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RESEARCH ARTICLE

Tactile feedback and timing accuracy in piano performance

Werner Goebl · Caroline Palmer

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Abstract Sequential actions such as playing a piano or tapping in synchrony to an external signal put high cognitive and motor demands on producers, including the generation of precise timing at a wide variety of rates. Tactile information from the fingertips has been shown to contribute to the control of timing in finger tapping tasks. We addressed the hypothesis that reduction of timing errors is related to tactile afferent information in pianists' finger movements during performance. Twelve pianists performed melodies at four rates in a synchronization-continuation paradigm. The pianists' finger motion trajectories toward the piano keys, recorded with a motion capture system, contained different types and amounts of kinematic landmarks at different performance rates. One landmark, a finger–key (FK) landmark, can occur when the finger makes initial contact with the key surface and changes its acceleration abruptly. Overall, there were more FK landmarks in the pianists' keystrokes, as the performance rate increased. The pianists were divided into two groups: those with low percentages of FK in the medium rates that increased with increasing performance rate and those with persistently high FK percentages. Low-FK pianists showed a positive relationship between increased tactile feedback from the current keystroke and increased temporal accuracy in the upcoming keystroke. These findings suggest that sensory information available at finger–key contact enhances the timing accuracy of finger movements in piano performance.

W. Goebl (✉) · C. Palmer
Department of Psychology, McGill University,
1205 Dr Penfield Avenue, Montreal, QC, H3A 1B1 Canada
e-mail: werner.goebl@mail.mcgill.ca

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Introduction

The human hand is equipped with cutaneous mechanoreceptors that are densely distributed in the skin of the fingertips. These tactile sensory inputs make the fingers dexterous and versatile tools for exploring and shaping the physical world (Jones 1996; Flanagan and Johansson 2002). As a result, even complex tasks such as typing on a keyboard or playing a musical instrument display high levels of spatial and temporal precision and accuracy (Soechting et al. 1996; Jerde et al. 2006). Precision of hand and finger movements is considerably impaired when tactile feedback is artificially inhibited; for example, anesthetizing participants' fingertips causes the reaching-to-grasp movements to become irregular and slower (Gentilucci et al. 1997), precision grip tasks to become less accurate and inter-muscle coherence to be reduced even when visual feedback is fully available (Fisher et al. 2002).

What role does tactile feedback play in the production of fast finger sequences such as those in typing and music performance? In touch-typing, tactile afferent information affects spatial error, but not timing (Gordon and Soechting 1995). Typists with anesthetized fingertips and blocked vision made significantly more typing errors and were unable to detect them; however, the timing of subsequent keystrokes as well as the movement kinematics remained relatively unaffected. In a further typing study with finger anesthesia, Rabin and Gordon (2004) found that increases in the endpoint variability were accounted for by start point variability, which suggests that tactile information is essential for spatial orientation (Rabin and Gordon 2004). However, typing requires only a correct serial ordering of events, but not precise timing.

Synchronization tasks, such as tapping to an external auditory stimulus, make considerable demands of temporal accuracy and precision (for overviews, see Repp 2005; Repp 2006). Aschersleben (2002) suggested that tactile information plays an important role in the control of timing in synchronization tapping. Aschersleben et al. (2001) found increased negative tap asynchrony relative to an auditory pacing signal (the onset of the produced tap precedes the pacing signal) when participants' fingertips were anesthetized, compared with normal tapping in which full tactile feedback was available. Other behavioral tasks that did not involve tactile feedback (finger wiggling) as well as unsynchronized high-speed tapping were not affected by local finger anesthesia. These findings cast doubt on the nerve-conduction hypothesis (Fraisse 1980) as an explanation of the negative tap asynchrony, according to which different sources of sensory information (usually tactile or auditory) are synchronized on a central level, but longer nerve conduction times for tactile feedback relative to auditory feedback lead to a negative tap asynchrony (see Aschersleben 2002).

A sensory accumulator model (SAM) was proposed (Aschersleben et al. 2004) as an extension to the nerve-conduction hypothesis. SAM assumes that central processing delays during integration of different sensory information are changed by the accumulation functions of tactile or kinesthetic signals. The amount of tactile afferent information determines the latency of this delay. Increased tactile input would increase the speed of processing (or decrease latency) and thus reduce negative asynchrony. Aschersleben et al. (2004) found smaller asynchronies when participants were instructed to tap with large finger motion amplitudes (entailing more afferent information) as compared with small amplitude movements. In another experiment, participants reported a perceived asynchrony between the auditory stimulus and an electrical tactile stimulation at the fingertip at −35 ms (a negative sign means the tactile stimulation came before the auditory stimulus) when the tactile stimulation was weak, but at −2 ms when the tactile stimulation was strong (Aschersleben et al. 2004, p 131). Conversely, the *absence* of the tactile part of a finger tap (through anesthesia) delays the central (cross-modal) integration of the signal and thus would entail a larger asynchrony, as found in their behavioral data (Aschersleben et al. 2001).

