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Auditory N1 reveals planning and monitoring processes during music performance

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Abstract

The current study investigated the relationship between planning processes and feedback monitoring during music performance, a complex task in which performers prepare upcoming events while monitoring their sensory outcomes. Theories of action planning in auditory-motor production tasks propose that the planning of future events co-occurs with the perception of auditory feedback. This study investigated the neural correlates of planning and feedback monitoring by manipulating the contents of auditory feedback during music performance. Pianists memorized and performed melodies at a cued tempo in a synchronization-continuation task while the EEG was recorded. During performance, auditory feedback associated with single melody tones was occasionally substituted with tones corresponding to future (next), present (current), or past (previous) melody tones. Only future-oriented altered feedback disrupted behavior: Future-oriented feedback caused pianists to slow down on the subsequent tone more than past-oriented feedback, and amplitudes of the auditory N1 potential elicited by the tone immediately following the altered feedback were larger for future-oriented than for past-oriented or noncontextual (unrelated) altered feedback; larger N1 amplitudes were associated with greater slowing following altered feedback in the future condition only. Feedback-related negativities were elicited in all altered feedback conditions. In sum, behavioral and neural evidence suggests that future-oriented feedback disrupts performance more than past-oriented feedback, consistent with planning theories that posit similarity-based interference between feedback and planning contents. Neural sensory processing of auditory feedback, reflected in the N1 ERP, may serve as a marker for temporal disruption caused by altered auditory feedback in auditory-motor production tasks.

Descriptors: FRN, N1, Sequence planning, Feedback monitoring, Sensorimotor memory, Music cognition

Humans produce complex auditory sequences such as speech and music with remarkable fluency. In order to produce these sequences with high speed and accuracy, speakers and musicians plan a subset, or increment, of sequence events that is updated as an auditory sequence is produced (Dell, 1986; Levelt, Roelofs, & Meyer, 1999; Palmer & Pfordresher, 2003). “Contextual” production errors, in which phonemes or tones are produced earlier or later than intended, provide evidence that producers possess access to a range of events at any given time during production (Fromkin, 1971; Garrett, 1976; Palmer & van de Sande, 1993). While some models suggest producers’ plans encompass both upcoming (future) and previously produced (past) events in sequences (Palmer & van de Sande, 1995), others have proposed that the anticipation of upcoming events during production results in greater activation of future events than past events (Dell, Burger, & Svec, 1997; Guenther, Hamson, & Johnson, 1998). Future-oriented models cite increased anticipatory errors in production of speech and music as performers gain practice or higher skill levels as evidence for “turning off” or unweighting past events during production (Dell et al., 1997; Drake & Palmer, 2000). According to these models, future events are more similar to one’s current performance plan than past events. Similarity-based interference and decay are two dominant psychological theories of memory loss (Brown, 1958; Keppel & Underwood, 1962). According to these theories, memory can fail when a similar or related idea generates interference, or when the original idea decays over time. When performers plan ahead during production of a sequence, they are activating memory for future events they prepare for production (Dell, 1986; Palmer & Pfordresher, 2003).

In addition to planning during auditory production, producers monitor the perceptual outcomes of their actions. Feedback monitoring involves identifying whether a perceived auditory outcome matches the intended outcomes of one’s actions (Levelt, 1983). Monitoring seems to be important for maintaining accurate and stable movements, as alterations of auditory feedback tend to disrupt

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production: Speakers alter their productions when hearing formant-shifted auditory feedback (Houde & Jordan, 1998), and delays in the timing of auditory feedback relative to key presses during music performance induce a slowing of production rate (Finney, 1997; Pfordresher, 2003; Pfordresher & Palmer, 2002). Behavioral effects of hearing altered auditory feedback during music performance differ depending on whether the feedback matches intended upcoming (future) key presses or previous (past) key presses (Pfordresher & Palmer, 2006), suggesting that feedback monitoring may be influenced by producers' concurrent planning processes. When pianists hear sound that activates a memory for a different tone in the melody—one that is similar to the tone that they are supposed to be performing—the memory activation of the "incorrect" feedback can cause similarity-based interference with the currently active (correct) planned events (Pfordresher & Palmer, 2006). Not all manipulations of auditory feedback, however, disrupt production: Musicians are able to continue performing well-learned music when auditory feedback is completely removed (Bangert, Jürgens, Häusler, & Altenmüller, 2006; Finney & Palmer, 2003; Repp, 1999), or when the feedback is highly different from the music being performed (Conde, Altenmüller, Villringer, & Ragert, 2012). Thus, current evidence suggests that disruption caused by altered auditory feedback during production may hinge on the similarity between the feedback and the performance plans. Future-oriented theories of planning predict greater disruption of production when perceiving the future compared to perceiving the past, since future events are assumed to be more strongly activated than past events at any given time during production.

Neural mechanisms underlying disruptive effects of altered auditory feedback on music performance remain largely unexplored; to our knowledge, no studies in the domains of speech or music production have examined neural responses to altered pitch feedback that matches future sequence positions. We propose that the auditory N1 ERP component, elicited about 100 ms following auditory onsets, could serve as a marker for the sensory processing of altered auditory feedback during production (Horváth, 2015). Amplitudes of the N1 component elicited by auditory onsets are decreased when sounds are self-generated compared to nonself-generated in button-pressing tasks (Aliu, Houde, & Nagarajan, 2009; Baess, Horváth, Jacobsen, & Schröger, 2011; Bendixen, San-Miguel, & Schröger, 2012), and self-generated speech elicits suppressed N1 responses compared to nonself-generated speech (Christoffels, van de Ven, Waldorp, Formisano, & Schiller, 2011). The similarity of altered feedback to concurrent speech production modulates N1 suppression effects: Graded increases in N1 amplitudes are observed for pitch feedback shifts of up to 200 cents during production, and no suppression is observed for shifts of 400 cents or more (Behroozmand & Larson, 2011). Thus, N1 amplitudes modulated by the similarity of perceived and intended feedback may indicate the degree to which sensory processing of auditory feedback is suppressed (less-negative N1 amplitudes) or enhanced (more-negative N1 amplitudes) during production. This leads to the prediction that hearing future altered auditory feedback, which is more similar to current performance plans than past altered auditory feedback, may generate greater similarity-based interference during music performance and decrease suppression of N1 amplitudes.

Altered auditory feedback tones during music performance elicit a feedback-related negativity (FRN) maximal around 150 to 250 ms following the altered tone onsets (Katahira, Abla, Masuda, & Okanoya, 2008; Loehr, Kourtis, Vesper, Sebanz, & Knoblich, 2013; Maidhof, Vavatzanidis, Prinz, Rieger, & Koelsch, 2010). The FRN component has also been observed in response to unexpected feedback such as losses or wins in guessing or gambling tasks (Gehring & Willoughby, 2002; Hajcak, Moser, Yeung, & Simons, 2005; Holroyd & Coles, 2002; Miltner, Braun, & Coles, 1997; Nieuwenhuis, Holroyd, Mol, & Coles, 2004), and may reflect neural processes related to violations of feedback-related expectations or error monitoring processes (Carter & Van Veen, 2007; Ferdinand, Mecklinger, Kray, & Gehring, 2012; Ferdinand & Opitz, 2014; Oliveira, McDonald, & Goodman, 2007). The FRN is associated with neural oscillations in the theta frequency range (4–8 Hz) that may reflect cognitive control mechanisms or stimulus-induced surprise (Cavanagh & Frank, 2014; Gehring & Willoughby, 2004). Altered auditory feedback tones during music performance also elicit a P3a ERP subcomponent maximal around 300 to 500 ms following pitch onsets (Maidhof et al., 2010). The P3a is elicited by novel or task-irrelevant stimuli, and may reflect the updating of stimulus memory representations (Donchin & Coles, 1988; Polich, 2007), decision-making processes (Nieuwenhuis, Aston-Jones, & Cohen, 2005), or endogenous shifts of auditory attention to unexpected stimuli (Escera, Corral, & Yago, 2002).

