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Role of auditory feedback in the control of successive keystrokes during piano playing

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Abstract

The purpose of this study was to elucidate the role of auditory feedback derived from one keystroke in the control of the rhythmicity and velocity of successive keystrokes during piano playing. We examined the effects of transient auditory perturbations with respect to the pitch, loudness, and timing of one tone on subsequent keystrokes while six pianists played short excerpts from three simple musical pieces having different tempi (“event rates”). Immediately after a delay in tone production, the inter-keystroke interval became shorter. This compensatory action depended on the tempo, being most prominent at the medium tempo. This indicates that temporal information provided by auditory feedback is utilized to regulate the timing of movement elements produced in a sequence. We also found that the keystroke velocity changed after the timing, pitch, or loudness of a tone was altered, although the response differed depending on the type of perturbation. While delaying the timing or altering the pitch led to an increase in the velocity, altering the loudness changed the velocity in an inconsistent manner. Furthermore, perturbing a tone elicited by the right hand also affected the rhythmicity and velocity of keystrokes with the left hand, indicating that bimanual coordination of tone production was maintained. Finally, altering the pitch sometimes resulted in striking an incorrect key, mostly in the slow piece, emphasizing the importance of pitch information for accurate planning and execution of sequential piano keystrokes.

Keywords

Feedback control; Auditory motor integration; Sequential movements; Bimanual control; Musicians; Pianists; Music

Introduction

Musical performance requires highly accurate spatiotemporal control of sequential movements. This involves monitoring and updating motor actions over time based on visual, auditory, and somatosensory information, since the state of our body and environment is inherently stochastic due to the noise in both motor commands and sensory input. Previous studies using electrophysiological and psychophysical techniques have demonstrated that

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auditory feedback information plays an important role (Katahira et al. 2008; Maidhof et al. 2009; see also review by Pfordresher 2006). For example, several studies have found profound effects of a persistent delay of tone production on the rhythmicity of movements during piano playing, namely a slowing of the tempo and increasing variability of the duration between successive keystrokes (Gates et al. 1974; Pfordresher and Palmer 2002; Pfordresher and Benitez 2007). Studies that persistently altered tone pitch during piano playing also showed an increase in frequency of striking a wrong key, but only when the tone sequence fed back to the players resembled the intended one (Pfordresher 2003, 2005), not when the feedback sequence was highly dissimilar to the intended one (Finney 1997). Although these findings underline the importance of auditory feedback for accurate music production, the use of a persistent perturbation paradigm in the previous studies leaves unanswered the role of auditory feedback provided by one single tone in the control of subsequent movements, such as occurs during spontaneous errors. However, transiently delayed auditory feedback during rhythmic finger tapping does affect the timing of subsequent taps (Flach 2005; Wing 1977), and one might expect a similar result for piano playing.

Researchers on speech motor control have also long employed the persistent auditory perturbation paradigm, particularly when studying the effect of delayed auditory feedback (Black 1951; Hashimoto and Sakai 2003; Howell and Archer 1984; Yates 1963). However, a few recent studies have investigated the effect of transient perturbation of pitch or loudness on subsequent vocal production during the uttering of a vowel or a word (Bauer et al. 2006; Munhall et al. 2009; Purcell and Munhall 2006). For example, speakers rapidly respond to transient, unexpected shifts of pitch and formant frequency by altering their vocal output in the direction opposite the shift (Munhall et al. 2009; Purcell and Munhall 2006). Similarly, a transient alteration of loudness results in rapid compensatory changes in the intensity of voice (Bauer et al. 2006). One may therefore expect similar compensations in response to transient perturbation of auditory feedback during musical performance. However, musical performance differs from speech production in several respects, such as the presence of temporal constraints, and the use of a different musculoskeletal system and underlying neural substrates. It is therefore unknown how the nervous system integrates auditory feedback from one single tone into accurate production of sequential movements during musical performance.

The present study addressed this issue by investigating the effect of a transient auditory perturbation with respect to timing, pitch, or loudness on the finger-key contact duration, tempo, and velocity of keystrokes during piano playing. Specifically, we attempted to determine what auditory information is responsible for the control of the rhythmicity and velocity of successive keystrokes. While several speech studies have shown that auditory perturbations can elicit compensatory motor actions, there is also some evidence of responses that are seemingly unrelated to the auditory perturbation, such as increased loudness of voice when auditory feedback of speech is delayed (Black 1951; Howell 1990). Furthermore, piano playing provides a unique opportunity to investigate the role of auditory feedback derived from one hand in the control of the other hand’s movements. The role of feedback control in bimanual movements has been studied by examining the effect of applying force perturbation to one hand on the other hand’s motion (Diedrichsen 2007; Mutha and Sainburg 2009). However, this issue has not been addressed in terms of auditory feedback. Finally, we addressed whether the effect of auditory perturbation would change with repeated exposure to auditory perturbation and whether prior knowledge of the time and nature of the perturbation plays a role.

More generally, a comparison of our results with those obtained by perturbing sensory feedback during the execution of movement sequences that are not subject to temporal constraints, such as typing, provides additional insights into the interaction between the demands of rhythmicity and sensory feedback.

Methods

Participants

Six pianists (4 women, 2 men, 22–55 years, all right-handed) participated in the study. Four of them were professional pianists who had been trained on the piano for more than 15 years, and the remaining two were amateur pianists. One of the amateurs practiced for 5–8 h every week, whereas the other played at most a few hours per week. The experimental protocol was approved by the University of Minnesota's Institutional Review Board, and all participants gave informed consent prior to the experiment.

Experimental design

We asked participants to play several measures of three musical pieces requiring use of both hands, which were arranged for the present experiment by one of the authors (Fig. 1). The selections chosen were short excerpts from three pieces with different event rate (number of tones per unit time). They were "Prelude in C major from Das wohltemperierte Klavier, Volume I No.1" by Johann Sebastian Bach (Fig. 1a), "Jesus bleibet meine Freude from Cantata 147" by Johann Sebastian Bach (Fig. 1b), and "Ah! Vous dirais-je maman" by Wolfgang Amadeus Mozart (Fig. 1c), the event rates of which were 4, 3, 2 Hz, respectively. For simplicity, we will refer to them as pieces with fast, medium, and slow tempo. The pianists played a digital piano (Roland ep-5, 61 keys), connected to a Windows computer (SONY VAIO VGN-Z90PS) via a MIDI interface (Roland EDIROL UA-4FX). They were provided with the score for each of the pieces and allowed practice to familiarize themselves with the piano and with the musical selection. During practice, participants played with a metronome (60 beats per minute) so that they could play consistently and accurately at the given tempo without making mistakes. At this tempo, the ideal inter-onset interval of successive tones for fast, medium, and slow pieces was 250, 333, and 500 ms, respectively. During this practice session, participants were allowed to play each piece 20 times.

After the practice session, the pianists played each of the three pieces in either *perturbed* or *normal* conditions. In *perturbed* conditions, one of three different types of auditory perturbation was produced at one note at two different places within each piece. The perturbations consisted of delaying the timing of tone production by 90, 150, or 210 ms (circle in Fig. 1), shifting the pitch up or down by one whole tone (square in Fig. 1), and changing tone loudness by ±20 MIDI velocity (diamond in Fig. 1). The pitch alteration elicited a tone of a white key adjacent to the struck one. Perturbations within a trial were separated by at least 6 s and were always of the same kind. The perturbed notes (which were the same for every trial for a particular condition) were chosen so that each type of perturbation occurred at a different tone, which made it unable for participants to know at which particular tone the initial perturbation would occur. Sheet music was available throughout the session.

Auditory feedback was altered using a custom-made script in LabVIEW (National Instrument Co.), running at 500 Hz for control and recording of MIDI data from the keyboard. In the *normal* condition, the participant played each piece without any auditory perturbation. The design consisted of eight conditions (3 timing, 2 pitch, 2 loudness, and 1 normal) × 20 trial repetitions for each of the three pieces, the 8 conditions being randomly presented. Given the randomized order of the 160 trials, the pianist could not know when a perturbation would occur and what it would be until experiencing the 1st perturbation within a trial. However, with experience, he/she could achieve the ability to predict the 2nd perturbation within the same trial based on the information from the 1st perturbation. We thus reasoned that only the effect of the 2nd auditory perturbation could change across trials if prior knowledge of auditory perturbation influenced the feedback control. To keep from fatiguing the participant, the experiment for each piece was performed on a separate day. The order of pieces to be played was also randomized across participants, and the participant could take a rest any time.

During the experiment, each trial started with the presentation of a metronome (tempo = 60 beats per minute) for 5 s, which was turned off immediately after the participant started to play. The participants were instructed to play as accurately as possible at the given tempo. They were also asked not to look at their hands and the keys as much as possible but to look at the sheet music instead.

Experimental procedures and data analysis

During the experiment, we recorded the time each key was depressed and the time it was released. In addition, we also recorded the speed with which each key was depressed, MIDI velocities provided by the interface ranging from 1 to 127. Using these data, we computed duration of finger-key contact and inter-keystroke interval (from key depression to key depression). We first scaled each trial in time, to match the average inter-keystroke interval of five successive strokes prior to the perturbation on a particular trial to the grand mean, so as to minimize inter-subject and inter-trial variability in timing. The changes in keystroke timing and loudness in response to the perturbation were evaluated by computing differences in the average values of each variable between the perturbed and normal conditions. There was no statistical difference in any of the variables between data obtained from the normal condition and the practice session (20 trials), which indicated that an auditory perturbation on previous trials did not affect the keystrokes in the normal condition.

To test for effects of the auditory perturbation, we used a two-way repeated measures analysis of variance (ANOVA) ($P < 0.05$) with conditions (perturbed and normal) and strokes as independent variables. The error term used for the ANOVA test was the between-participant variance. Newman–Keuls post hoc tests were performed where appropriate to correct for multiple comparisons. Furthermore, we performed a paired *t* test to evaluate differences in the amount of disruption between 1st (initial) and 20th (final) trials.

Results

We analyzed changes in the finger-key contact duration, inter-keystroke interval, and keystroke velocity between perturbed and normal conditions to determine how auditory perturbation influenced the production of keystrokes. We initially describe the results for the keystrokes of both hands during the fast piece and the right-hand keystrokes during the medium and slow pieces and later show the results for the left-hand keystrokes during the medium and slow pieces. As stated in the Methods section, one of three types of auditory perturbation was produced at two different times within each trial. We will refer them as 1st and 2nd perturbations for simplicity. Note that the *i*th inter-keystroke interval is measured between the *i*th and i+1st keypresses, whereas the *i*th finger-key contact duration represents the interval between the ith keypress and key-release. Also, we refer to *i*th velocity as the intensity of *i*th keypress. The difference of these variables between the perturbed and normal conditions at strokes before a note with a perturbation was minimal, confirming consistent keystrokes between the perturbed and normal conditions.