The role of sensory feedback in tapping tasks was examined involving cases of individuals with peripheral somatosensory loss (e.g., Billon et al. 1996; Stenneken et al. 2006). Stenneken et al. (2006) performed tapping experiments in which patients with a complete loss of cutaneous touch and movement sense below the neck (deafferented participants) and matched normal controls tapped to an auditory cue either with or without full visual and auditory feedback. In the condition without any visual or auditory feedback, the deafferented participants tapped far ahead of the acoustic stimulus (−95 ms), whereas the normal controls showed around −30 ms asynchrony. When acoustic and visual feedback of their tapping was allowed, the deafferented participants tapped almost in synchrony with the stimulus, while the controls still tapped at around −30 ms asynchrony (Stenneken et al. 2006). The authors suggested that the deafferented participants had learned over more than 30 decades to rely on information from other modalities (auditory and visual) to perform well. The healthy participants were unaffected by the auditory and visual information and relied apparently more on proprioceptive and tactile information that was available to them in both experimental conditions (Stenneken et al. 2006).

The present study focuses on tactile information available during pianists' production of timed complex finger sequences in piano performance. Skilled pianists are highly trained in timed finger movements and are able to produce complex finger sequences with high spatial, serial, and temporal precision and accuracy at a wide variety of performance rates (Palmer 1989; Finney and Palmer 2003; Palmer and Pfordresher 2003). Furthermore, they use purposefully different types of touch to produce a wide variety of intensities on the piano keyboard (Askenfelt and Jansson 1990a). Touch is usually referred to as the physical interaction of the finger with the piano key (Báron 1958). Two prototypical types of touch have been reported: a "struck touch," referring to a sudden increase of finger force toward the key, usually produced by a finger arriving from a certain distance above the key surface, and a "pressed touch," involving a gradual increase of finger force during a key press (Ortmann 1925; Askenfelt and Jansson 1990b; Goebl et al. 2005; Kinoshita et al. 2007). These two types of touch might entail differences in keystroke dynamics (Goebl et al. 2005) that might be an important source of information for the performing artist (Askenfelt and Jansson 1992). We explore here the role played by these touch-related motion dynamics in pianists' performance.

Two main questions are addressed in this study. First, we investigate the change of kinematic variables (velocity, acceleration) in highly skilled performers' finger movements across different performance rates while they perform simple melodies. Kinematic landmarks in the pianists' finger motion (such as peak accelerations) associated with particular types of touch are identified for each keystroke and their distribution is studied across rate conditions. Specifically, two kinematic landmarks can result from the interaction of the pianist's finger with rigid bodies (piano keys), both defined by a peak acceleration in the finger height trajectories: a finger–key contact and a key–bottom contact. Key–bottom contacts occur (always) when the finger is stopped as the piano key arrives at the key bed. Finger–key contacts can occur when the finger makes initial contact with the key surface and changes its acceleration abruptly. These kinematic landmarks may provide measures of tactile information available to the performer that change with the dynamics of finger–key interaction. Second, we examine how these kinematic landmarks are related to measures of temporal accuracy. Extending the scope of the sensory accumulator model from predictions for synchronization behaviors to predictions for continuation, we hypothesize that increases in tactile afferent information might help to facilitate the planning and execution of an upcoming event: a keystroke that has been performed with a touch that entails significant tactile feedback may be followed by a more accurately timed keystroke than one performed with minimal tactile feedback.

Method

Participants

Twelve highly-trained pianists from the Montreal area, 20 to 33 years old,[1] (M = 27 years) participated in the experiment. They had 10–25 years of piano lessons (M = 18.7 years) and most were university students studying piano performance in Montreal. All participants gave informed consent according to the procedures approved by the Institutional Review Board of McGill University (complying with the 1964 Declaration of Helsinki). All but two pianists indicated they were right-handed and none reported any hearing impairment.