The current study presented altered auditory feedback corresponding to previous (past) and upcoming (future) actions during a music performance task. ERPs, evoked oscillatory potentials, and the timing of piano key presses in response to altered auditory feedback pitches were measured in order to determine the neural and behavioral foundations of performers' monitoring and planning processes. Pianists memorized and performed isochronous tone sequences. Altered auditory feedback was manipulated in four conditions: future, past, noncontextual, and baseline. In the future condition, participants heard an altered pitch (at a random location) that matched the next intended pitch in the produced sequence. In the past condition, participants heard an altered pitch that matched the previously intended (notated) pitch. In the noncontextual condition, participants heard a pitch that was not present in the sequence; this control condition tested effects of hearing an altered feedback pitch that was unrelated to performers' planning processes. Finally, in the baseline condition, participants heard the expected auditory feedback with no pitch alterations. We tested three predictions: First, future altered auditory feedback was expected to induce greater interference with current plans than past altered auditory feedback, based on the notion that producers' plans are weighted toward upcoming events (Dell et al., 1997). Pianists were therefore expected to show greater slowing of production rate following future altered auditory feedback compared to other types of feedback. Second, greater temporal disruption during performance was expected to result from similarity-based interference of planned movements with their auditory outcomes (Palmer & Pfordresher, 2003), resulting in decreased suppression of the N1 component following future compared to past feedback. Third, future, past, and noncontextual altered feedback pitches were expected to elicit FRN and P3 ERP components, along with corresponding theta oscillations within the time frame of the FRN.

Method

Participants

Twenty-eight right-handed adult pianists from the Montreal community with at least 6 years of private piano instruction were recruited. Four participants were excluded from analysis due to insufficient data after removal of trials containing pitch errors ($n = 2$) or EEG artifacts ($n = 2$). The remaining 24 pianists (13

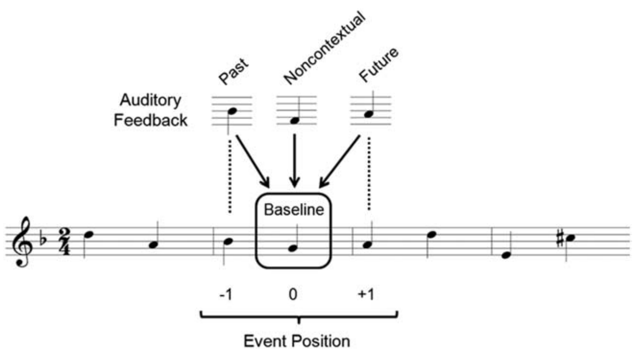

Figure 1. Example of a stimulus melody used in the experiment. Example altered feedback pitches for the four auditory feedback conditions (past, future, noncontextual, baseline), and the three event positions over which interonset intervals (IOIs) and ERPs were analyzed (-1, 0, +1), are shown. Event positions are numbered with respect to the distance from the target pitch. Arrows show the location at which the altered feedback pitches occurred, and dashed lines indicate the origin of the altered feedback pitches.

women, age *M* = 21.6 years, *SD* = 4.5) had between 6 and 20 years of piano lessons (*M* = 11.4 years, *SD* = 3.6 years). Participants reported having no hearing problems. Participants provided written informed consent, and the study was reviewed by the McGill University Research Ethics Board.

Materials and Procedure

Stimulus materials. Four novel melodies that were notated in a binary meter (2/4 time signature), conforming to conventions of Western tonal music, were used in the study. All melodies were isochronous (containing only eight quarter notes), were notated for the right hand, and were designed to be repeated without stopping three times in each trial (totaling 24 quarter-note events). The four melodies were composed in the keys of G major, D minor, C major, and B minor. Suggested fingering instructions were also notated.

During the experiment, auditory feedback pitches heard by participants while performing the melodies were occasionally replaced by an altered pitch. The altered pitches were chosen from the same diatonic key as the original melody to maintain the melodic contour of the original melody, and to avoid tritone intervals. Altered feedback pitches occurred in one of eight possible locations within each trial; half of the locations were on weak metrical accents and half were on strong metrical accents, as predicted by a binary metrical hierarchy (Lerdahl & Jackendoff, 1983).

Altered pitches were chosen to create three altered feedback conditions: future pitches, past pitches, and noncontextual pitches. Examples of the altered feedback pitches for one of the stimulus melodies are shown in Figure 1. In the *future* condition, participants heard the pitch that corresponded to the next intended (notated) pitch in the melodic sequence. In the *past* condition, participants heard the pitch that corresponded to the previously intended (notated) pitch in the melodic sequence. In the *noncontextual* condition, participants heard a pitch from the same diatonic key as the melody that was not present in the melodic sequence. The noncontextual condition was intended to serve as a control condition, to test effects of hearing an altered feedback pitch that was unrelated to performers' planning processes. Finally, in a *baseline* condition, no auditory feedback pitches were altered (participants heard the intended auditory feedback).

Each trial was designed to contain three and a half iterations of a repeated melody. Each trial began with a 12-beat metronome sounded at 500 ms; the first four beats indicated the intended pace and the remaining eight beats coincided with the pianists' first iteration of the melody, forming the synchronization phase of the trial. The metronome stopped and the auditory feedback continued for two more iterations of the melody, forming the continuation phase of the trial, during which an altered feedback pitch could occur. Then, auditory feedback ended to signal the end of the trial. A minimum of zero and maximum of two pitches were altered within a single trial, with a maximum of one altered pitch per melody iteration. When two altered pitches occurred in a single trial, they were always separated by at least three unaltered pitch events. No alterations occurred on the first pitch of any iteration.

Equipment. Participants performed the stimulus melodies on a Roland RD-700SX musical instrument digital interface (MIDI) keyboard (Roland Inc., Richmond, BC, Canada) in a sound- and electrically attenuated chamber while EEG was recorded. As pianists performed, sound was emitted from a Roland Edirol SD-50 system (Roland Inc.) and delivered through EEG-compatible air-delivery earphones (ER1-14B, Etymotic Research Inc.). Two channels were used for auditory feedback: GMT piano 002 for piano key press auditory feedback, and Rhy 001 for the metronome that signaled the performance rate at the start of each trial. Auditory feedback pitches were controlled using FTAP software (Finney, 2001), which presented preprogrammed pitches at the time that pianists pressed each key, and measured key press timing information with 1-ms resolution.

Design. The study used a repeated measures within-participant design in which altered auditory feedback pitches were manipulated in four conditions: future, past, noncontextual, and baseline. Participants completed three blocks each corresponding to an altered auditory feedback type (future, past, noncontextual). Trials that contained no altered auditory feedback (baseline condition) were intermixed equally often within the three blocks. Each block contained 32 trials, or 64 iterations, which were grouped within the block by melody. Within each block, 50% of performed iterations (32 iterations) within the continuation period of the trials contained no altered auditory feedback, and 50% of iterations (32 iterations) contained an altered feedback pitch. Each trial containing altered auditory feedback was unique within the context of the experiment and therefore was heard only once by participants during the course of the experiment. Block and melody orders were counterbalanced across the 24 participants. Participants performed a total of 96 (3 blocks × 32) trials, or 192 continuation iterations (32 future, 32 past, 32 noncontextual, and 96 baseline), over the course of the entire experiment.