Characteristics of unperturbed keystrokes

In the normal condition, the mean inter-keystroke interval while playing fast, medium, and slow pieces across all participants was 247, 327, and 514 ms, respectively, confirming that the participants successfully played at the target tempo (see Fig. 2). Timing of keystrokes was quite consistent across notes, with a mean within-trial standard deviation of 6, 6, and 12 ms for these three pieces, respectively. The mean keystroke velocity was variable, ranging from 70 to 102 units across notes with a mean between-trial standard deviation of 4.7, 5.8, and 4.9 units for fast, medium, and slow pieces, respectively. The variability from note to note in velocity reflected the individual's musical expression, and the mean value of the velocity corresponded to 75, 86, and 97 units for fast, medium, and slow pieces, respectively. The mean finger-key contact duration across all participants was 291, 352, and 166 ms for fast, medium, and slow pieces, respectively. Thus, except for the slow piece, one key was typically released after the next key was depressed. However, this was not the case when the same key was struck repetitively (e.g., the contact duration was 211 ms at the first of two repeated notes in the medium piece). Musically, the fast and medium pieces were played with legato touch, whereas the slow piece was played staccato. The timing of key-release was relatively variable across notes within a piece, with a mean within-trial standard deviation of 36 ms, but that for any particular note was more consistent, with a mean between-trial standard deviation of 12 ms. With respect to differences between the experts and amateurs, we only found a larger within-trial variability for the timing of both key depression and key-release in the fast piece played by the least-practiced amateur when compared to the experts (around 78% larger for this amateur).

Delaying tone production

Figure 3 illustrates the mean changes of the features of keystrokes before and after the 1st perturbation of the timing of a tone production across all participants while they played pieces with fast, medium, and slow tempi. The perturbation was a delay of 90, 150, or 210 ms, as shown by different color symbols. The most remarkable change after the perturbation across all pieces was a transient increase in the keystroke velocity. This increase occurred as soon as the next stroke, and it could persist over several strokes. The response magnitude ranged from 2 to 5 units of keystroke velocity and was most pronounced in the fast piece. Using condition (perturbed or normal) and stroke (six strokes) as independent variables, a two-way ANOVA with repeated measurements was performed on the velocity measures for each piece. The results revealed that the velocity for the perturbed condition was significantly greater than for the normal condition at all tempi (see Table 1). A subsequent post hoc analysis identified the notes at which the velocities differed significantly in the perturbed condition. These are indicated by the * in Fig. 3.

Only in the piece played at a medium tempo, delaying the tone production also transiently decreased the inter-keystroke interval and finger-key contact duration by 10–15 ms (Table 1). This effect was true for the initial interval containing the perturbation and persisted for several intervals. These indicated earlier timing of both the current key-release and the next keypress after the delay.

To see whether the disruptions of contact duration and inter-keystroke interval following the perturbation were related to each other, a regression analysis on the relation between the changes of these two variables across trials for each participant was performed for each tone with a significant difference between the perturbed and normal conditions. The mean *r*-squared value across participants ranged from 0.34 ± 0.23 to 0.59 ± 0.17 across tones, and the number of participants with a significant correlation ranged from 3 to 6 across tones. The observed correlation of the effects on interval and duration indicates that the temporal relation between a keypress and release of the previous key was maintained. This was more

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straightforwardly evaluated by performing a regression analysis on the relation between the changes of the timing of the current key-release and next keypress across trials, which demonstrated a significant correlation ($P < 0.05$). The mean r-squared value across participants ranged from 0.43 to 0.67, where at least five participants showed a significant correlation.

For the slow piece, the inter-keystroke interval also became temporarily shorter by around 10 ms immediately after the perturbation, but the difference between the perturbed and normal conditions did not reach statistical significance due to a large inter-participant variability (ANOVA: $F_{(1,5)} = 5.2$ and 5.3, $P = 0.071$ and 0.068 for 150 and 210 ms, respectively). (One of the amateurs had a prolonged inter-keystroke interval following the delayed feedback, differing from the other five pianists in this respect.) Surprisingly, none of the three variables showed a systematic change in response to the delay length.

To examine differences in the consistency of keystrokes following a perturbation, we also computed the inter-trial variability of the three parameters within each condition. A two-way ANOVA with repeated measures revealed that there was no difference in variability between the perturbed and normal conditions except for a few isolated values: (the finger-key contact duration: 3rd stroke for 90 and 150 ms ($F_{(5,25)} = 4.3$ (90 ms) and 4.2 (150 ms), $P < 0.01$), keystroke velocity: 2nd stroke for 210 ms ($F_{(5,25)} = 2.7$, $P < 0.05$), both for the fast piece. In each case, the variability was greater in the perturbed condition).

Changes in keystrokes in response to the 2nd perturbation of the timing of tone production (Fig. 4) were quite similar to those elicited by the 1st perturbation (Fig. 3), even though the musical context for this perturbation was different from that for the 1st perturbation (Fig. 1). Again, there was a transient increase in keystroke velocity by around 4 units as soon as the next stroke (e.g., medium: 150 ms) or second stroke (e.g., fast: 90, 150 and 210 ms) after the perturbation, and it could persist over several strokes. A repeated measures ANOVA confirmed that the velocity for the perturbed condition was significantly greater than that for the normal condition at all tempi (Table 1). The inter-keystroke interval became shorter by 5–17 ms immediately after the perturbation in the medium and slow pieces, but a significant speeding-up was observed only in the piece with medium tempo for the longer delays (Table 1). Similarly, the finger-key contact duration of the stroke containing the perturbation also briefly became shorter by around 20 ms after the perturbation in the medium piece (Table 1). Therefore, the timing of both the key-release at this note and the next keypress occurred earlier after the perturbation. The correlation between the changes in contact duration and inter-keystroke interval across trials for the medium tempo piece was significant for each participant ($P < 0.05$), with a mean r-squared value across participants of 0.46 ± 0.28 (0th stroke, 150 ms) and 0.43 ± 0.20 (0th stroke, 210 ms). Concerning the inter-trial variability, none of the three variables showed a significant difference between the perturbed and normal conditions in all three pieces.

Shifting tone pitch

Figure 5 illustrates the mean changes of the features of keystrokes before and after the 1st perturbation that shifted tone pitch for pieces played with fast, medium, and slow tempi. When the pitch was increased, keystroke velocity increased by around 3 units in all pieces. The effect was most pronounced for the medium piece, occurring as soon as the next stroke, and persisted over several strokes. The increase was, however, significant only at the 5th stroke after the perturbation for the slow piece. A repeated measures ANOVA with the variables of conditions (perturbed and normal) and strokes revealed a significant difference in velocity between the perturbed and normal conditions (condition: $F_{(1,5)} = 10.9$ (medium), interaction: $F_{(5,25)} = 3.7$ and 3.3 (fast and slow); $P < 0.05$). When the tone pitch was lowered, there were also slight increases in keystroke velocity across all pieces, but the difference between the perturbed and normal conditions did not reach statistical significance (ANOVA: $P > 0.05$). Neither the inter-keystroke interval nor finger-key contact duration of the subsequent keystrokes showed any changes in response to elevating or lowering the pitch (ANOVA: $P > 0.05$). Furthermore, the inter-trial variability did not change except for a few isolated values: (contact duration: 3rd stroke for higher and lower ($F_{(5,25)} = 2.9$ (higher) and 2.7 (lower), $P < 0.05$), keystroke velocity: 1st stroke for higher ($F_{(5,25)} = 2.8$, $P < 0.05$), both for the fast piece).

Similar to instances of the 1st perturbation, the 2nd perturbation also increased the keystroke velocity mainly when the pitch was elevated (Fig. 6). This occurred at around the 2nd stroke for the medium piece, and it could persist over several strokes. A repeated measures ANOVA revealed a significant difference in the velocity between the conditions for the medium and slow pieces (interaction: $F_{(5,25)} = 4.3$ and 3.2 (medium and slow); $P < 0.05$). Again, neither the finger-key contact duration nor inter-keystroke interval showed statistically significant changes in response to pitch alterations in all pieces. Concerning the inter-trial variability, none of these variables showed a significant difference between the perturbed and normal conditions.

Changing tone loudness

Figure 7 illustrates the mean changes of the spatiotemporal features of keystrokes before and after the 1st perturbation of the loudness of a tone. When the tone became louder, velocity of subsequent keystrokes became slightly smaller, in a compensatory fashion, by around 3 units of velocity. This was found as soon as the next stroke (slow) or later (medium) after the perturbation and could intermittently persist over several strokes. A repeated measures ANOVA confirmed that the difference in velocity was significant between the perturbed and normal conditions for the pieces at medium (interaction: $F_{(5,25)} = 2.9$) and slow (condition: $F_{(1,5)} = 6.9$) tempi ($P < 0.05$). An increase in tone loudness also resulted in decreases in both inter-keystroke interval and contact duration at the third post-perturbation stroke of the piece with medium tempo (condition: $F_{(1,5)} = 85.3$ (interval); interaction: $F_{(5,25)} = 3.4$ (duration) ANOVA: $P < 0.05$). By contrast, decreasing tone loudness did not lead to any appreciable changes in the subsequent keystrokes. Furthermore, none of the three variables showed a significant difference in the inter-trial variability between the perturbed and normal conditions.

Responses to the 2nd perturbation that altered the tone loudness differed slightly from those elicited by the 1st perturbation (Fig. 8). Following a louder tone, keystroke velocity increased for the fast and medium pieces (ANOVA: condition: $F_{(1,5)} = 7.0$ (fast) and 6.9 (medium); $P < 0.05$). This occurred occasionally and in a non-systematic manner (e.g., fast: 1st and 3rd stroke, medium: 5th stroke). By contrast, in the slow piece, an increase and decrease in the tone loudness transiently decreased and increased the keystroke velocity, respectively, in a compensatory fashion (ANOVA: condition: $F_{(1,5)} = 7.2$ (higher) and 6.9 (lower); $P < 0.05$). Only in the fast piece did the perturbation in loudness briefly affect finger-key contact duration. While the louder tone shortened the contact duration at the 4th stroke, a softer tone prolonged it at the 1st stroke (ANOVA: interaction: $F_{(5,25)} = 3.8$ (higher) and 3.0 (lower); $P < 0.05$). Concerning the inter-trial variability, none of the variables showed a significant difference between the perturbed and normal conditions.

