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Sequential and biomechanical factors constrain timing and motion in tapping
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Abstract

We examined how timing accuracy in tapping sequences is influenced by sequential effects of preceding finger movements and by biomechanical interdependencies among fingers. Skilled pianists tapped sequences at three rates; in each sequence a finger whose motion was more or less independent of other fingers' motion was preceded by a finger to which it was more or less coupled. Less independent fingers and those preceded by a more coupled finger showed more timing error and more change in motion due to the preceding finger's motion; motion change was correlated with shorter intertap intervals and increased with rate. Thus, timing of sequence elements is not independent of the motion trajectories used to produce them; neither motion nor its relationship to timing is invariant across rates.

Keywords: finger tapping, movement, timing

Sequential and biomechanical factors constrain timing and motion in tapping

An important goal in the production of long sequences such as music and speech is to accurately time the individual sequence elements (Palmer, 1997). The movements used to produce sequences of precisely timed elements can be influenced by various constraints, such as preceding or upcoming sequence items (as in speech coarticulation; Farnetani & Recasens, 1999) or biomechanical interdependencies between effectors (as in finger motion enslaving; Hager-Ross & Schieber, 2000). Information-processing approaches suggest that the timing of sequence elements in production is independent of the movements used to produce them (Schmidt, 1975, 2003; Wing, 2002), whereas dynamical systems approaches suggest that timing is an emergent property of those movements (Kelso, 1995, 2001). The current study examined the influence of sequential and biomechanical constraints on timing, motion, and the relationship between them in pianists' tapping of finger movement sequences.

Pianists are skilled at accurately timing long sequences of finger movements. They produce highly consistent expressive timing patterns across repeated performances (Palmer, 1989; Repp, 1995) and perform isochronous sequences with low timing variability (Pfordresher & Palmer, 2002). Pianists' training often involves extensive practice of finger exercises designed to overcome timing irregularities that may be caused by biomechanical interdependencies between fingers (Jerde, Santello, Flanders, & Soechting, 2006). Despite this practice, pianists' motion trajectories still reveal influences of biomechanical constraints (Loehr & Palmer, 2007). Finger motions are constrained by biomechanical interdependencies such as the soft tissues in the webs between fingers and connections between the tendons of the finger muscles (Schieber & Santello, 2004). As a result, producing a motion with one finger causes movement in other fingers. This is particularly true for Finger 4 (the ring finger), the most coupled of the fingers. Finger 2, the least coupled of the fingers (excluding the thumb), is relatively less affected by other fingers' motion (Hager-Ross & Schieber, 2000). In addition, physically adjacent fingers have more impact on a given finger's motion than do non-adjacent fingers (Hager-Ross & Schieber, 2000; Loehr & Palmer, 2007). These biomechanical constraints may cause preceding finger taps in a sequence to influence a given finger's motion. For example, Finger 4's velocity and acceleration change most when it is preceded by a physically adjacent finger compared to when it is preceded by a non-adjacent finger (Loehr & Palmer, 2007). In sum, a given finger's motion depends both on the degree to which it moves independently of other fingers and on the sequence elements that precede it.

Do these constraints on finger motion also systematically affect the timing of sequence elements? Information processing and dynamical systems approaches to movement timing suggest different relationships between motion and timing. According to an information-processing approach, time is represented independently of movement parameters (Wing, 2002). The two-level timing model proposed by Wing and Kristofferson (1973a, 1973b) attributes timing variance to the independent processes of central timing and peripheral motor implementation. Extended versions of the model successfully account for timing in paced and unpaced unimanual tapping, rhythm production, and bimanual tapping (Wing, 2002). This suggests that timing accuracy may be independent of motion constraints. According to the dynamical systems approach, timing is not controlled explicitly but emerges from the dynamics of the movements themselves (Kelso, 1995, 2001; Schöner, 2002; Turvey, 1990). Movement timing therefore cannot be separated from other aspects of the movement. Researchers have

argued that emergent timing characterizes continuous movement tasks such as circle drawing but not tasks in which movements are marked by discrete events such as tapping a table (Zelaznik et al., 2005). Evidence from timed finger movements indicates an association between timing error and the degree of velocity asymmetry between the flexion and extension phases of contact-free finger oscillations (Balasubramaniam, Wing, & Daffertshofter, 2004), which suggests that timing accuracy is not independent of motion constraints in contact-free finger movement. We sought to determine whether timing accuracy is independent of motion constraints in sequences of finger taps; specifically, we examined whether the influence of sequential and biomechanical constraints on motion trajectories preceding finger-table contact impacts the accuracy with which taps are timed.