Procedure. Participants first completed a musical background questionnaire, followed by a piano performance memory test. Participants who were able to perform a short right-hand melody from memory to a note-perfect criterion within three attempts, after up to 3 min of practice with the notation, were admitted to the experiment. All pianists met this criterion. Following completion of the memory test, participants were outfitted with EEG caps and electrodes. Participants were then asked to complete three practice trials prior to beginning the experiment in order to become familiar with the task. At the start of the practice trials, the participants were presented with the music notation of the single-hand melody that they had previously performed in the memory test. They were asked to memorize the melody with the goal of performing it from memory. Following memorization, the music notation was removed and replaced with a fixation cross. Participants were then asked to perform the melody from memory at the rate indicated by four clicks of a metronome cue (500 ms per quarter-note beat), and they were told that they would sometimes hear a tone that did not match the key that they pressed, but that they should keep performing at the rate cued by the metronome and try not to stop or slow down. Participants were also instructed to view the fixation cross while they were performing. In each of the three practice trials, a single feedback pitch was altered to correspond to the future, past, and noncontextual experimental conditions. The order of the three practice trials was counterbalanced across participants.

Following the three practice trials, participants were presented with the music notation of one of the four stimulus melodies. They were asked to practice the melody for a maximum of 3 min, using the notated fingering, with the goal of performing it from memory. Following memorization, the notation was removed and replaced with a fixation cross. Participants then performed the melody from memory in the synchronization-continuation trials. The first three synchronization-continuation trials contained no altered feedback, so that the experimenters could verify that participants had successfully memorized the melody; all participants were able to perform at least one of the three verification trials without producing any pitch errors. In each synchronization-continuation trial, participants were instructed to perform the melody from memory at the rate indicated by the metronome (500 ms per quarter-note beat), to not stop or slow down if they heard a tone that did not match the key that they pressed, and to continuously repeat the melody until they stopped hearing auditory feedback from their key presses. The metronome stopped when the participant began the second iteration of the melody. Participants were asked to refrain from moving their head or body while performing in order to minimize movement-related EEG artifacts. Since the duration of each synchronization-continuation trial exceeded 15 s, participants were not asked to refrain from blinking during the trial. Following each trial, participants indicated when they were ready to proceed to the next trial. This procedure was repeated for each of the four stimulus melodies and for each of the three feedback blocks. The synchronization-continuation trials lasted approximately 45 min.

Behavioral Data Analysis

Temporal disruption associated with the detection of altered auditory feedback was evaluated by analyzing interonset intervals (IOIs) of pitches that occurred before, during, and after the altered auditory feedback pitch. We refer to these pitches in terms of their distance relative to the altered feedback pitch (as indicated in Figure 1), with the pitch preceding the altered feedback designated Position -1, the pitch at which altered feedback occurred Position 0, and the pitch following the altered feedback Position +1. IOIs for each position were computed as the time, in ms, elapsed from that position's tone onset to the next position's tone onset. Errors in pitch accuracy were identified by computer comparison of pianists' performances with the information in the notated musical score (Large, 1993). Pitch additions, deletions, and corrections (errors in which pianists stopped after an error and corrected their performance) were treated as errors. A mean of 6.3% of trials ($SD = 7.1\%$) across subjects and conditions contained pitch errors; these trials were excluded from all analyses, since any error that added or subtracted a tone from the melodic sequence changed the relationship between the participants' key presses and the preprogrammed auditory feedback.

Electrophysiological Methods

EEG data were recorded with 64 Ag/AgCl electrodes configured according to the International 10-20 system with a BioSemi Active-Two system (BioSemi, Inc.). The EEG signal was recorded at 0–1600 Hz bandwidth with a resolution of 24 bits and a sampling rate of 1024 Hz. Data were recorded referenced to a ground formed from a common mode sense (CMS) active electrode and driven right leg (DRL) passive electrode (see http://www.biosemi.com/faq/cms&drl.htm). Electrodes below and above the right eye monitored vertical eye movements, and two electrodes placed adjacent to the outer canthi of the eyes monitored horizontal eye movements.

EEG signals were analyzed using BrainVision Analyzer 2.0.2 (Brain Products GmbH). Electrodes were rereferenced offline to the average of all scalp electrodes. The EEG signals were band-pass filtered between 0.1 and 30 Hz. Data were segmented into 500-ms epochs beginning 100 ms prior to the onset of pitch onsets at Positions -1, 0, and +1, using EEG activity 100 ms prior to the target pitch as a baseline. An epoch duration of 500 ms was selected since it included activity that was shorter than three standard deviations below the mean IOI of the continuation period, and therefore avoided contamination of the observed waveforms with ERPs related to the subsequent pitch onset. Artifact rejection was performed automatically using a $\pm$ 50 μV rejection threshold at the 64 scalp electrodes, as well as the horizontal and vertical electrooculogram. Artifacts were considered excessive for a given subject when more than half of the trials from a given condition of the experiment exceeded the $\pm$ 50 μV rejection threshold at one of the 64 scalp electrodes, or the horizontal or vertical electrooculogram. Trials containing any pitch errors were also excluded from EEG analyses, leaving a mean of 28.0 epochs for each position ($SD = 3.5$) in the future condition, 28.2 epochs ($SD = 3.2$) in the past condition, 27.6 epochs ($SD = 4.1$) in the noncontextual condition, and 85.3 epochs ($SD = 8.2$) in the baseline condition (which contained three times as many stimuli as the other conditions).

Average ERPs for each participant and each of the four experimental conditions were then computed, time-locked to the onset of the target pitch. Mean ERP amplitudes were statistically evaluated at three topographic regions of interest (ROIs): anterior (Fz, FCz), central (Cz, CPz), and posterior (Pz, POz). Forty-ms time windows for statistical analysis of ERP components were centered on grand-averaged peak amplitude latencies as follows: 80–120 ms (labeled N1), 180–220 ms (labeled FRN), and 250–290 ms (labeled P3a). All ERP components (N1, FRN, P3a) were maximal at the anterior ROI. We therefore report results for the anterior ROI only, following previous work (Gehring & Willoughby, 2004; Scheurmann, Endrass, & Kathmann, 2012). Repeated measures analyses of variance (ANOVAs) on ERP component amplitudes by feedback type (past, future, noncontextual, baseline) were run to analyze effects of feedback condition on ERP amplitudes. Scalp topographic maps showing ERP component distributions were generated by plotting amplitude values on the scalp. Activity was averaged across the time window used for the analysis of each component.

To reduce the possibility that component overlap contributed to the ERP effects observed in the average waveforms, we analyzed the average ERP data using time-frequency analysis. Extracting FRN-related activity within a 4–8 Hz frequency band eliminates influences of slower or faster overlapping components (Gehring & Willoughby, 2004). Time-frequency decompositions were calculated for each participant based on their average ERP waveforms for each experimental condition using a Morlet wavelet transform (Bertrand, Bohorquez, & Pernier, 1994). On the basis of previous