Changes in the effect of perturbation across trials

To test whether the effect of auditory perturbation on keystrokes would change across trials, we statistically compared the magnitude of the change in the parameters in response to the perturbation between initial and final trials. This comparison was made only where a significant difference between the perturbed and normal conditions was confirmed. Only

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after the 2nd perturbation of the pitch and loudness did we find a significant difference in keystroke velocity between the initial and final trials for the piece played at medium tempo (see Figs. 6 and 8). At each of 2nd, 3rd, and 4th strokes after the 2nd perturbation that elevates the pitch, the magnitude of increase in keystroke velocity in the final trial was significantly smaller than that in the initial trial (paired *t* test: $P < 0.05$ for all of these strokes). The magnitude of increase in the velocity at the 5th stroke after the 2nd perturbation that increased loudness also differed between the initial and final trials, showing a smaller value for the last trial (paired *t* test: $P < 0.05$). Concerning any of the other variables and strokes, there was no significant difference between the initial and final trials.

Effects of perturbations on the left hand

Figure 9 displays the mean changes of the features of keystrokes before and after the 1st and 2nd perturbations of the timing of tone production (*left two panels*) and of tone pitch (*right two panels*) for the keys struck with the left hand and the piece played at medium tempo. Here, we do not show the results of the loudness perturbation, since it produced no discernible and statistically significant change in the subsequent keystrokes by the left hand. Note that the stroke numbering shown in the figure corresponds to that used for the right hand (Figs. 3, 4, 5, 6).

In the normal condition, the mean key-contact duration and inter-keystroke interval across strokes were 1,085 and 994 ms, respectively. This again indicated that the key-release occurred after the next keystroke in the left hand (i.e., legato touch). The relative timing of keystroke and key-release between the right and left hands was on average 6 ± 5 and 60 ± 14 ms earlier for the right hand, respectively. The average keystroke velocity was 63 units, which was smaller than the right hand. The values for timing for the two hands were highly correlated across trials with a mean *r*-squared value of the correlation of 0.58 ± 0.21 and 0.60 ± 0.14 for the timing of keystroke and key-release, respectively ($P < 0.05$). Keystroke velocity of the two hands was less closely linked, with a mean *r*-squared value of 0.13 ± 0.07 ($P > 0.05$).

In the perturbed condition, both the finger-key contact duration and inter-keystroke interval became shorter when the right-hand tone was delayed during that interval for both the 1st and 2nd perturbations. A repeated measures ANOVA confirmed that all of these differences were significant (contact duration: *interaction effect*, $F_{(2,10)} = 6.7$ (150 ms) and 5.9 (210 ms) for the 1st perturbation, and $F_{(2,10)} = 7.1$ (150 ms) and 5.1 (210 ms) for the 2nd perturbation; inter-keystroke interval: *main effect*, $F_{(1,5)} = 5.1$ (150 ms) and 17.7 (210 ms) for the 1st perturbation, and $F_{(1,5)} = 5.0$ (150 ms) and 10.0 (210 ms) for the 2nd perturbation, *interaction effect*, $F_{(2,10)} = 9.5$ (150 ms) for the 2nd perturbation. $P < 0.05$). There was also a transient increase in the velocity of the following keystroke, which was significant only in the case of the 2nd perturbation (ANOVA: interaction: $F_{(2,10)} = 5.6$, 5.4, and 5.0 for 90, 150, and 210 ms, respectively, $P < 0.05$). When the pitch was altered, keystroke velocity increased at the first stroke following the 1st perturbation (ANOVA: $F_{(2,10)} = 13.0$ (higher) and 8.7 (lower), $P < 0.01$). In addition, the inter-keystroke interval spanning the 2nd perturbation that elevated the pitch decreased (ANOVA: $F_{(2,10)} = 5.0$, $P < 0.05$). Note that these changes in response to the perturbations were similar to those observed for the right hand in terms of the magnitude and latency.

Even though the effects of the perturbations on keystrokes executed with the left hand were similar to the effects on the right hand, changes in the parameters in the two hands were not significantly correlated. For the timing of the keystroke, timing of key-release, and keystroke velocity, the mean r-squared value across participants was 0.15 ± 0.07, 0.11 ± 0.06, and 0.07 ± 0.03, respectively ($P > 0.05$). The relative timing of keystroke and key-release between the right and left hands after the perturbation was 9 ± 7 and 69 ± 22 ms earlier for the right hand, respectively; however, the relative timing of keystroke and key-release between the two hands was also not significantly correlated (0.22 ± 0.17 and 0.14 ± 0.08, respectively, $P > 0.05$).

For the slow piece (not shown in Fig. 9), only when the timing of tone production was delayed were there also changes at the left-hand keystrokes in response to the perturbation. In agreement with the findings for the medium tempo piece, both the 1st and 2nd perturbations resulted in a shorter inter-keystroke interval and greater keystroke velocity. The changes in the interval occurred at the first and second strokes after the 1st perturbation (210 ms) and the first stroke after the 2nd perturbation (210 ms) (ANOVA, condition: $F_{(1,5)} = 6.9$ (1st) and 7.1 (2nd); $P < 0.05$). The changes in the velocity occurred at the second stroke (150 and 210 ms) and third stroke (150 ms) following the 2nd perturbation (ANOVA, interaction: $F_{(5,25)} = 8.7$ (150 ms) and 3.9 (210 ms); $P < 0.01$). There was no effect of the perturbation on the finger-key contact duration. Furthermore, neither perturbations of the tone pitch nor loudness had an apparent and significant effect on the variables.

Number of trials with pitch error

During the experiment, the participants sometimes struck an incorrect key (“pitch error”) following the perturbed auditory feedback. We counted the number of trials where the participants made a pitch error within five strokes after the perturbation. When tone production was delayed, the participants did not make a pitch error in almost all trials. The exception was that one amateur pianist made a pitch error once in both fast and medium tempo pieces for a tone delayed by 150 ms. When the pitch of a tone was altered, some participants made a pitch error for the pieces with medium and slow tempi. For the medium piece, there was one participant who made a pitch error following the pitch elevation. For the slow piece, four of six participants made a pitch error after the 1st perturbation that elevated the pitch, whereas two participants made a pitch error after the 2nd perturbation that lowered the pitch. Note that all of these pitch errors induced by altering the pitch in the slow piece occurred only in the 1st trial and did not occur in the subsequent trials. In addition, these pitch errors were characterized by either striking the previous key again or striking a key adjacent to the correct key. When tone loudness was changed, none of the participants made a pitch error.

Discussion

The present study demonstrates that accurate production of tone sequences in piano performance can be affected by auditory feedback derived from an individual keystroke. We found that the inter-keystroke interval became shorter following delayed auditory feedback so as to maintain the tempo, suggesting that temporal information provided by auditory feedback is utilized in regulating the timing of movement elements produced in a sequence. This is in agreement with previous reports that the rhythmicity of successive keystrokes was disrupted when tone production was persistently delayed (Pfordresher and Palmer 2002; Wing 1977), but not when the pitch was shifted (Pfordresher 2003; Maidhof et al. 2009). Our results are also consistent with the finding of a local disruption of inter-keystroke interval following a transient delayed auditory feedback during tapping (Flach 2005). We also found that the keystroke velocity changed after the timing, pitch, and loudness of a tone was altered, although the response differed depending on the type of perturbation. While altering the timing or pitch led to an increase in the velocity, altering the loudness changed the velocity in an inconsistent manner. Furthermore, perturbing a tone elicited by the right hand also affected the rhythmicity and intensity of keystrokes of the left hand, indicating that bimanual coordination of tone production was maintained.

Changes in keystroke velocity in response to auditory perturbation

Mostly for slower pieces, the keystroke velocity decreased after the loudness was transiently increased, in a compensatory fashion. However, the compensatory change was much less prominent when the loudness was decreased. This asymmetric compensation was also reported when voice loudness feedback was transiently altered while participants uttered a vowel (Bauer et al. 2006). Bauer et al. found that although a compensatory change in voice loudness occurred in both directions, its magnitude was greater when loudness was increased than when it was decreased. These asymmetric compensations may be attributed to a bias in the perception of loudness; our auditory system overestimates the change in magnitude of a continuously increasing loudness level of a tone relative to an equivalent decreasing level (Neuhoff 1998). This suggests that an unexpected increase in tone loudness disrupts intended verbal and musical communication more than does a decrease.

After the 2nd perturbation resulting in an increase in loudness, however, the keystroke velocity transiently became larger. A similar phenomenon was reported during a voice production, where a transient increase in the loudness occasionally resulted in louder voice production (Larson et al. 2007). In the fast piece played in quadruple time, the tone with the 1st perturbation was at the end of four grouped notes, whereas that with the 2nd perturbation was the third of a sequence of four tones (Fig. 1). Thus, in the latter case, a stronger keystroke following louder auditory feedback may be of help for maintaining consistency of loudness within a tone sequence.

Keystroke velocity was consistently increased after tone production was delayed, at all tempi and in both the 1st and 2nd perturbations. A similar phenomenon was reported during speech, where participants increased their voice loudness while listening to delayed auditory feedback (Black 1951; Howell 1990). Striking a key harder could conceivably also be a compensatory response to a perceived delay between a keypress and the tone production, suggesting a malfunction of the keyboard. However, we also saw consistent increases in keystroke velocity when the pitch of one tone was elevated (Figs. 5 and 6), especially for the piece played at the medium tempo. It is hard to interpret these results as being compensatory, and the same can be said for the increases in keystroke velocity that were occasionally observed when loudness was increased (fast piece, Fig. 8).

Possibly, the increase in keystroke velocity following a perturbation may reflect the role of somatosensory feedback in the control of rhythmic movements. Several studies have reported that a perturbation and/or block of somatosensory feedback profoundly disrupts the rhythmicity of sequential movements such as tapping (Aschersleben et al. 2001; LaRue et al. 1995) and gait (Dietz 2002; Zehr and Duysens 2004). More recently, Goebl and Palmer (2008) found a correlation between the peak finger acceleration at the moment of finger-key contact and the temporal accuracy of the subsequent inter-keystroke interval during successive piano keystrokes. This suggested that a stronger keystroke facilitates the timing accuracy of the subsequent keystrokes due to enhanced somatosensory feedback. Hence, a stronger keystroke following a perturbation could reflect a strategy of enhancing somatosensory feedback.

