented.

$P < 0.05$. Similar to previous findings,[20] pitches in the fast tempo condition ($M = 62.5$) were produced with significantly more force (yielding greater tone intensities) than pitches in the medium tempo condition ($M = 60.8$). There was also a significant effect of event type on production intensity, $F(2, 46) = 31.52$, $P < 0.001$. *Post hoc* comparisons (Tukey HSD = 1.50, $\alpha = 0.05$) indicated that, on average, correct tones were produced with greater intensity than both pre-error tones and error tones, while pre-error and error tones did not differ in intensity. Thus, the locus of the error effect extended to the amount of force with which performers produced pre-error tones. There was no significant interaction of tempo and event type.

The position of sequential events within a piece's metrical framework may influence the intensity with which errors and correct tones are produced. To examine metrical effects on tone intensities, correct and error tones were coded for metrical accent strength according to a 4-tier metrical grid, consistent with the time signature and smallest notated duration in the musical score of the pieces, as shown in Figure 3 for one piece.[21]

It is possible that online adjustments to the execution of pre-error tones reflect preparation specific to the pre-error position, in addition to (or in place of) preparation of the upcoming error. For example, the metrical accent strength of an error and of the tone preceding it may influence the production of both the error and the tone preceding it. To test this possibility, we compared mean tone intensities for correct events, pre-error events, and errors within each performance by the metrical accent level with which they were aligned, as prescribed in Figure 3. Figure 4 shows the mean intensities of correct, pre-error, and error tones as a function of the metrical accent strength with which those tones aligned in the musical score.

A repeated measures ANOVA on performance intensities by tempo, event type, and metrical accent strength (1–4) indicated again the significant main effects of event type, $F(2, 46) = 22.84$, $P < 0.001$, and tempo, $F(1, 23) = 5.24$, $P < 0.05$, such that correct events and events in fast-tempo performances were played with greater intensity on average. There was also a significant main effect of accent, $F(3, 69) = 53.72$, $P < 0.001$. Tones aligned with stronger metrical accents (metrical tiers 3 and 4) were produced with significantly greater intensity than tones that were aligned with weaker metrical accents (tiers 1 and 2) (Tukey HSD = 1.94, $\alpha = 0.05$), similar to other reports.[22] In addition, tones were produced with significantly greater intensity when they aligned with metrical accent tier 2 than when aligned with tier 1 (Tukey HSD = 1.94, $\alpha = 0.05$). There were no interactions of metrical accent with other variables.

If pre-error events are distinguished from correct events due to a temporal overlap of processing with errors, they may inherit the properties of the errors they precede. To test this possibility, we reexamined the intensities of pre-error tones in terms of the metrical accent strength of the error they preceded (as opposed to their own metrical accent strength shown in Fig. 4). Figure 5 shows the intensity of pre-error tones as indexed by the metrical accent strength of the error they precede; this pattern differs distinctly from the intensities of the pre-error tones as indexed by their own metrical accent strength (Fig. 4, middle) as well as by the metrical accent strength of correct tones and error tones. Thus, pre-error tones, while reflecting some properties of the errors they precede (weaker intensities), retain their

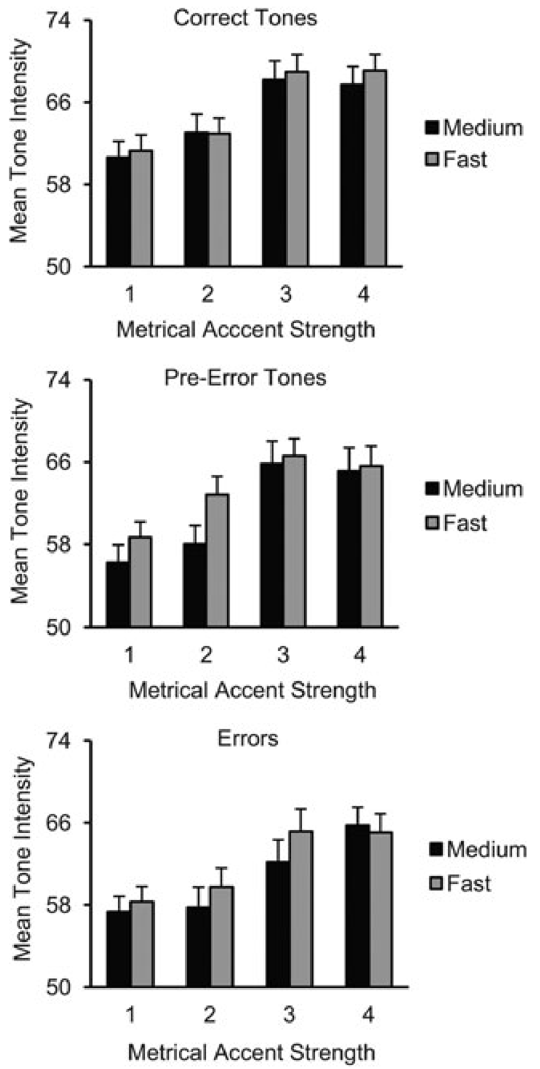

Figure 4. MIDI values as a function of metrical accent strength and tempo. Correct tone intensities on top; pre-error tones in middle; and error tones on bottom.

own metrical accent strength and are not completely defined by the error.