Stimulus materials

Two isochronous 16-tone melodies were created that were easy to perform with the right hand and could be continuously repeated. The melodies were designed to not include any finger passing-over or passing-under requirements so that the fingertips could be seen by the cameras at any point in time. They were presented to the participants in standard musical notation with no indications of dynamics, articulation or any particular expression.

[1] One participant was 60 years old and had 40 years of piano lessons. To check for possible age effects, this participant's data were compared with those of the other participants and no significant differences were observed. The mean data reported comprise all participants.

Equipment

A three-dimensional motion capture system (Vicon V460 with 6 MCam2 infrared cameras by Vicon, Los Angeles, CA, USA) monitored the motion of the participants' right hand and the piano keys at a frame rate of 250 Hz; 25 reflective markers (4 mm diameter) were glued on the finger nails, finger joints and the hand as well as markers on the top of each struck key on the MIDI digital piano (RD-700SX by Roland Corporation, Los Angeles, CA, USA). The digital piano allowed for an unobstructed view of the fingertips by the cameras (both acoustic and upright pianos have key lids that impede the cameras' view of the front of the fingers). Data from the 5 fingertips are reported here.

The participants heard their performances through AKG K-271 closed headphones plugged directly into the digital piano, to reduce noise from the keyboard as well as any auditory delays; the volume was adjusted to the participants' comfort with the volume controls on the digital piano. The MIDI data, the sound of the digital piano and the metronome signal (Dr. Beat DB-88) were recorded separately by a computer and were subsequently aligned with the motion data via the metronome click audio signal, which was recorded on both the analog input of the Vicon system and the sound card that recorded the MIDI keystrokes.[2]

Design and procedure

The main independent variable was performance rate, which ranged from medium to very fast (2, 4, 6 and 7 tones per second or 500, 250, 167 and 143 ms inter-onset interval, respectively) and was presented on a metronome in a synchronization–continuation paradigm. One trial consisted of six repetitions (cycles) of a melody: one synchronization cycle and five continuation cycles. Each trial was repeated four times per rate condition and melody. The first and the last continuation cycle were dropped from data analysis; thus, a total of 12 cycles per rate condition and melody were produced by each pianist, resulting in 96 trials in all, which contained 1,536 played tones for each participant (4 rates $\times$ 12 cycles $\times$ 2 melodies $\times$ 16 tones).

At the beginning of the experimental session, the participants saw the scores of the melodies and were asked to practice them until they had memorized them. They performed a trial of a melody by first synchronizing with the beat of the metronome, which was switched off after

[2] The metronome click audio signal was recorded on the analog input of the Vicon System (a 32-channel Mezzanine card operating at a sampling rate of 10 kHz) and on the digital soundcard (Motu 828 mkII, operating at 44.1 kHz) using Cubase software. The synchronization error of this method was less than 1 ms.

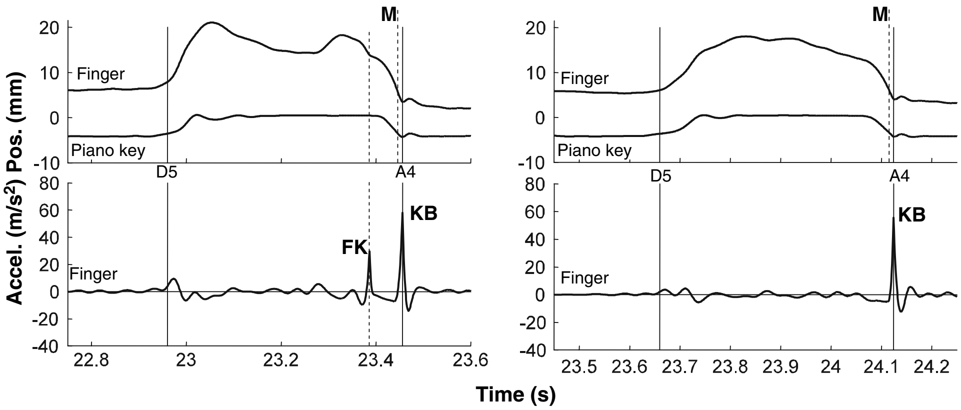

Fig. 1 Fingertip height motion of a pianist's middle finger playing the A4 key. *Left-hand side panels* show finger and key position, *right-hand side panels* depict finger acceleration. Two types of touch are contrasted: a struck touch (*left-hand side*), exhibiting a finger–key landmark (*FK*, *dotted line*), and a pressed touch (*right-hand side*) without such a landmark. Both keystrokes have comparable sound intensity (measured in MIDI velocity units), and both keystrokes contain a key–bottom landmark (*KB*, *solid line*) occurring when the finger is finally stopped at the key bed. The MIDI onset is indicated by *dashed lines* in the *upper panels* (*M*)