However, since the increase in keystroke velocity following a perturbation was a general phenomenon, irrespective of the type of perturbation, it could also reflect a state of increased alertness and arousal following an unexpected perturbation. Our studies were not designed to resolve this issue.

Changes in keystroke timing in response to auditory perturbation

For the piece played at a medium tempo with delayed auditory feedback of one note, the subsequent inter-keystroke intervals and the finger-key contact durations decreased. The decrease in inter-keystroke interval is likely also a strategy of compensating for the delay to maintain the overall tempo as accurately as possible, which is essential in music performance. The decrease in the finger-key contact duration reflects the temporal coordination between the release of one key and the depression of another one. However, there was no systematic change in the extent of change in timing in relation to the length of delay, and the change in timing was much shorter than the temporal delays imposed.

In contrast to our study, a persistent delay of auditory feedback during speech (Black 1951; Howell and Powell 1987; Yates 1963), tapping (Finney and Warren 2002; Wing and Kristofferson 1973), and playing the piano (Gates et al. 1974; Pfordresher and Palmer 2002) results in a decrease of the global tempo (see review by Howell 2004). In addition, we found no consistent effect of the magnitude of delay on the rhythmicity of keystrokes, which was reported in some of these previous studies (e.g., Pfordresher and Palmer 2002). Consequently, transient and persistent delays of auditory feedback result in distinctly different responses.

For the slow piece, the change in timing after the delayed feedback was not significant. However, with the exception of the least-practiced amateur pianist who consistently showed a prolonged inter-keystroke interval following the perturbation, the other five pianists also decreased the inter-keystroke interval on the next two strokes. Since this piece was played staccato, the lack of a change in the finger-key contact duration is to be expected.

For the piece played at the fast tempo, we did not find any appreciable changes in timing for all participants. It is possible that the interval between keypresses (~250 ms) was too short for auditory feedback to influence subsequent keypresses (Ruiz et al. 2009). However, the changes in keystroke velocity observed for this piece would argue against that interpretation.

Pitch error

When the pitch of a tone was altered, participants sometimes struck an incorrect key. This involved either striking the previous key again or striking a key adjacent to the correct key. Striking the previous key again should entail false selection of a finger to be used. This was therefore likely an error of movement planning rather than execution. Indeed, the pitch error after altering pitch has been attributed to interference with memory retrieval, according to which hearing a tone located in a planned tone sequence unexpectedly during playing interferes with the retrieval of the correct tone from memory, resulting in the pitch error (see review by Pfordresher 2006). This idea was based on the finding that the frequency of striking an incorrect key was increased only when the tone sequence fed back to the players resembled the intended one (Pfordresher 2003, 2005), but not when the feedback sequence was highly dissimilar to the intended one (Finney 1997) or absent (Repp 1999). In agreement with this, the pitch error in the present study was observed mostly after transposing a note with one that was played just before or to be played soon after.

Striking a key adjacent to the intended key is a common error in typing, and its frequency is increased when the finger-tip is anesthetized (Gordon and Soechting 1995). The inaccuracy of the finger movements following anesthesia was accounted for by the variability of the finger's start location (Rabin and Gordon 2004). Thus, production of an accurate movement requires spatial information about the starting point of movement. On the piano, the spatial information of the key is uniquely related to the pitch of a note, and expert pianists have a tightly coupled auditory-motor mapping between a note and the corresponding motor action (D'Ausilio et al. 2010; Drost et al. 2005). Shifting the pitch by one whole tone higher or lower can therefore result in the illusory perception of striking the key adjacent to the correct one, affecting the accurate execution of the subsequent keystrokes. Note that the inter-keystroke intervals immediately following the errors were greatly prolonged during typing

(Gordon and Soechting 1995), which was not apparent in the present study. This difference was presumably due to the temporal constraint specific to music performance.

The present pianists made a pitch error mostly when playing the slow piece whose inter-keystroke interval was about 500 ms. This was the same as the tempo used in previous studies of the effect of altered auditory feedback (Pfordresher 2003, 2005). However, our participants hardly made a pitch error while playing faster pieces even with the pitch perturbation. Possibly, the role of pitch information on a single tone in planning and execution of sequential finger movements depends on tempo. Given that pianists account for a group of musically relevant notes (phrase) when planning movements (Shaffer 1989), they may integrate information on a greater number of tones into movement planning at faster tempo.

Temporal coordination of a sequence of key-release and keystroke

Following the delay of a tone production, the finger-key contact duration was transiently shortened mostly in the piece with medium tempo. Counterintuitively, the timing of key-release became earlier when the tone was delayed. However, the effect of tone delay on the contact duration was quite similar in both latency and magnitude to the effect on inter-keystroke interval. A positive correlation of these variables indicated that the temporal relationship between the release of one key and the striking of the subsequent one was maintained even after the perturbation. Thus, pianists sped up only the local tempo but kept the extent of temporal overlap of two successive tones constant.

Feedback control of keystrokes with the left hand

Following the perturbation of the timing and pitch of a tone elicited by the right hand, the left hand showed similar changes as the right hand (Fig. 9). Changes of bimanual movement after unimanual perturbation were also observed in a bimanual reaching task (Diedrichsen 2007). In that study, corrective movement against external force applied to one hand was found at both hands when the participants moved a cursor, whose location was determined by the locations of both hands, toward a target. In contrast, when reaching with two hands toward two separate targets, online correction occurred only at the perturbed arm. These findings suggested that bimanual feedback control depended on the extent to which both hands should be coordinated to fulfill the task requirement. Our findings of compensatory changes in the left keystrokes therefore suggested that pianists took account of the temporal and harmonic relationship of melodies played with the two hands during polyphonic music. However, the timing of both keystroke and key-release between the right and left hands, which was correlated in the normal condition, was not correlated after both the timing and pitch perturbations.

Auditory feedback in sequential movement production

Previous studies of speech motor control have shown that speakers respond to transient, unexpected shifts of pitch or loudness by altering their vocal output in the direction opposite the shift (Bauer et al. 2006; Munhall et al. 2009; Purcell and Munhall 2006). In some instances, we also found compensatory responses such as the decrease in the inter-keystroke interval and contact duration following transiently delayed auditory feedback, which is likely to help in maintaining global tempo even at the cost of a local disruption of tempo. In contrast, many of our results were not compensatory, such as the increase in the keystroke velocity following the perturbation in pitch or, occasionally, an increase in the loudness of a tone. Furthermore, in many instances, a perturbation in one parameter led to changes in another parameter. This is in contrast to studies of proximal limb motion, which have provided evidence for separate mechanisms for controlling direction and amplitude, the effect of a perturbation in one parameter being restricted to that parameter (cf. Sainburg and

Wang 2002; Scheidt and Ghez 2007). However, a perturbation in the pitch, indicating an erroneous note, did not affect the timing of the subsequent keypress. This is in contrast with the results of studies in typing, in which an erroneous keystroke, indicated by altered tactile feedback, caused a delay in the execution of the next keypress (Gordon and Soechting 1995). The difference between this and our findings suggests that rhythmic demands influence the feedback control of sequential movements.

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References

Aschersleben G, Gehrke J, Prinz W. Tapping with peripheral nerve block. A role for tactile feedback in the timing of movements. Exp Brain Res. 2001; 136:331–339. [PubMed: 11243475]

Bauer JJ, Mittal J, Larson CR, Hain TC. Vocal responses to unanticipated perturbations in voice loudness feedback: an automatic mechanism for stabilizing voice amplitude. J Acoust Soc Am. 2006; 119:2363–2371. [PubMed: 16642849]

Black JW. The effect of delayed sidetone upon vocal intensity and rate. J Speech Hear Disord. 1951; 16:56–60.

D'Ausilio A, Brunetti R, Delogu F, Santonico C, Belardinelli MO. How and when auditory action effects impair motor performance. Exp Brain Res. 2010; 201:323–330. [PubMed: 19847407]

Diedrichsen J. Optimal task-dependent changes of bimanual feedback control and adaptation. Curr Biol. 2007; 17:1675–1679. [PubMed: 17900901]

Dietz V. Proprioception and locomotor disorders. Nat Rev Neurosci. 2002; 3:781–790. [PubMed: 12360322]

Drost UC, Rieger M, Brass M, Gunter TC, Prinz W. Action-effect coupling in pianists. Psychol Res. 2005; 69:233–241. [PubMed: 15069559]

Finney SA. Auditory feedback and musical keyboard performance. Music Percept. 1997; 15:153–174.

Finney SA, Warren WH. Delayed auditory feedback and rhythmic tapping: evidence for a critical interval shift. Percept Psychophys. 2002; 64:896–908. [PubMed: 12269297]

Flach R. The transition from synchronization to continuation tapping. Hum Mov Sci. 2005; 24:465–483. [PubMed: 16213045]

Gates A, Bradshaw J, Nettleton N. Effect of different delayed auditory feedback intervals on a music performance task. Percept Psychophys. 1974; 14:21–25.

Goebl W, Palmer C. Tactile feedback and timing accuracy in piano performance. Exp Brain Res. 2008; 186:471–479. [PubMed: 18193412]

Gordon AM, Soechting JF. Use of tactile afferent information in sequential finger movements. Exp Brain Res. 1995; 107:281–292. [PubMed: 8773246]

Hashimoto Y, Sakai KL. Brain activations during conscious self-monitoring of speech production with delayed auditory feedback: an fMRI study. Hum Brain Mapp. 2003; 20:22–28. [PubMed: 12953303]

Howell P. Changes in voice level caused by several forms of altered feedback in fluent speakers and stutterers. Lang Speech. 1990; 33:325–338. [PubMed: 2133911]

Howell P. Assessment of some contemporary theories of stuttering that apply to spontaneous speech. Contemp Issues Commun Sci Disord. 2004; 31:122–139. [PubMed: 18259590]

Howell P, Archer A. Susceptibility to the effects of delayed auditory feedback. Percept Psychophys. 1984; 36:296–302. [PubMed: 6522222]

Howell P, Powell DJ. Delayed auditory feedback with delayed sounds varying in duration. Percept Psychophys. 1987; 42:166–172. [PubMed: 3627937]

Katahira K, Abla D, Masuda S, Okanoya K. Feedback-based error monitoring processes during musical performance: an ERP study. Neurosci Res. 2008; 61:120–128. [PubMed: 18359117]

Larson CR, Sun J, Hain TC. Effects of simultaneous perturbations of voice pitch and loudness feedback on voice F0 and amplitude control. J Acoust Soc Am. 2007; 121:2862–2872. [PubMed: 17550185]

LaRue J, Bard C, Fleury M, Teasdale N, Paillard J, Forget R, Lamarre Y. Is proprioception important for the timing of motor activities? Can J Physiol Pharmacol. 1995; 73:255–261. [PubMed: 7621364]

Maidhof C, Vavatzanidis N, Prinz W, Rieger M, Koelsch S. Processing expectancy violations during music performance and perception: an ERP study. J Cogn Neurosci. 2009 (in press).