Overall, meter influenced how forcefully tones were produced irrespective of their accuracy: pre-error tones inherited the metrical strength of their intended positions, as opposed to that of the error they preceded. This finding suggests that the online correction interpretation, consistent with the mismatch detection hypothesis, does not extend to all aspects of pre-error tones. Thus, the produced intensity of pre-error tones was influenced by both the position of the tones relative to upcoming errors, and by the metrical hierarchy with which the pre-error tones aligned.

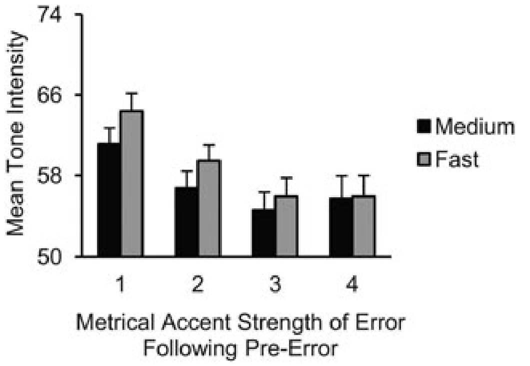

Figure 5. MIDI values of pre-error tones as a function of tempo and metrical accent strength of the following error.

Discussion

Pianists' errors produced during speeded performance documented pre-error intensity reductions arising from the reduced force with which pianists' fingers struck the keys, consistent with predictions of an error monitoring hypothesis. Pre-error events indicated some evidence of slowing as well, though not as large as found in previous literature, perhaps due to the task demands to perform at a fixed tempo. These findings extend comparisons of correct events and errors[16,17] to pre-error events which, like partial errors, inherit some unintended (incorrect) properties of the errors they anticipate (reduced tempo, decreased intensity) but retain their own pitch features in performance. The current findings also extend the previous findings to performances at different tempi; the rate at which pre-error events are produced is modulated by both the intended rate and by the upcoming error, features that are typical of partial errors.

Coles *et al.*[5] proposed that subthreshold motor activity associated with partial errors may affect the way in which correct responses are produced, and thus hypothesized that the processing system noticed partial errors and adjusts its behavior. The partial errors noted in the current study were not uniquely predictive of upcoming errors; that is, the distributions of timing and intensity features of partial errors overlapped with the same properties of error events; this is likely due, we believe, to the rapid tempi at which the sequences were performed, yielding overlapping time-courses of processing.

Pianists' pitch errors and the partial errors that precede them may be distinguished by electrophysiological markers of ERNs. Partial errors observed in button-pressing tasks[13,23] tend to elicit ERNs whose amplitudes[6] and latencies[24] are associated with reduced force during response production. If the ERN signals error correction, then ERNs that occur sooner before an error outcome should be more likely to be associated with a partial error (and reduced response force) than those that occur later.[25] The reduced force that we observed for pre-error events was suggestive of a corrective signal that precedes error production by at least 180 ms; this timecourse is consistent with Ruiz and colleagues'[17] findings that pre-error slowing was detected at least 125 ms before pianists' pitch errors.

Pre-error events inherited some properties of upcoming outcomes while retaining other unique (correct) features, consistent with the fact that many errors in music performance arise from response competition among intended sequence events, called contextual errors.[19] The idea that response competition effects are graded (not all or none) fits with musicians' task demands to produce a sequence of pitches, many of which repeat in the sequence and, therefore, recur as viable responses. Given a musical context of speeded sequences of repeating responses, it is reasonable to expect that the time-courses of errors and pre-error events overlap; thus, it is possible that pre-errors resemble errors in part because their time-course overlaps with that of planned error actions, as well as because pre-errors have registered as too slow or quiet (intensity) in their own right. The fact that we were able to demonstrate the same patterns of pre-error tone properties (slowing and reduced force) in fast and medium performances suggests that the properties shared between errors and pre-error tones are not solely due to their overlapping time-courses.

Pianists' increased performance tempi yielded higher intensities (faster finger forces) and shorter interonset intervals for all tones (correct events, errors, and pre-error events). The performance tempi were both fairly fast and elicited relatively high error rates. Thus, perhaps it is not surprising that the pre-errors did not change their features across the similar performance tempi. A wider range of performance tempi may provide a more sensitive test of the overlapping influences of pre-error and error tones.

The piano performances of two-handed novel musical pieces elicited more errors, and thus more pre-error events, compared with previous studies of piano performance.[16,17] Ruiz and colleagues[17] studied fast performances of single-handed musical excerpts, which tended to elicit fewer planning demands and less slowing in tempo attributable to musical difficulty.[18] Maidhof *et al.*[16] used scales and octaves, which also may not have taxed pianists as much as the novel musical pieces used here. Thus, some experimental differences may have accounted for why so many partial errors resulted in this study. It would be revealing to examine whether partial errors that retain their own properties elicit a smaller ERN than those that inherit most characteristics of the error they anticipate.

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Conflicts of interest

The authors declare no conflicts of interest.

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