the first cycle of the melody. The pianists then continued playing until they were stopped by the experimenter after five continuation cycles. The experimental trials with each melody were recorded in two separate blocks; within each block, each rate condition was repeated twice. The rate conditions were always kept in ascending order (slowest to fastest). There was a short pause between experimental blocks. The order of the melodies was counterbalanced across participants. At the end of the experiment, participants completed a questionnaire about their musical backgrounds. The entire experiment, including other melodies not included in the present study, lasted approximately 90 min and the participants received a nominal fee.

Data analysis

The three-dimensional data space was rotated so that the height dimension was orthogonal to the keyboard plane. Occasional missing data in the fingertip trajectories (less than 0.17% of all data) were interpolated. Before the motion trajectories were smoothed, two kinematic landmarks were identified in the keystrokes that resulted from interaction of the finger with rigid bodies: a finger–key contact (FK) and a key–bottom contact (KB). The KB occurred when the finger was stopped as the piano key arrived at the key bed, characterized by an acceleration peak in the finger height trajectory. The KB landmark occurred for every keystroke in our data set. An FK, on the other hand, *can* occur when the finger makes initial contact with the key surface and changes its acceleration abruptly. An FK landmark was identified when an acceleration peak (local maximum) in the finger trajectory was larger than 25 m/s^2 within 30–150 ms before the KB landmark; the 25 m/s^2 threshold corresponds to the 94th percentile of all acceleration values during the event region prior to a keystroke.[3]

The motion data were then converted to a functional form using functional data analysis (Ramsay and Silverman 2005). Order 6 b-splines were fit to the second derivative (acceleration), with knots placed every five data points, and smoothed using a roughness penalty on the fourth derivative ($\lambda = 10^{-18}$), which smoothed the second derivative (acceleration). The λ parameter was chosen to generate a smallest possible generalized cross-validation estimate to the raw data (Ramsay and Silverman 2005). In order to preserve the identified kinematic landmarks through the smoothing process, three additional knots were added at each landmark, which results in an edge in the acceleration trajectories at those particular points. Peak acceleration values were then computed from the functional data for both FK and non-FK keystrokes (those whose accelerations were less than 25 m/s^2). Functional data for sample finger and key motion trajectories are shown in Fig. 1 for a keystroke with and without FK landmarks.

Inter-onset timing (IOI, in ms) was determined by calculating the time interval between one MIDI onset and the following one; thus: $\mathrm{IOI}_x = t_{x+1} - t_x$, with x referring to one tone of a melody and t_x being its MIDI onset time. The MIDI timing information was preferred over information from the motion data (e.g., KB) because it reflects the point in time when the acoustic signal is triggered (cf. Goebl 2001), and it has a finer temporal resolution (1 ms compared to 4 ms of the movement data). The MIDI onset occurred 6.4 ms before the KB landmark on average (SD = 2.75 ms, see also Fig. 1), which is comparable to the delay measured between a MIDI onset and key–bottom

[3] The choice of the time window was made based on measurement data on typical key movement behavior reported in Goebl et al. (2005).

contact on computer-monitored acoustic grand pianos (Goebl and Bresin 2003; Goebl et al. 2005). The MIDI onset is very close in time to the physical onset of the sounding tone. The MIDI velocity is the only parameter that controls the sound intensity on a digital piano.

To account for the pianists' occasional tendencies to speed up or slow down over the course of one trial, the IOIs were detrended from linear tempo drifts using regression analysis, as in previous synchronization–continuation studies (Pfordresher and Palmer 2002; Zelaznik et al. 2002; Loehr and Palmer 2007). The adjusted IOIs were derived from the mean original (non-log) IOIs plus the residuals from the regression of original IOIs on their serial position per trial. All further timing analyses were based on these detrended data.

Results

Motion data

The two examples of keystrokes shown in Fig. 1 reflect the same pitch performed in one melody (the middle finger striking an A4 on the piano keyboard) and are comparable in intensity (measured by MIDI velocity). One of the examples (Fig. 1a) contains an FK landmark prior to the KB landmark, whereas the other does not (Fig. 1b). Of the total 18,432 individual keystrokes, 82.4% contained an identifiable FK landmark. The percentage of FK keystrokes for each pianist indicated a significant main effect of rate [$F(3,30) = 88.94$, $P < 0.001$]. At the slowest rate (500 ms IOI), only half of the keystrokes (M = 53.2%) had an FK landmark, while at the fastest rate almost all of them had an FK landmark (M = 97.3%). This suggests that pianists altered the finger dynamics while approaching the keys in a non-linear fashion as they performed the melodies faster.