Munhall KG, MacDonald EN, Byrne SK, Johnsrude I. Talkers alter vowel production in response to real-time formant perturbation even when instructed not to compensate. J Acoust Soc Am. 2009; 125:384–390. [PubMed: 19173425]

Mutha PK, Sainburg RL. Shared bimanual tasks elicit bimanual reflexes during movement. J Neurophysiol. 2009; 102(6):3142–3155. [PubMed: 19793874]

Neuhoff JG. Perceptual bias for rising tones. Nature. 1998; 395:123–124. [PubMed: 9744266]

Pfordresher PQ. Auditory feedback in music performance: evidence for a dissociation of sequencing and timing. J Exp Psychol Hum Percept Perform. 2003; 29:949–964. [PubMed: 14585016]

Pfordresher PQ. Auditory feedback in music performance: the role of melodic structure and musical skill. J Exp Psychol Hum Percept Perform. 2005; 31:1331–1345. [PubMed: 16366793]

Pfordresher PQ. Coordination of perception and action in music performance. Adv in Cog Psychol. 2006; 2:183–198.

Pfordresher PQ, Benitez B. Temporal coordination between actions and sound during sequence production. Hum Mov Sci. 2007; 26:742–756. [PubMed: 17764772]

Pfordresher PQ, Palmer C. Effects of delayed auditory feedback on timing of music performance. Psychol Res. 2002; 66:71–79. [PubMed: 11963280]

Purcell DW, Munhall KG. Compensation following real-time manipulation of formants in isolated vowels. J Acoust Soc Am. 2006; 119:2288–2297. [PubMed: 16642842]

Rabin E, Gordon AM. Tactile feedback contributes to consistency of finger movements during typing. Exp Brain Res. 2004; 155:362–369. [PubMed: 14689143]

Repp BH. Effects of auditory feedback deprivation on expressive piano performance. Music Percept. 1999; 16:409–438.

Ruiz MH, Jabusch HC, Altenmu¨ller E. Detecting wrong notes in advance: neuronal correlates of error monitoring in pianists. Cereb Cortex. 2009; 19:2625–2639. [PubMed: 19276327]

Sainburg RL, Wang J. Interlimb transfer of visuomotor rotations: independence of direction and final position information. Exp Brain Res. 2002; 145:437–447. [PubMed: 12172655]

Scheidt RA, Ghez C. Separate adaptive mechanisms for controlling trajectory and final position in reaching. J Neurophysiol. 2007; 98:3600–3613. [PubMed: 17913996]

Shaffer LH. Cognition and affect in musical performance. Contemp Music Rev. 1989; 4:381–389.

Wing AM. Perturbations of auditory feedback delay and the timing of movement. J Exp Psychol Hum Percept Perform. 1977; 3:175–186. [PubMed: 864391]

Wing AM, Kristofferson AB. Response delay and the timing of discrete motor responses. Percept Psychophys. 1973; 14:5–12.

Yates AJ. Delayed auditory feedback. Psychol Bull. 1963; 60:213–232. [PubMed: 14002534]

Zehr EP, Duysens J. Regulation of arm and leg movement during human locomotion. Neuroscientist. 2004; 10:347–361. [PubMed: 15271262]

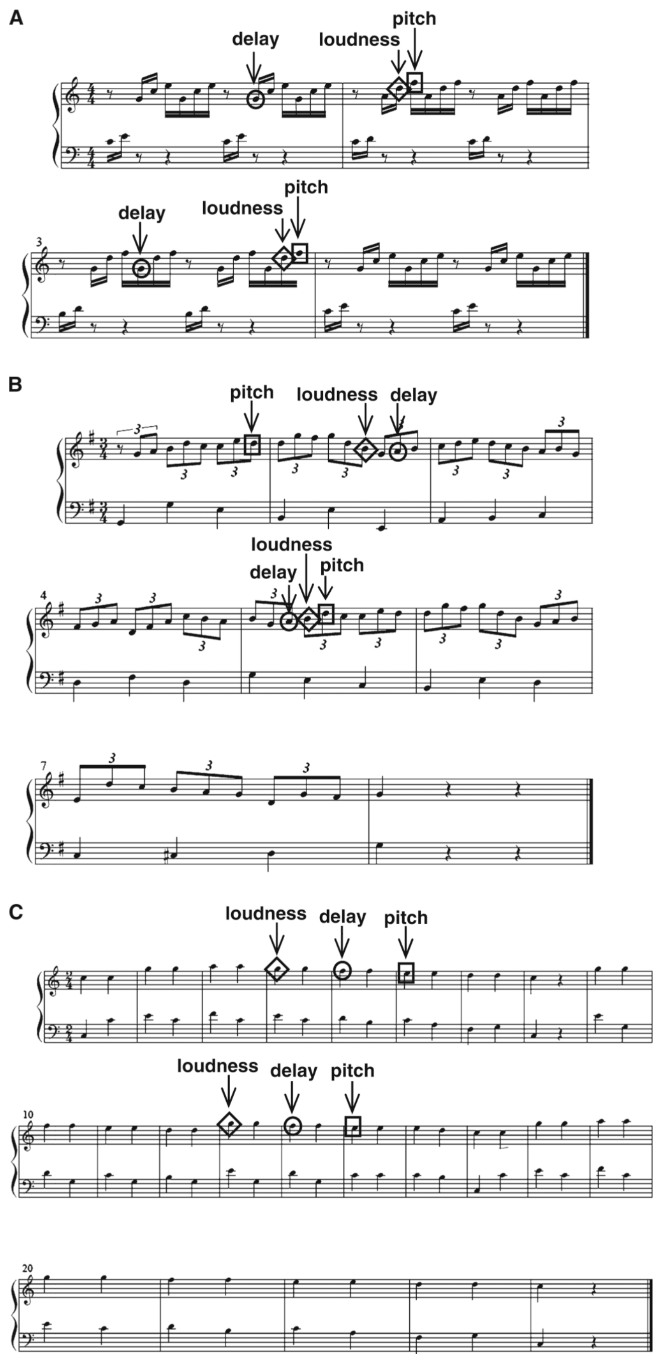

Fig. 1.

Scores of three pieces used in the experiment. **a** “Prelude from Das wohltemperierte Klavier, I-1” by J. S. Bach (fast), **b** “Jesus bleibet meine Freude from Cantata 147” by J. S. Bach (medium), **c** Ah! Vous dirais-je maman by W. A. Mozart, (slow). *Symbols* represent the notes whose timing was delayed (*circle*), pitch was shifted (*square*), or loudness was changed (*diamond*). Note that the same perturbation occurred at the same note twice in each piece. All other notes were presented with normal auditory feedback

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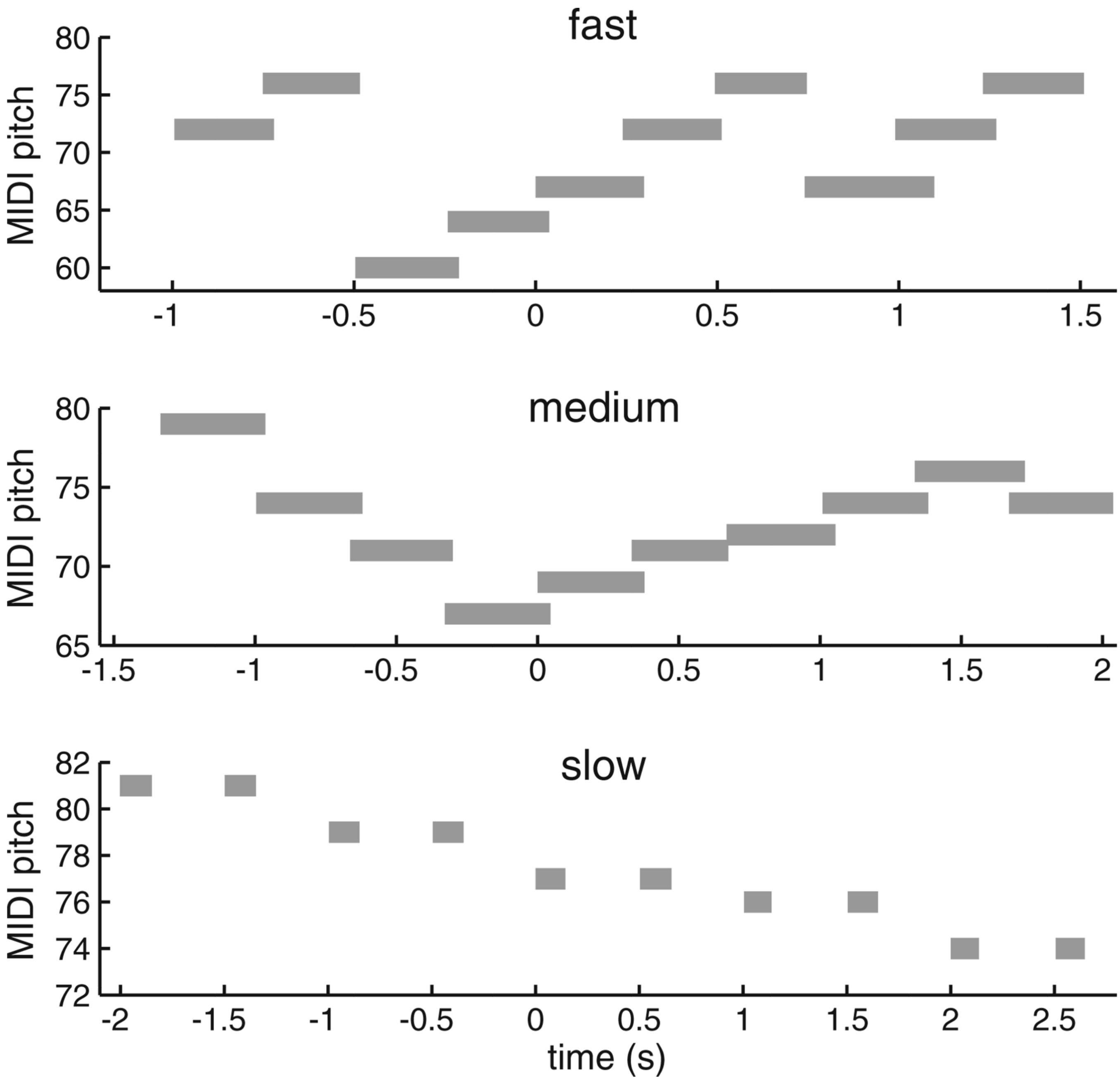