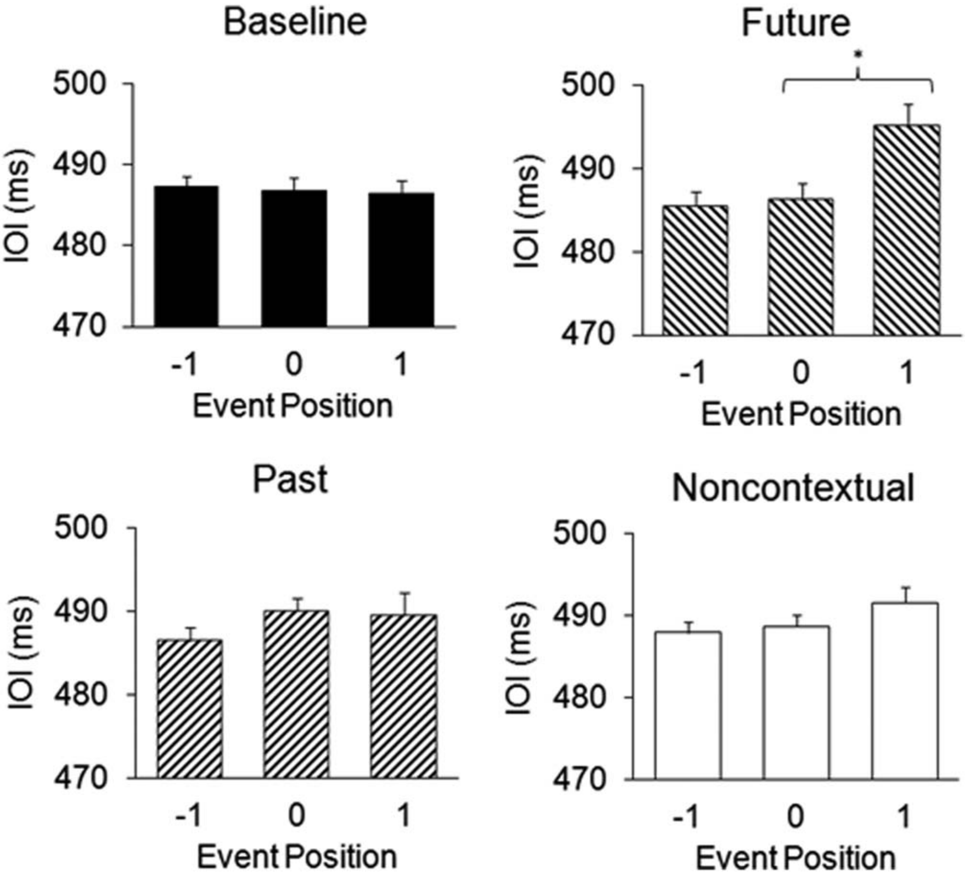

Figure 2. Pianists' mean IOIs by auditory feedback condition (past, future, noncontextual, baseline) and target pitch location (−1, 0, +1). Error bars represent one standard error. Asterisks indicate $p < .05$.

studies showing an increase in power within the 4–8 Hz (theta) frequency range (Cavanaugh & Frank, 2014; Gehring & Willoughby, 2004), we computed spectral power in the 4–8 Hz frequency range at the anterior ROI within a -500 to +500 ms epoch. To achieve sufficient temporal resolution for the theta frequency range, the number of Morlet wavelet cycles was set to $\eta = 7$. Mean power in the -150 to -50 ms prestimulus baseline period was subtracted from the mean power across the whole epoch. Theta power following pitches that showed ERP effects of altered feedback conditions (pitches at Positions 0 and +1) was analyzed. To examine changes in theta power related to the FRN ERP component, we computed the mean power within a time window that occurred 200–300 ms following target pitch onsets, based on previous work investigating changes in theta power related to the FRN (Gehring & Willoughby, 2004). Repeated measures ANOVAs on theta power by feedback type (past, future, noncontextual, baseline) and position (0, +1) were run to analyze effects of feedback conditions on theta power.

Results

Behavioral Results

The mean overall performed IOI during the continuation phase of the synchronization-continuation trials was 486.2 ms (*SE* = 1.0 ms). An ANOVA on mean IOIs within the continuation phase × Feedback condition yielded no main effect of feedback, $F(3,66) = 0.30$, $p = .82$, $\eta^2 = .0015$, suggesting that performance rates were roughly equivalent across the four conditions (future: $M = 485.7$ ms, $SE = 2.0$; past: $M = 486.5$ ms, $SE = 1.7$; noncontextual: $M = 486.6$ ms, $SE = 2.1$; baseline: $M = 486.2$ ms, $SE = 1.8$). Thus, performers successfully maintained the same tempo for all feedback conditions, with slightly faster rates than the prescribed rate overall, consistent with previous studies (Pfordresher & Palmer, 2002).

Figure 2 shows IOIs at melody positions preceding, following, and at the locations of the altered feedback pitches and the contextually identical baseline pitches. An ANOVA on mean IOIs × Feedback (future, past, noncontextual, baseline) × Position (-1, 0, +1) revealed a main effect of position, $F(2,46) = 7.26$, $p < .005$, $\eta^2 = .040$. Overall, IOIs were significantly longer at Position +1 compared to Position -1 (Tukey's HSD = 2.50, $p < .05$). IOIs at Position 0 did not differ from IOIs at Position -1 or +1. Feedback type significantly interacted with position, $F(6,138) = 6.12$, $p < .001$, $\eta^2 = .053$. IOIs at Position +1 were significantly longer than IOIs at Position -1 and 0 for the future feedback condition only (Tukey's HSD = 4.91, $p < .05$). IOIs did not significantly differ between Position -1, 0, and +1 for any other condition. There was no main effect of feedback type on IOIs ($p = .30$). Thus, the only condition in which the altered auditory feedback temporally disrupted performance was the future feedback condition, in which performers slowed down at the event following the altered feedback.

Figure 3 shows the percentage of trials containing pitch errors for the four experimental conditions. There was a significant main effect of feedback condition on produced errors, $F(3,69) = 6.66$, $p = .001$, $\eta^2 = .12$. Pitch errors occurred more often during the three altered feedback conditions (future: $M = 7.7\%$, $SE = 1.7$;

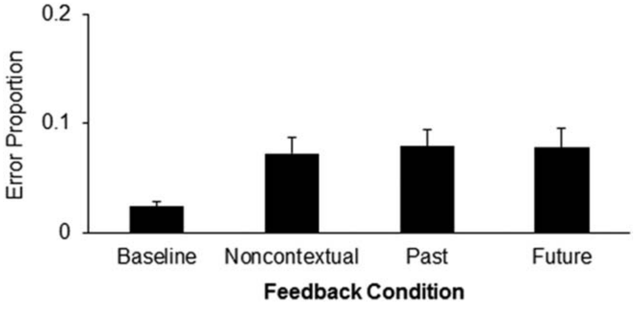

Figure 3. Proportion of pitch errors produced by pianists per trial by auditory feedback condition. Error bars represent one standard error.

past: $M = 7.9\%$, $SE = 1.6$; noncontextual: $M = 7.2\%$, $SE = 1.5$) compared to the baseline condition ($M = 2.4\%$, $SE = 4.8$), (Tukey's HSD = 3.68, $p < .05$). Percentages of trials containing errors did not significantly differ across the three altered feedback conditions. Therefore, though error rates were low across all conditions, manipulations of altered auditory feedback reliably increased the proportion of pitch errors that were produced by participants.

EEG Results

ERPs. Figure 4 shows grand-averaged ERP waveforms time-locked to key press onsets, averaged across correct response trials. ERP components are time-locked to altered feedback pitch onsets at Position 0, as well as to Position -1 (preceding location) and +1 (following location). Three components, labeled in Figure 4, were observed. First, an N1 component maximal between 80–120 ms was observed at Position -1, 0, and +1. Second, a FRN was observed at feedback pitch Position 0, which was maximal between 180–220 ms. Third, a later positive component (P3a) was observed at feedback pitch Position 0, which was maximal between 250–290 ms. Scalp topographies corresponding to these ERP component time ranges for altered and baseline feedback pitches are shown in Figure 5. Analyses of each of the three components are reported in turn.