In addition, the maximum finger accelerations obtained at the FK landmark increased with the performance rate [$F(3,30) = 94.31$, $P < 0.001$]. The faster the melodies were played, the larger the maximum acceleration values (at a rate of 2 tones/s M = 31.6 m/s^2; while at a rate of 7 tones/s M = 106.1 m/s^2).

Next, we investigate the individual differences in the pianists' FK landmarks. Some pianists ($n = 4$) showed extremely low FK proportions at slow rates and almost 100% FK landmarks at the fastest rate, whereas other pianists showed high FK proportions at all rates ($n = 8$). Figure 2 shows the FK proportions for each rate condition (ordered from medium to fast) per participant. A threshold of 70% FK across rate conditions was chosen to split the participants into two groups. Four pianists had values above this threshold at all rate conditions, referred to here as the "high-FK" group, while the remaining eight formed

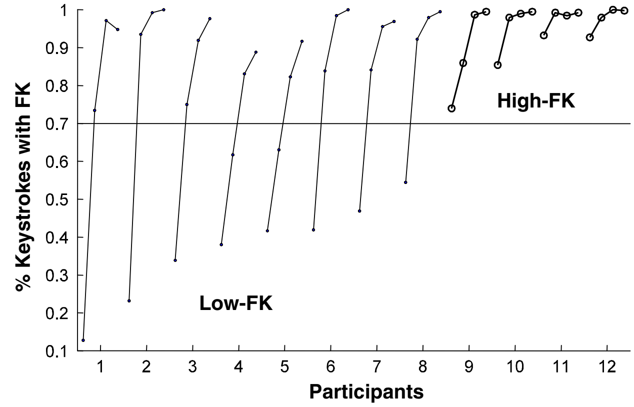

Fig. 2 Percentage of keystrokes with an FK landmark as a function of rate condition by participant, ordered by increasing rate

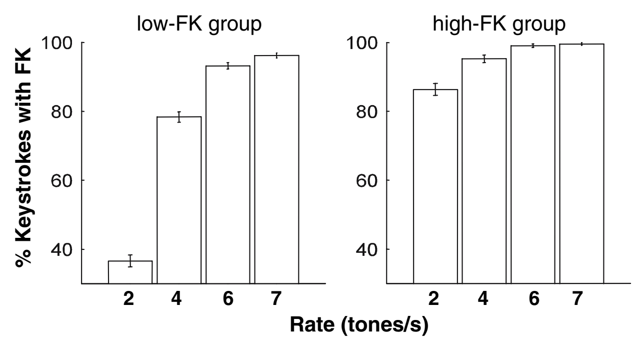

Fig. 3 Mean percentage of keystrokes with an FK landmark by group (low-FK group, $n = 8$, versus high-FK group, $n = 4$) and rate condition, with standard *error bars*

the "low-FK" group having considerably lower FK proportions in the slowest rate conditions (Fig. 2). The following statistics focus on these potential group effects.

The mean proportions of keystrokes containing an FK landmark are plotted in Fig. 3 separately by FK-group and rate. A two-way ANOVA on the FK landmark percentages with rate as within-subjects and group as between-subjects factor yielded significant main effects of rate (reported above) and group [$F(1,10) = 27.28$, $P < 0.001$], as well as a significant interaction of rate and group [$F(3,30) = 21.81$, $P < 0.001$]. Pairwise post hoc comparisons (Tukey's HSD[4] = 17.95, $P < 0.01$) revealed significant differences between groups at the two slow rate conditions (2 and 4 tones/s, see Fig. 3). Related to the criterion used for splitting the participants into two groups, the low-FK group showed lower percentages of FK landmarks at the two slowest rate conditions than the high-FK group, whereas all participants exhibited values close to 100% at the fast conditions.

[4] Due to the different *n* in the two groups, a Tukey-Kramer modification of the HSD test for unequal sample *n*'s was used (Kirk 1982, p. 119).