Fig. 2.
The mean values of keypress and key-release timings across all participants in the normal condition while they played pieces with fast, medium, and slow tempi. Tones bracketing the 1st timing perturbation are displayed (i.e., the note with the 1st circle in Fig. 1 corresponds to time zero)

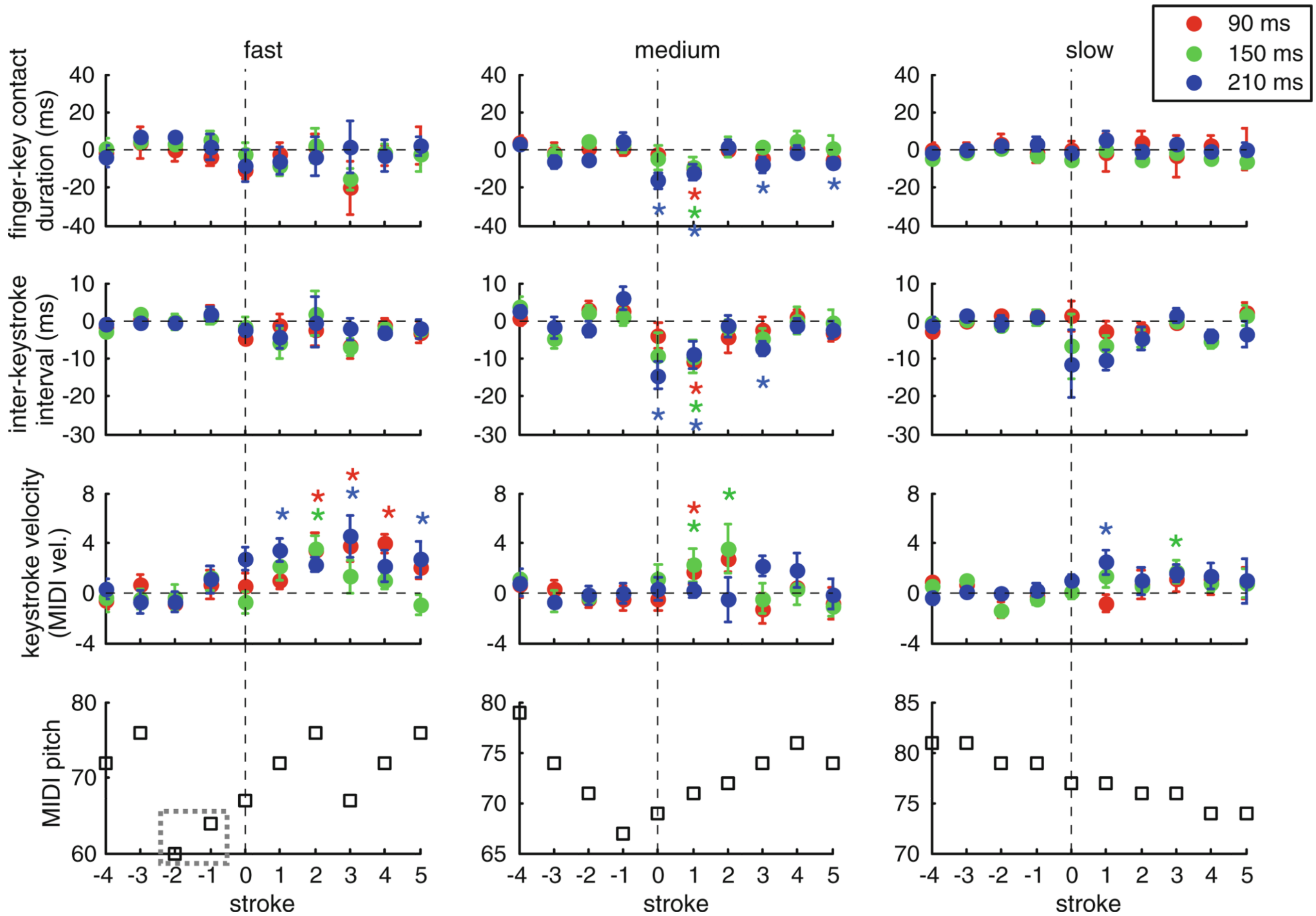

Fig. 3.

The mean changes of finger-key contact duration, inter-keystroke interval, and keystroke velocity before and after the 1st perturbation of the timing of a tone production across all participants while they played pieces with fast, medium, and slow tempi. A *circle in red green*, and *blue* represents the instance of 90, 150, and 210 ms of delay, respectively. The MIDI pitch of struck keys is also depicted for reference. Note that all strokes at the medium and slow pieces were made with the right hand, whereas those at the fast piece were played with both the right and left hands in sequence (see Fig. 1). A *dotted square* in gray in the fast piece represents the notes played with the left hand. The 0th stroke denotes the occurrence of the perturbation. The *error bars* represent ±1 SEM between participants. Note that the 0th inter-keystroke interval refers to the interval between the 0th and the 1st keypress, the latter normally occurring at least 250 ms (fast piece) after the onset of the perturbation. * denotes instances in which the changes were statistically different from 0 ($P < 0.05$)

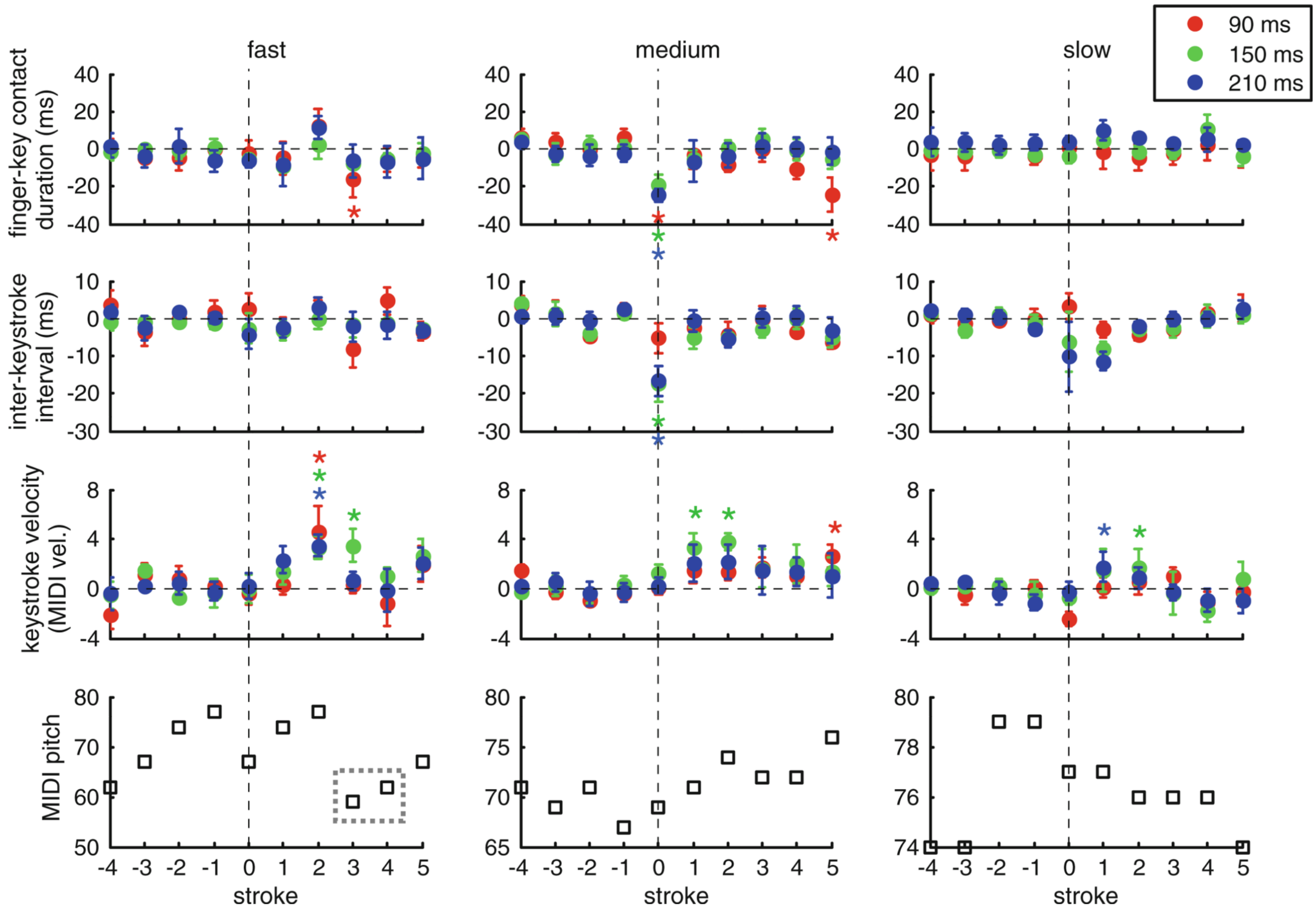

Fig. 4.