N1 component (80–120 ms). Analysis of amplitudes within the N1 time window at Position -1 yielded no significant main effect of feedback type, $F(3,69) = .96$, $p = .42$, $\eta^2 = .015$. Thus, as expected, N1 components elicited by tones that occurred prior to perceiving altered feedback showed no differences across conditions. Analysis of N1 amplitudes at Position 0 yielded a significant main effect of feedback type, $F(3,69) = 3.33$, $p < .05$, $\eta^2 = .055$. The N1 elicited by past altered feedback was significantly more negative than the N1 elicited by future altered feedback (Tukey's HSD = .94, $p < .05$). The N1 amplitude elicited by past altered feedback did not significantly differ from that elicited by noncontextual or baseline altered feedback. Finally, analysis of N1 amplitudes at Position +1 yielded a significant main effect of feedback type, $F(3,69) = 13.00$, $p < .001$, $\eta^2 = .19$. The N1 elicited following future altered feedback conditions was significantly more negative than that elicited following past and noncontextual altered feedback, and all three altered feedback types elicited a significantly more negative N1 than baseline feedback pitches (Tukey's HSD = 1.32, $p < .05$). Thus, N1 amplitudes elicited by both the altered feedback pitch (Position 0) and the subsequent pitch (Position +1) distinguished past and future altered feedback types, and N1 amplitudes at Position +1 distinguished all three altered feedback conditions from baseline.

FRN component (180–220 ms). Analysis of amplitudes within the FRN time window at Position 0 yielded significant main effect of feedback type, $F(3,69) = 75.53$, $p < .001$, $\eta^2 = .65$. All three altered feedback types elicited a significantly more negative FRN compared to the baseline condition, and the FRN elicited by

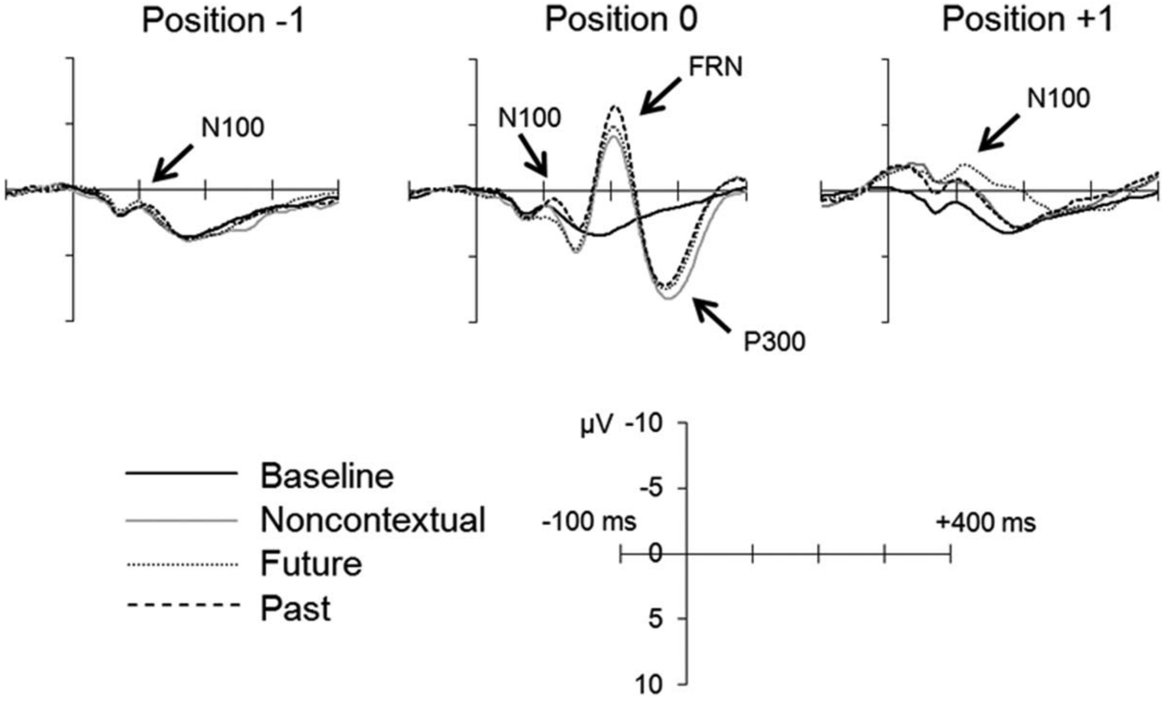

Figure 4. Grand-averaged ERPs elicited by the four experimental conditions for trials in which participants did not produce any pitch errors. Activity within the anterior-midline topographic region of interest (ROI) is shown. Activity shown is averaged across all electrodes contained within the ROI. Negative is plotted upward.

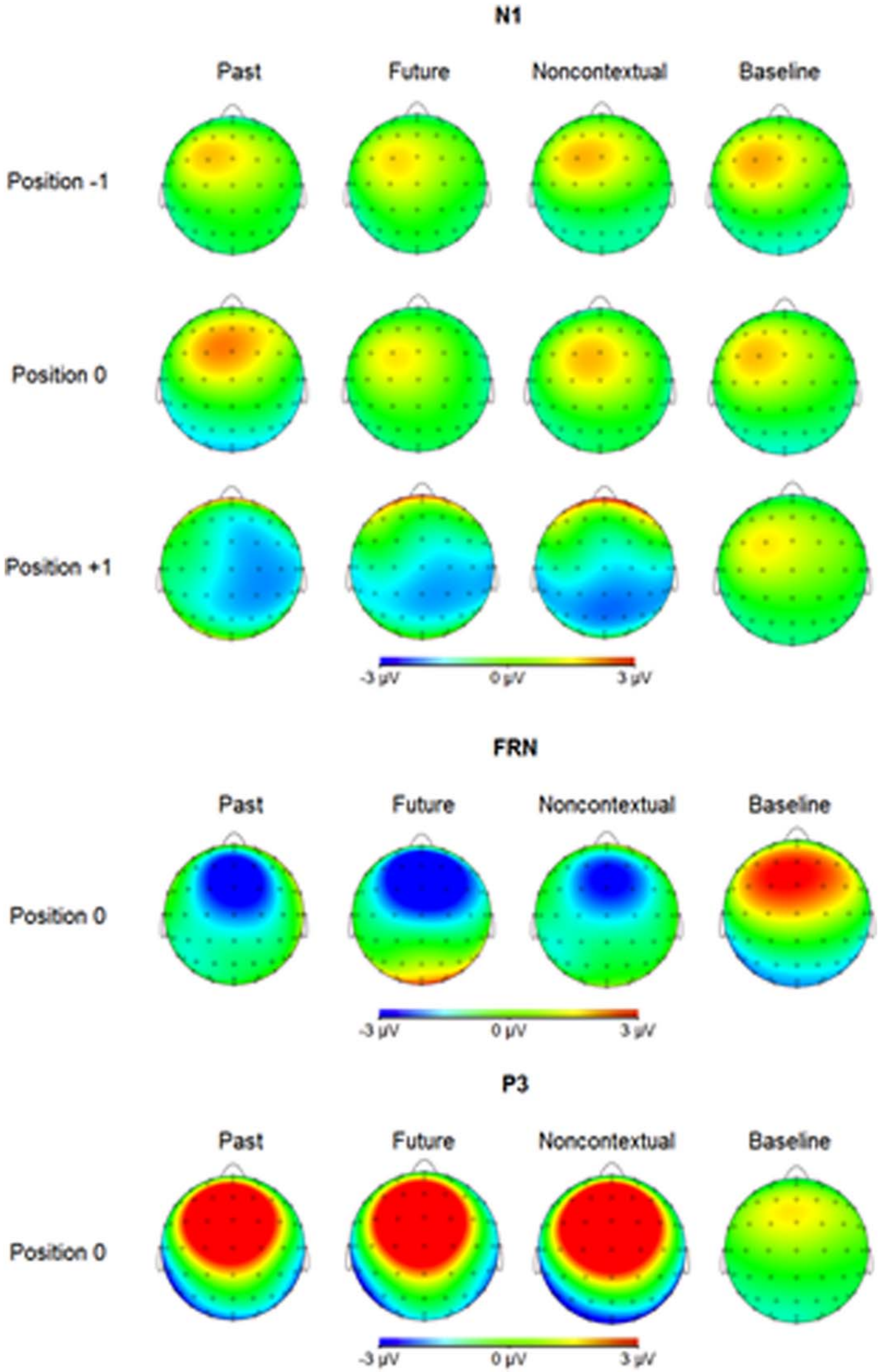

Figure 5. Voltage (in μV) scalp topographies at event Position -1, 0, and $+1$ relative to the location of the altered feedback pitches by altered feedback condition. Activity averaged over 40 ms surrounding each component's grand-averaged peak is shown (see Method for details).