There were also group differences in the maximum finger accelerations (Fig. 4). A two-way ANOVA on the maximum finger accelerations showed significant main effects of rate (reported above) and group [$F(1,10) = 7.13$, $P < 0.05$] and a significant interaction between rate and group [$F(3,30) = 3.11$, $P < 0.05$]. The post hoc analysis (Tukey's HSD = 28.19, $P < 0.01$) revealed similar effects as before: only the two slower rate conditions differed significantly between the two groups (2 and 4 tones/s), suggesting that the low-FK group gained different amounts of tactile information as the high-FK group at slow tempi but not at faster tempi.

In order to examine whether the two groups of pianists showed differences in their attained skill level, we ran ANOVAs on both years of lessons and total years of playing the piano in the questionnaire, with group as the between-subject factor. There was a small tendency of the high-FK group to have played their instrument less long and to have received piano lessons over a shorter period; however neither group effect reached significance.

Timing data

The pianists' temporal precision while performing the melodies was very high. The overall coefficient of variance ($CV = SD_{IOI}/mean_{IOI}$) of the inter-onset timing was 0.052. A two-way ANOVA on the CV per cycle (melody repetition) revealed a significant main effect of rate [$F(3,30) = 109.27$, $P < 0.001$] with a CV of 0.030 at the slowest rate and 0.077 at the fastest rate, but no significant group effect or interaction. The observed precision is comparable to those reported for performances of simple melodies (Pfordresher and Palmer 2002), but considerably more precise than studies involving two-octave scales (MacKenzie and Van Eerd 1990) or finger tapping (e.g., Zelaznik et al. 2002).

The pianists were also accurate in timing across the rate conditions. Relative timing error was defined as the signed difference in each inter-onset interval (IOI) from its

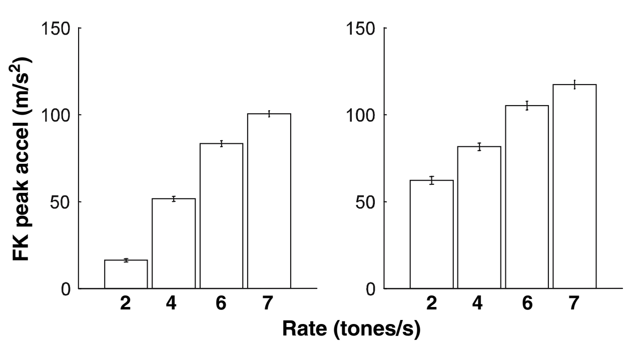

Fig. 4 Mean peak accelerations (in m/s^2) of the fingertip height trajectory at the FK landmark by group and rate condition, with standard *error bars*

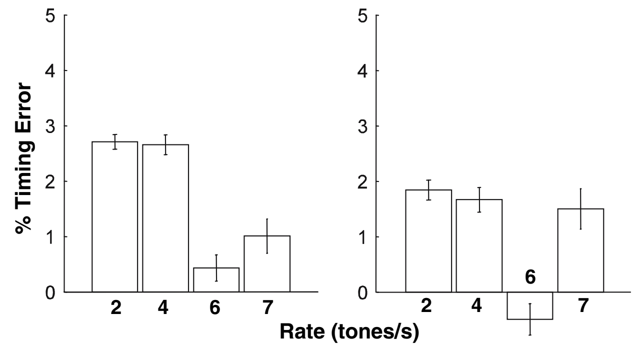

Fig. 5 Mean timing error in percentage [$(IOI_{exp} - IOI_{obs})/IOI_{exp}$] by group (low-FK versus high-FK) and rate condition, with standard *error bars*

expected value (the metronomic value): $T_{err}\% = (IOI_{exp} - IOI_{obs})/IOI_{exp}$ (the same as "constant error," Schmidt and Lee 1999).[5] A timing error *larger* than zero indicated that an IOI was played *faster* than the nominal value. The overall timing error was very small (M = 1.51%). The mean relative timing error is shown in Fig. 5 by group and rate. To examine the potential group differences in timing error, a two-way ANOVA on percent timing error revealed a main effect of rate [$F(3,30) = 10.57$, $P < 0.001$], but no significant main effect or interaction involving group. When the 12 repetitions per rate condition and participant were treated as independent cases, the effect of group [$F(1,142) = 8.88$, $P < 0.01$] and the interaction with rate were significant [$F(3,426) = 6.75$, $P < 0.001$]. Post hoc comparisons (Tukey-Kramer HSD = 0.84%, $P < 0.05$) revealed significant group differences for all rate conditions but the fastest rate. Those conditions in which the pianists had more FK landmarks and higher maximum finger accelerations were also more accurate in relative timing.