The mean changes of finger-key contact duration, inter-keystroke interval, and keystroke velocity before and after the 2nd perturbation of the timing of a tone production across all participants while they played pieces with fast, medium, and slow tempi

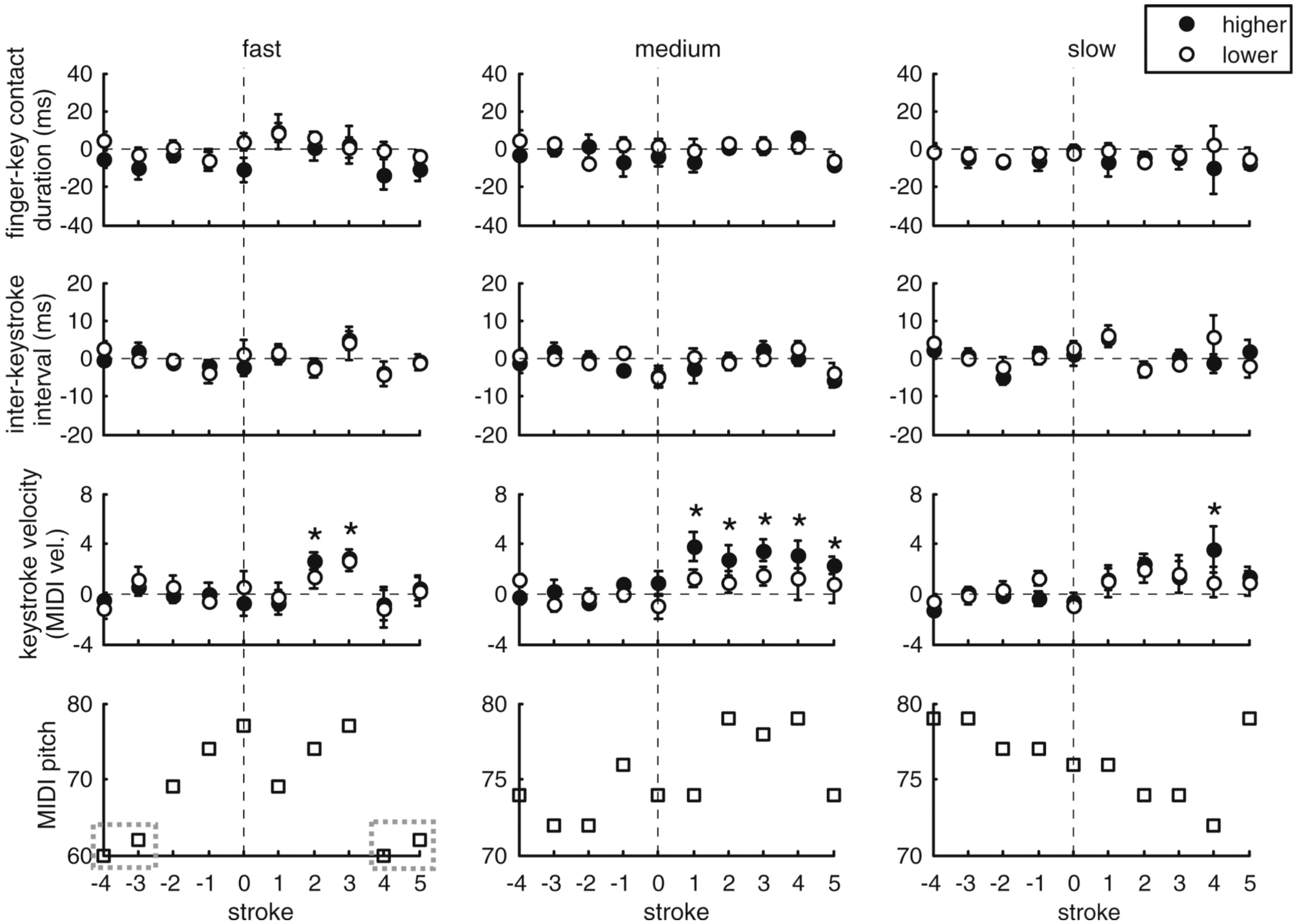

Fig. 5.

The mean changes of finger-key contact duration, inter-keystroke interval, and keystroke velocity before and after the 1st perturbation that shifted tone pitch for pieces played with fast, medium, and slow tempi. A *filled* and *open circle* represents the instance of higher and lower shift of pitch, respectively. The * indicates an instance for which the difference was statistically significant when pitch was elevated. The *error sbars* represent ±1 SEM

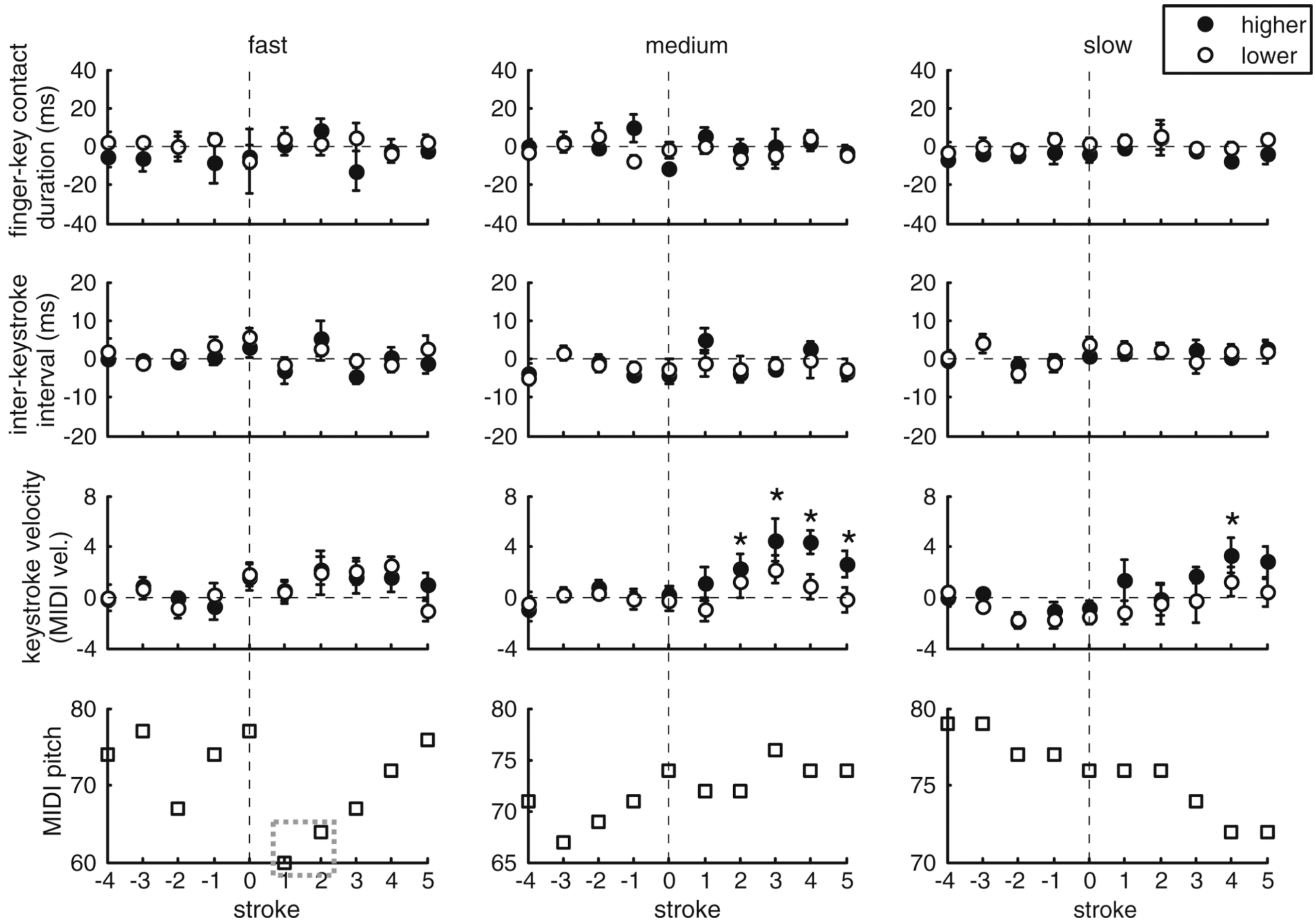

Fig. 6.
The mean changes of finger-key contact duration, inter-keystroke interval, and keystroke velocity before and after the 2nd perturbation that shifted tone pitch for pieces played with fast, medium, and slow tempi. The * indicates an instance for which the difference was statistically significant when pitch was elevated

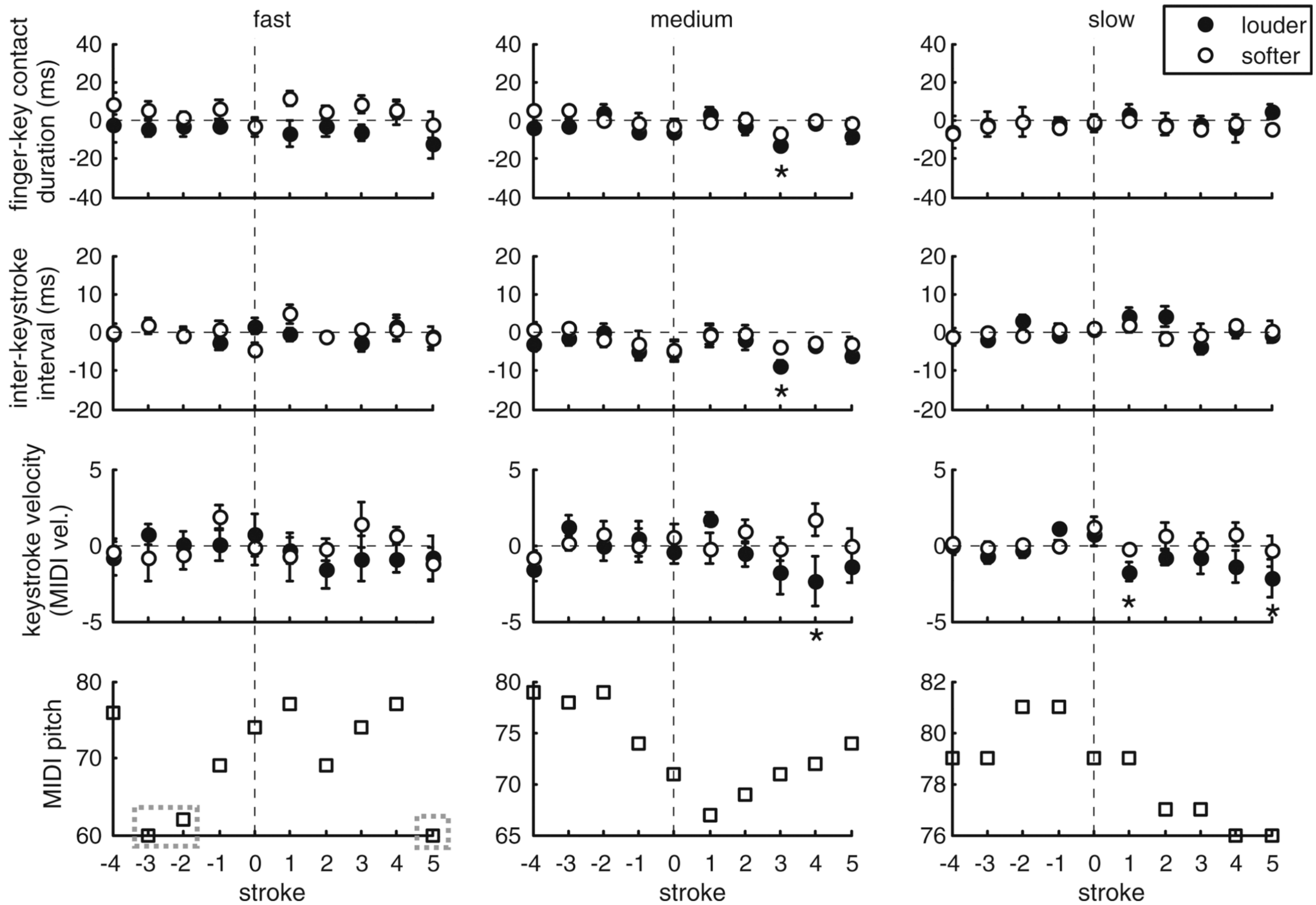

Fig. 7.
The mean changes of finger-key contact duration, inter-keystroke interval, and keystroke velocity before and after the 1st perturbation that changed tone loudness for pieces played with fast, medium, and slow tempi. A *filled* and *open circle* represents the instance of an increase and decrease in the loudness, respectively. The * indicates an instance for which the difference was statistically significant. The *error bars* represent ±1 SEM