past altered feedback was significantly more negative than that elicited by noncontextual altered feedback (Tukey's HSD = 1.56, $p < .05$). No other comparisons reached significance. Thus, as predicted, all three altered auditory feedback types elicited an FRN response, and FRN amplitudes did not distinguish between altered feedback corresponding to past events or to future events.

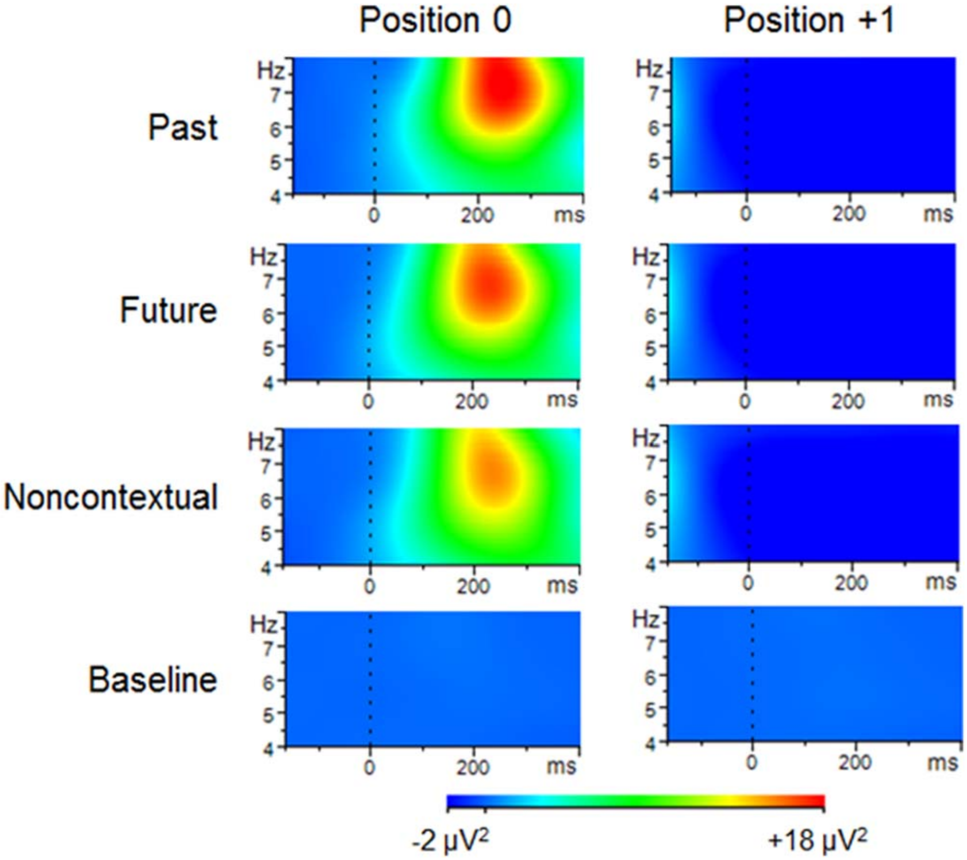

Figure 6. Evoked spectral power within the 4–8 Hz (theta) frequency range following pitch onsets at Position 0 and +1. Brighter colors indicate greater spectral power. Power within a −150 to +400 ms interval is shown.

P3a component (250–290 ms). Analysis of amplitudes within the P3a time window at Position 0 yielded a significant main effect of feedback type, $F(3,69) = 34.99$, $p < .001$, $\eta^2 = .40$. All three altered feedback types elicited a significantly more positive P3a compared to the baseline condition (Tukey's HSD = 1.78, $p < .05$). Thus, as predicted, all three altered auditory feedback types elicited a P3a response, and P3a amplitudes did not distinguish between altered feedback corresponding to past events or to future events.

Evoked oscillatory responses. The FRN is associated with enhancement of theta (4–8 Hz) power over frontal cortex, which may reflect stimulus unexpectedness (Cavanagh & Frank, 2014). Since the past altered feedback pitch presented at Position 0 was a repetition of the pitch at Position -1, and since the future altered feedback pitch presented at Position 0 was a repetition of the pitch at Position +1, it is possible that differences in ERPs at Position 0 and +1 between conditions can be attributed to whether a pitch was repeated, rather than whether it was altered or unaltered. We tested for effects of pitch repetition by analyzing evoked theta power following pitches at Position 0 and +1.

Spectral power within the 4–8 Hz (theta) frequency range following pitch onsets at Position 0 and +1 is shown in Figure 6. Analysis of theta spectral power within the time period occurring 200–300 ms following pitch Onset × Feedback (past, future, noncontextual, baseline) × Position (0, +1) yielded main effects of both feedback condition, $F(3,69) = 15.93$, $p < .001$, $\eta^2 = .060$, and position, $F(1,23) = 55.59$, $p < .001$, $\eta^2 = .57$. There was also a significant interaction of Feedback × Position, $F(3,69) = 25.31$, $p < .001$, $\eta^2 = .19$. Theta power was greater for the three altered feedback conditions compared to the baseline feedback condition at Position 0 (Tukey's HSD = 508.57, $p < .05$). Theta power was also greater for the three altered feedback conditions at Position 0 compared to the same three altered feedback conditions at Position +1 (Tukey's HSD = 508.47, $p < .05$). In sum, theta power increased following altered feedback pitches that occurred at Position 0, but not following unaltered feedback pitches that occurred

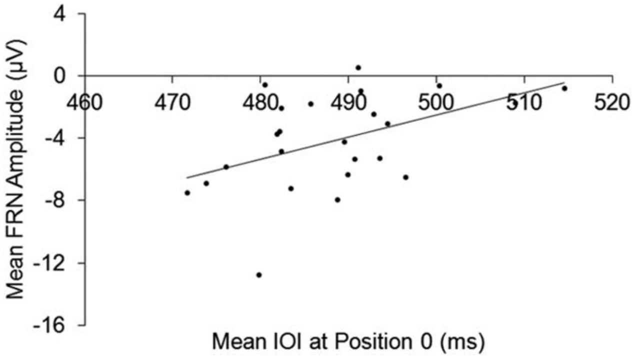

Figure 7. Correlation of mean IOIs at Position 0 across the three altered feedback conditions (past, future, noncontextual) with mean FRN amplitudes elicited by altered feedback across the three altered feedback conditions (past, future, noncontextual).