We tested also for possible effects of musical skill level on the participants' accuracy and precision of timing production. There were no significant correlations between measures of skill level (years of playing the piano and years of piano lessons) and measures of timing (timing error and CV), with or without one participant with long age-related periods of piano training.

To further investigate the relationship between the properties of the kinematic landmarks and the timing accuracy, the peak finger acceleration (how much the finger was decelerated at arrival on the key surface) and the relative timing error for the successive IOIs were correlated separately for the two groups of pianists. This correlation was significant for the low-FK group, both when the data were combined by participant and rate conditions ($r = -0.404$,

[5] All calculations were based on the detrended IOIs. We repeated the timing analyses on log IOIs (Desain and Honing 1994) to account for timing differences across rates. These alternative calculations yielded qualitatively similar results as those reported below.

$P < 0.05$, $n = 32$) and considered separately for melodies and sequence positions ($r = -0.117$, $P < 0.001$, $n = 1{,}024$). These results underpin the connection: the larger the finger–key surface impact, the more accurately timed the upcoming event would be. The equivalent correlation measures between peak finger acceleration and timing error for the high-FK group did not reach significance ($r = 0.040$, $P = 0.36$, $n = 512$). The same correlations computed within individual pianists held for the majority of the pianists in the low-FK group: five out of eight from the low-FK group showed a significant decrease in timing error with increase in FK landmarks, but none of the high-FK pianists. Thus, timing errors decreased as finger accelerations increased in the low-FK group, but not in the high-FK group: the low-FK group's finger motions indicated different kinematic landmarks across performance rates as the fingers struck the keys, and this group improved most in timing accuracy as FK landmarks increased. In contrast, the high-FK group performed with constantly high FK landmark proportions in all rate conditions; temporal accuracy did not improve across performance rates.

Finally, we considered other measures of group differences potentially related to temporal accuracy: keystroke duration and tone intensity (loudness, measured through MIDI velocity). Keystroke duration refers to the time interval between FK and KB and thus may be related to how far apart in time the resulting tactile sensations are.[6] Keystroke duration was computed only for key presses that contained an FK landmark A two-way ANOVA revealed a significant effect of rate [$F(3,30) = 27.63$, $P < 0.001$] and a significant interaction between rate and group [$F(3,30) = 4.65$, $P < 0.05$], but no significant effect of group. Keystroke durations became monotonically shorter as rate increased (from medium rate 79.3 ms to fast 60.7 ms). Post hoc analyses indicated that the significant interaction was due to the slowest tempo condition at which the low-FK group had longer keystroke durations (85.0 ms) compared with the high-FK group (67.8 ms, Tukey's HSD = 12.39, $P < 0.01$). In the perspective of the sensory accumulator model (SAM, cf. Aschersleben 2002), increased tactile feedback (high-FK group) speeds up central processing so that this information might integrate with the auditory feedback even over a shorter keystroke duration than without increased tactile feedback (low-FK group). The same two-way ANOVA on MIDI velocities yielded a significant main effect of rate [$F(3,30) = 9.55$, $P < 0.001$]. Pianists played slightly louder as the rate increased (66.8 MIDI velocity units at 2 tones/s; 72.8 MIDI velocity units at 7 tones/s), consistent with findings of other studies (Todd 1992; Palmer and Dalla Bella 2004). Neither the effect of group nor the rate × group interaction reached significance; although the two groups played with different kinds of touch, they did not produce significantly louder or softer tones on average.

[6] Goebl et al. (2005) used a similar measure, which they termed "travel time." It referred to the duration between FK and the actual tone onset (hammer-string contact).

Discussion

This study investigated the role of tactile afferent information available to pianists as they produced accurately timed finger sequences in music performance. First, pianists' finger motion trajectories toward keys contained different types and amounts of kinematic landmarks at different performance rates: the faster they played, the more finger–key (FK) landmarks occurred in their finger movements. Finger–key landmarks can arise from the arrival of the finger at the piano key surface. Second, there were differences among pianists regarding the prevalence of finger–key landmarks, especially at slower performance rates. Some pianists showed persistently high proportions at all rates, while the majority of the pianists had low percentages at the slower rates that became as high as the other group at fast rates. Finally, those pianists with the most increase in landmarks across performance rates showed a positive relationship between increased tactile feedback and increased temporal accuracy for the upcoming keystroke.