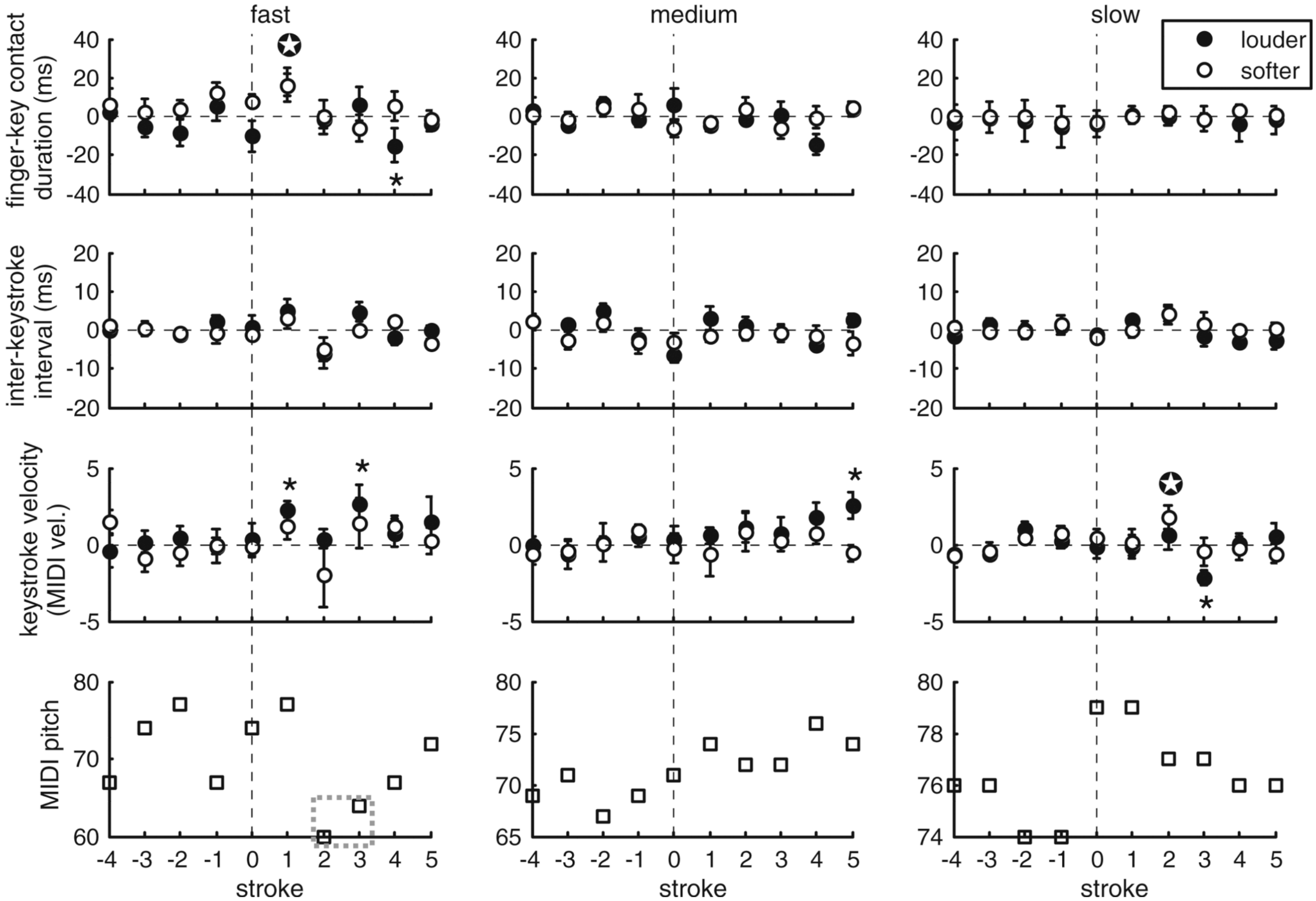

Fig. 8.

The mean errors of finger-key contact duration, inter-keystroke interval, and keystroke velocity before and after the 2nd perturbation that changed tone loudness for pieces played with fast, medium, and slow tempi. The * and ✪ indicate an instance for which the difference was statistically significant when loudness increased or decreased, respectively

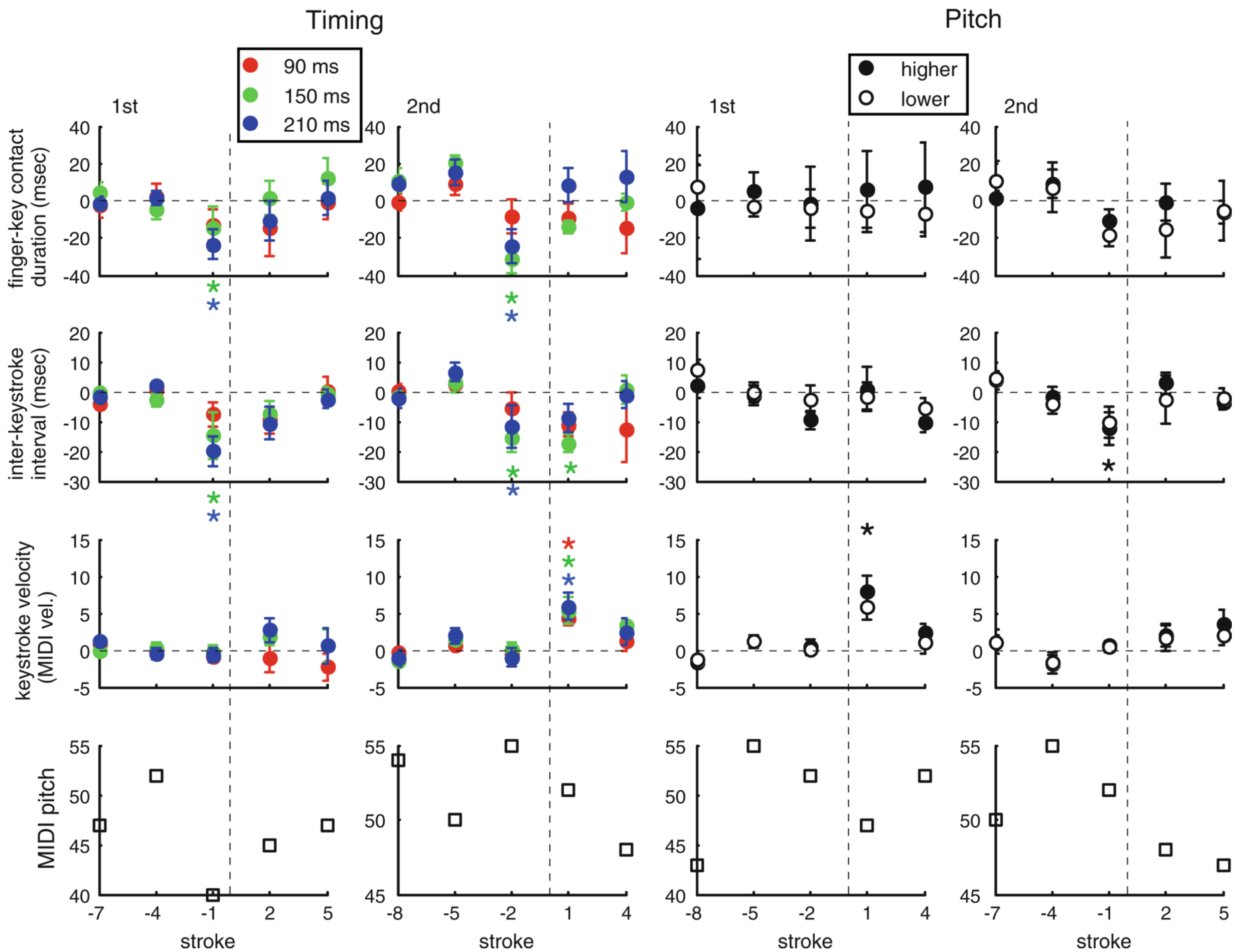

Fig. 9.

The mean errors of finger-key contact duration, inter-keystroke interval, and keystroke velocity before and after the 1st and 2nd perturbations of the timing of a tone production (*left two panels*) and the tone pitch (*right two panels*) for the keys struck with the left hand and the piece played at medium tempo. The * and ✪ indicates an instance for which the difference was statistically significant when pitch was elevated or lowered, respectively. The stroke numbering shown in the figure corresponds to that used for the right hand

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Table 1

F values of two-way ANOVA for comparisons between delayed tone perturbations and normal conditions

	Delay (condition) $F_{(1,5)}$			Interaction (cond × stroke) $F_{(5,25)}$		
	90 ms	**150 ms**	**210 ms**	**90 ms**	**150 ms**	**210 ms**
1st perturbation						
Velocity-slow	2.4	6.9*	7.3*	0.9	1.6	1.1
Velocity-med	0.3	0.9	0.2	2.8*	3.1*	2.5
Velocity-fast	53.7**	3.3	28.1**	1.9	3.9**	0.6
Interval-med	8.0*	6.9*	23.5**	1.7	1.2	3.8*
Cont Dur-med	17.2**	0.3	11.1*	1.0	2.8*	3.8*
2nd perturbation						
Velocity-slow	0.1	0.1	0.0	0.2	2.7*	3.2*
Velocity-med	8.6*	6.6*	1.5	1.3	2.0	0.5
Velocity-fast	1.8	6.7*	19.3**	2.8*	2.6	1.3
Interval-med	2.1	15.4*	4.2	1.1	4.3**	7.2**
Cont Dur-med	40.7**	1.9	3.4	1.7	3.4*	3.3*
Cont Dur-fast	0.3	0.0	0.0	3.0*	0.7	1.0

Slow, med, and fast refer to the tempo of the piece

Interval: inter-keystroke interval

Cont Dur: finger-key contact duration

* $P < 0.05$,

** $P < 0.01$