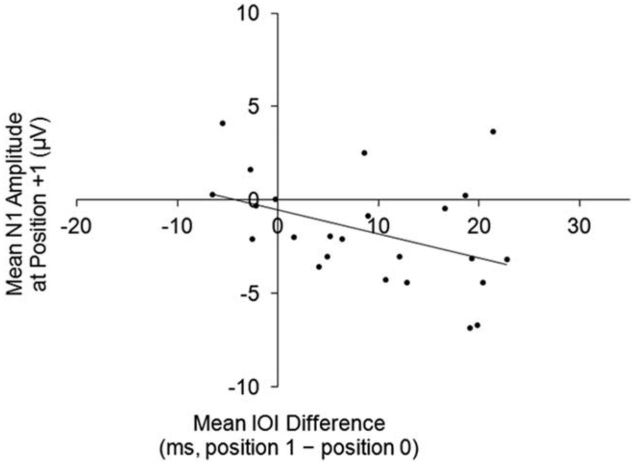

Figure 8. Correlation of mean IOI differences between Position +1 and Position 0 for the future altered feedback condition with mean N1 amplitudes elicited by tones in the future altered feedback condition at Position +1.

at Position +1. Thus, changes in theta power depended on whether a feedback was altered versus unaltered, and not whether it was repeated versus unrepeated.

Correlations of ERP Amplitudes with Timing Measures

Mean IOIs following the presentation of altered feedback pitches across the three altered feedback conditions (future, past, noncontextual) were compared with the mean FRN amplitudes generated following the altered feedback pitches across the same conditions. The mean IOIs correlated significantly with mean FRN amplitudes across the three altered feedback conditions, $r(22) = .47$, $p < .05$. FRN amplitudes that were more negative were associated with shorter IOIs at Position 0. Mean FRN amplitudes did not correlate significantly with mean IOIs from the baseline condition at matched melody locations, $r(22) = .27$, $p = .20$. To ensure that the correlation in Figure 7 was not simply due to a general change in tempo across the trial, we correlated each pianist's mean IOI during the continuation trial period with FRN amplitudes for the three altered feedback conditions. This correlation was not significant, $r(22) = .31$, $p = .14$, suggesting that FRN responses to altered auditory feedback pitches were unrelated to overall production rates.

Finally, we tested whether temporal disruption caused by future altered auditory feedback was correlated with ERP amplitudes. Disruption was computed as the IOI of the altered feedback tone (IOI at Position 0) subtracted from the IOI of the tone following the altered feedback (IOI at Position +1). Larger values indicated greater slowing following the altered auditory feedback. As shown in Figure 8, IOI differences correlated significantly with mean N1 amplitudes elicited by pitches at Position +1 for the future altered feedback condition only, $r(22) = -.42$, $p < .05$. No other ERP component amplitudes correlated significantly with IOIs or with IOI differences at event positions preceding or following altered auditory feedback.

Discussion

The current study investigated the relationship between planning processes and feedback monitoring during music performance. Skilled musicians produced short melodies from memory and heard occasional altered auditory feedback pitches, which corresponded to previous (past) pitches, upcoming (future) pitches in the sequence, or unrelated (noncontextual) pitches that fit the key of the melodic sequence. The study yielded four main findings. First, only altered auditory feedback corresponding to future events in the melodies temporally disrupted musicians' performances. Neither past altered feedback pitches nor noncontextual altered feedback pitches yielded temporal disruption. Second, the amount of temporal disruption following future altered auditory feedback was correlated with amplitudes of N1 neural potentials elicited by the tone following the altered auditory feedback. Third, all types of altered auditory feedback elicited FRN and P3a potentials, which occurred approximately 200 and 300 ms after the altered feedback pitch onsets, respectively. Fourth, the FRN amplitudes were correlated with the amount of time it took performers to initiate the next pitch following the altered feedback pitch. Taken together, these findings suggest that performers monitor the contents of auditory feedback while producing complex musical sequences, and that similarity-based interference of future-oriented plans with unexpected feedback influences the disruption caused by the unexpected feedback.

Behavioral Findings

The timing of pianists' performances was disrupted following the perception of altered auditory feedback that corresponded to future events. More specifically, future altered feedback caused pianists to slow down: Key presses following the altered feedback were longer than those that followed unaltered feedback. In contrast, past altered feedback pitches, as well as noncontextual altered feedback pitches that were not contained within the melodies, did not reliably affect performance timing. Slowing of production rate has previously been observed following self-generated errors, called *post-error slowing*, in many tasks including music performance (Hajcak, McDonald, & Simons, 2003; Palmer, Mathias, & Anderson, 2012), and is considered to be an adaptive response that allows producers more time to process internal and external information (Rabbitt, 1966). Feedback corresponding to future events may have disrupted production most because the future-altered feedback may have generated similarity-based interference with performers' future-oriented planning processes. According to theories of future-oriented planning (Dell et al., 1997), and those in which actions and their auditory effects share common cognitive representations (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Pfordresher, Palmer, & Jungers, 2007), altered auditory feedback pitches that are related to the contents of concurrent plans may compete for production along with currently planned pitch events. Greater activation of future pitch events within performers' plans may have led to greater interference of future altered auditory feedback compared to past altered auditory feedback. Although some theories emphasize a role of motoric factors in determining effects of altered auditory feedback (Howell, 2004), current findings support a more cognitive framework, as motor factors (such as movement of fingers toward or away from keys) were kept constant across feedback conditions, and therefore would have generated similar disruptive effects across the three altered feedback conditions.

Cognitive control theories of error production such as conflict monitoring theory explain post-error slowing in terms of compensatory error-correction mechanisms or strategies (Gehring, Coles, Donchin, Goss, & Meyer, 1993). Future studies could investigate a potential role of response conflict in post-error slowing by manipulating the relationship between finger movements required to produce altered and concurrent correct pitches. Other theories propose that slowing reflects attentional capture following error production (Notebaert et al., 2009), as slowing is often interpreted to reflect a processing cost as opposed to facilitation (Neill, 1977). The altered feedback pitches used in the current study resemble naturalistic errors in piano performance, which tend to be single-tone errors, the great majority of which (95%) come from the set of pitches (key) from which the produced musical sequence is composed (Palmer & van de Sande, 1993). In contrast to the current study in which a sole pitch was altered during performance, previous studies to introduce future altered pitches during music performance manipulated auditory feedback so that future pitches occurred continuously for every produced event in a pitch sequence (Couchman, Beasley, & Pfordresher, 2012; Pfordresher & Palmer, 2006); these studies did not observe reliable effects of future altered feedback on the timing of pianists' performances. One explanation for the different disruptive effects may be that, when acoustic feedback is continuously and consistently altered during production, performers may develop strategies to adjust for predictable deviations from expected auditory feedback. The current study did not allow performers to adjust to the alterations, as altered auditory feedback pitches reverted to correct pitches within one tone. In addition, the sequence locations at which altered feedback pitches occurred were randomly chosen for each trial. Thus, the current study suggests that alterations of single pitch events during music performance can induce behavioral adaptations similar to those observed in other cognitive and motor tasks (Debener et al., 2005; Hajcak, McDonald, & Simons, 2003).

EEG Findings

As predicted, auditory feedback pitches attenuated subsequent N1 suppression. Reduction of N1 suppression was greater for pitches following future altered auditory feedback compared to past auditory feedback: Pitches that followed future altered feedback pitches elicited increased N1 amplitudes compared to pitches that followed past altered feedback. Additionally, larger N1 amplitudes were associated with greater post-error slowing following future altered feedback. The auditory N1 component is linked to the sensory processing of acoustic information and is generated by primary auditory regions (Näätänen & Winkler, 1999). Its amplitude is attenuated or suppressed during auditory production (Horváth, 2015). Reduced N1 suppression following altered auditory feedback pitches suggests that performers may have identified the altered pitches as nonself-generated, and then began to perceive subsequent feedback as if it were generated by an external sound source rather than by their own movements. A likely explanation for the reduced N1 suppression hinges on the similarity-based interference that is specific to the future-oriented feedback pitches: Future altered feedback may generate greater disruption during sequence production because it interferes with future-oriented planning processes. As future-oriented planning theories have posited (Dell, 1986; MacKay, 1987), sequence production requires that future-oriented planning continue, whether or not the present is in error. Thus, the N1 potential may serve as a marker for disruptive effects of mismatch between plans and auditory feedback during music performance.