Moderate rates of performance generated a lower occurrence of finger–key landmarks, whereas the very fast rates used in the current study (which were harder to perform, as evidenced in higher CVs) generated occurrences close to 100%. The largest differences in touch between individual participants were observed at the moderate rates, suggesting that they employed different performance techniques at slowest tempi, and performances became more similar as the performance rate increased. This finding is consistent with the idea that performers have more degrees of freedom in how they perform a sequence at slower rates, when there is more time to plan, than at faster rates, when limited time may restrict the set of possible trajectories. This finding adds new insight as to how pianists' touch is related to the tempo at which they play; previous studies on touch in piano performance addressed this issue solely on the basis of single tones (Ortmann 1925; White 1930; Báron 1958; Askenfelt and Jansson 1990a; Koornhof and van der Walt 1994; Goebl et al. 2005).

Although the present study was conducted on an electronic keyboard to avoid occlusions of pianists' fingertips that can arise with acoustic pianos, responses from the pianists at the end of the experiment suggest that the findings may generalize to acoustic pianos. The pianists indicated high satisfaction with the digital piano used in this study and in particular with the response of the action, suggesting that the participants felt comfortable and supposedly performed as they would have on an acoustic piano. The exact frequencies and range of kinematic landmarks might differ across instruments, due to different masses of the levers moving inside a grand piano action, but we expect that the results would not be qualitatively different; this has yet to be confirmed in future work. A potential limitation of the current study is that kinematic variables were studied only under natural conditions of auditory feedback. It would be interesting to examine the same kinematic variables under various manipulations of auditory feedback, another topic for future investigation.

The finding that maximum finger accelerations at finger–key contact increased as the accuracy of the subsequent inter-onset interval increased was seen in the majority of the pianists (low-FK group), who changed their touch considerably as the performance rate increased. The others (high-FK group) always used high finger accelerations at finger–key contact and did not show improvement in temporal accuracy across performance rates. These findings suggest that tactile feedback available in finger accelerations at key contact aids in planning and executing upcoming events. In particular, the FK landmark was accompanied by increased delay between FK and KB at the slowest performance rates, allowing more accumulation of information over a larger time interval.

Why might tactile information arising at finger–key contact be important, when it is optional? In contrast to the synchronization tasks such as those used by Aschersleben and Prinz (1995), the present study involves a continuation task that requires the maintenance of an established rate without any external temporal feedback: the only feedback available is generated by the performer. Thus, the continuation task is more demanding than synchronization because it relies on the accuracy of internal mechanisms to maintain the timing. Furthermore, one source of tactile feedback that is always present during a key press is the key–bottom contact. Tactile information from the key–bottom contact might suffice for maintaining timing.

However, as key–bottom contact is temporally close to (within 10 ms) the physical onset of the auditory feedback (as measured by the MIDI onset in electronic instruments), a time period much smaller than mean negative asynchronies during synchronization tapping (e.g., Aschersleben and Prinz 1995; Aschersleben et al. 2001), the tactile information from the key–bottom contact may not be perceived as synchronous with the acoustic information that it generates. Tactile feedback from finger–key contact, however, precedes the acoustic onset (earlier by 69 ms on average), and might be perceived as synchronous with the subsequent acoustic onset. Thus, finger–key landmarks may offer a more important trigger for timing control than the key–bottom landmark. The difference in timing between the finger–key and key–bottom landmarks and the resulting acoustic event (the tone) might explain why touch in music performance is important to pianists: it may be a veritable means for regulating timing.

Other sensory information is available to performers in addition to tactile information. Balasubramaniam (2006) suggested that proprioceptive feedback reflected in changes of movement kinematics aids the sensory regulation of timing in the absence of tactile feedback. Participants moved their fingers in synchrony with an auditory pulse "in the air" (without any physical contact to a surface, Balasubramaniam et al. 2004). Asymmetric movement patterns were found with larger accelerations within the downward motion towards the beat, suggesting that such proprioceptive information resulting from increased accelerations provides useful feedback for accurate timing of movements (Balasubramaniam et al. 2004). In piano performance, the downward motion toward a key press is executed with higher finger accelerations than the key releases. In contrast to Balasubramaniam's study, the present study involves both tactile and proprioceptive information during playing. It has been suggested that tactile feedback is more salient than proprioceptive sensations, due to the high density of mechanoreceptor innervation in the fingertip skin and the large cortical areas involved in processing tactile information from the fingers (Jones 1996). How much each component contributes to the sensory regulation of timing is a topic for further research.

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