N1 amplitudes are also known to be influenced by auditory attention processes; selectively attending to one auditory object while ignoring another increases amplitudes of the N1 component elicited by the attended auditory object (Snyder, Alain, & Picton, 2006). It might therefore also be suggested that increased N1 amplitudes following altered auditory feedback pitches could indicate greater selective attention to pitches following the altered auditory feedback compared to unaltered pitches. This is unlikely, however, since N1 suppression during auditory production is uninfluenced by whether attention is directed toward or away from one's own actions or their auditory effects (Timm, SanMiguel, Saupe, & Schröger, 2013). Another possible explanation for post-error slowing following future altered auditory feedback (or lack of slowing following past altered auditory feedback) and corresponding N1 amplitude increases is that these effects were due to pitch repetitions. The future condition involved a pitch that was repeated at Position 0 and +1, the past condition involved a pitch that was repeated at Position -1 and 0, and the other conditions did not contain any repeating pitches. Pitch repetition cannot explain the current findings, however, for several reasons. First, suppression of N1 amplitudes typically increases as a function of stimulus repetition. As pitches are repeated, they elicit progressively smaller (more positive) N1 responses (Grau, Fuentemilla, & Marco-Pallares, 2007). Based on this repetition priming effect on N1 responses, we would have expected repeated pitches to elicit more positive N1 amplitudes than the pitches that preceded them. This was not the case for both the past and future feedback conditions: A larger N1 was observed in response to the repeated past pitch compared to nonrepeated conditions, and a larger N1 was observed in response to the repeated future pitch compared to nonrepeated conditions. Second, repetition of past and future pitches had opposite effects: The repeated pitch in the past condition was not associated with slowing, but the repeated pitch in the future condition was associated with slowing. Third, one could speculate that pianists may have not slowed down following repeated pitches in the past condition because the repeated pitches were also altered; however, noncontextual altered feedback pitches also did not elicit slowing, and these noncontextual altered pitches were not repetitions. Fourth, FRN components and corresponding increases in theta power, which is interpreted as reflecting stimulus-induced surprise or unexpectedness (Cavanagh, Zambrano-Vazquez, & Allen, 2012; Cavanagh & Frank, 2014), were only elicited by altered feedback pitches and not by subsequent pitches. Thus, neural responses to altered feedback pitches seemed more tuned to whether a pitch was altered or not, rather than whether it was a repetition or not. This conclusion suggests that the way in which producers perceived auditory feedback was biased by their goal of feedback monitoring—to identify whether auditory feedback pitches matched concurrent movements—as opposed to the recognition of pitch repetition.

Amplitudes of the N1 component elicited by pitches that followed altered auditory feedback were related to the temporal disruption caused by the altered feedback. This was not the case for amplitudes of the N1 elicited by the altered feedback pitches themselves. Instead, past altered feedback pitches elicited larger N1 amplitudes than future altered feedback pitches. Future-oriented theories of planning have proposed that, in addition to activating future events during production, past events are deactivated or turned off (Dell et al., 1997). We propose that the enlarged N1 response elicited by past auditory feedback may reflect performers' tendency to deactivate the past: The sensory processing of altered auditory feedback corresponding to deactivated past events may differ from the processing of altered feedback corresponding to other types of events (noncontextual and future).

All three types of altered auditory feedback that were presented in the current study elicited FRN and P3 components, and increases in theta power occurred about 200–300 ms following altered pitch onsets. P3 amplitudes were equivalent across past and future feedback conditions. Previous studies have observed FRN and P3 components in response to altered auditory feedback pitches (Katahira et al., 2008; Loehr et al., 2013; Maidhof et al., 2010), but no studies have compared responses across different types of altered auditory feedback. The frontal P3a observed in the current study closely resembles the frontally maximal P3a previously observed following randomly altered auditory feedback during piano performance (Maidhof et al., 2010). The magnitude of the FRN may correspond to the magnitude of rewards or losses in gambling tasks (Bellebaum, Polezzi, & Daum, 2010; Goyer, Woldorff, & Huettel, 2008). One explanation for equivalent FRN amplitudes elicited by future and past altered auditory feedback is that, since the pianists performed the pitch sequences from memory, these altered pitches were equally discrepant with respect to pianists' memory representations for the performed sequences. This memory-violating aspect of the altered pitches could have led to ceiling effects (equivalent amplitudes) with regard to FRN and P3 responses. The fact that both FRN and P3 component amplitudes were equally large across past and future altered feedback conditions suggests that what distinguishes the future-oriented condition is less likely to be its recognition as error, but its similarity to the current planning processes. Some previous studies have found that FRN amplitudes are sensitive to the perceptual distinctiveness of different feedback stimuli (Jia et al., 2007; Liu & Gehring, 2009). These studies have been taken as evidence that the FRN may not only reflect the detection of action-related feedback in the environment, but also the extent to which feedback stimuli violate producers' expectations (Ferdinand et al., 2012; Oliveira et al., 2007). The noncontextual control condition in the current study partially addresses this issue by demonstrating that, even when altered feedback pitches are unrelated to the contents of a performer's plan, they still elicit FRN and P3 responses. This finding suggests that FRN and P3 responses observed following altered feedback pitches may be more a reflection of perceptual expectations than of performers' plans. Indeed, any mismatch between monitored feedback and concurrent key presses poses a strong violation of well-learned auditory-motor associations for skilled musicians. The finding also fits with theories suggesting that theta activity indexes lower-level rather than higher-level perceptual feedback attributes (Bernat, Nelson, & Baskin-Sommers, 2015).

Interestingly, FRN-like components have been observed following gains and losses that occur even in the absence of participant responses (Donkers, Nieuwenhuis, & van Boxtel, 2005). Early negative ERP components observed during the perception of deviant pitches that do not match previously learned movement sequences have been called N2 components (Maidhof et al., 2010; Mathias, Palmer, Perrin, & Tillmann, 2015; Mathias, Tillmann, & Palmer, 2016). Similarly, studies using flanker gambling tasks have shown effects of perceptual properties of feedback stimuli on FRN amplitudes (Liu & Gehring, 2009; Liu, Nelson, Bernat, & Gehring, 2014). Analysis of EEG activity within only the theta frequency range in the current study, which reduced the likelihood of FRN contamination from other ERP components such as the P3, yielded an equivalent increase in theta power following all altered feedback pitches. This finding suggests that the FRN may simply reflect the mismatch of an auditory target with perceived auditory feedback, as opposed to an auditory-motor mismatch (Lutz, Puorger, Cheethma, & Jancke, 2013).

Conclusion

In sum, our findings suggest that the contents of producers' plans interact with feedback monitoring processes during the production of auditory sequences. Evidence for future-oriented planning comes from the selective disruptive effects of hearing the future during production compared to the past, as well as a greater reduction in N1 suppression following future altered auditory feedback compared to past altered feedback. These findings support models of planning during auditory sequence production that weight future events (Dell et al., 1997), and similarity-based interference as a mechanism that explains the selective disruption of future-oriented feedback (Palmer & Pfordresher, 2003). The neural sensory processing of auditory feedback reflected in the N1 potential could serve as a marker for interference generated by altered auditory feedback.

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