The information processing and dynamical systems views also make different predictions with respect to how the relationship between motion and timing changes with rate. From a generalized motor program perspective, movements are thought to be controlled by abstract representations that specify invariant features of the movements such as the necessary muscle contractions and the temporal relations between them (Heuer, Schmidt, & Ghodsian, 1995). These invariant features remain constant across changes in rate (Heuer et al., 1995; Schmidt, 1985; 2003). Other findings indicate that rate manipulations can yield transitions between different types of motion trajectories (Diedrich & Warren, 1998) and changes in the relative timing of two effectors' motions (Kelso, 1995). The examination of rate invariance in the expressive timing of music performance has met with mixed results. Desain and Honing (1994) showed that expressive timing of music performance did not scale proportionally across changes in tempo, whereas Repp (1994) reported expressive performances in which timing was close to invariant across rates. Departures from rate invariance have also been documented when timing in a musical task is affected by finger constraints (MacKenzie & Van Eerd, 1990); thus, it is possible that departures from rate invariance occur when timing is constrained by motor variables. Changes in the relationship between timing and motion across rates would provide support for this hypothesis.

We examined whether pianists' metronomic timing of finger taps depends on the movements used to produce the taps and how this relationship changes with rate. A tapping task was employed to control sequential relationships between finger movements, which are often quite complex in music performance. We manipulated biomechanical constraints by examining the motion of Fingers 2 and 4, the least and most dependent fingers, respectively, when preceded by a physically adjacent (strongly coupled) or non-adjacent (weakly coupled) finger in the sequence. Given that pianists' finger motions show influences of biomechanical constraints (Loehr & Palmer, 1997), we hypothesized that changes in motion due to finger coupling and preceding finger adjacency should be associated with decreased timing accuracy. We also hypothesized that faster rates might reveal a stronger relationship between timing and motion than slower rates because the degree to which a given finger's motion affects other fingers' motion increases with rate (Hager-Ross & Schieber, 2000).

Method

Participants

Four male and twelve female pianists, ranging in age from 19 to 39 years ($M = 23.9$, $SD = 5.23$), were recruited from the McGill community for this study. All participants had at least 7 years of piano instruction ($M = 10.28$, $SD = 2.47$), and all but one were right-handed. Experienced pianists were asked to participate so as to maximize potential for finger independence and to ensure familiarity with producing sequences of finger movements at a metronomic rate. All subjects gave informed consent according to the procedures approved by the Institutional Review Board of McGill University and all procedures were consistent with the Helsinki Declaration.

Stimulus Materials.

Eight 4-finger sequences with no repeating finger movements within a cycle were designed for the study. The sequences are presented in Table 1; fingers are numbered from 1 (thumb) to 5 (pinky). Each sequence contained either Finger 4 (the most coupled of the fingers) or Finger 2 (the least coupled of the fingers), termed the critical finger of the sequence. Note that Finger 2 could appear in sequences in which Finger 4 was the critical finger and vice versa. Within each sequence, the critical finger was preceded by either a physically adjacent finger (more strongly coupled to the critical finger; top two rows of Table 1) or by a non-adjacent finger (less coupled; bottom two rows of Table 1). Both critical finger and preceding finger adjacency were manipulations of coupling between fingers; the terms 'critical finger' and 'preceding finger adjacency' are used here to distinguish the manipulations. The serial position of the critical finger was balanced across the sequences. Each sequence was presented as a set of four finger movements to be tapped 16 times, forming a 64-tap sequence.

Equipment

The three-dimensional motion of each finger was recorded using Optotrak's (Northern Digital Inc., Waterloo, Ontario, Canada) infrared-emitting diodes (IREDs) at a sampling rate of 200 Hz. Optotrak's active sensors measure the 3-dimensional position of the markers with a precision of 0.1 mm at high sampling rates (Pettito, Holowka, Sergio, Levy, & Ostry, 2004). One diode was placed on the fingernail of each right hand finger close to the tip of the fingernail. For the thumb, a diode was placed on the skin to the right of the fingernail to ensure that the diode was facing the same direction as the diodes on the fingers. A sixth diode was placed on the head of the ulna, the bone protruding on the side of the wrist. As the IREDs are small and lightweight, interference with tapping was minimal. Metronome pulses were produced by a Dr. Beat DB-90 metronome and were presented over AKG-K271 headphones.

Design and Procedure

Each participant tapped all eight sequences at each of three rates (550, 400, and 250 ms/tap) in a within-subjects design. Four pseudo-random trial orders of the eight stimuli were created with the constraint that Finger 2 trials alternated with Finger 4 trials. Each participant was randomly assigned to one of the orders across three blocks of eight trials each. Metronome rates were presented in fixed order (slow to fast) across the three blocks, so that participants tapped all eight sequences at one rate before moving on to the next rate.

Pianists were asked to tap the four-finger patterns on a tabletop with the right hand, the dominant hand in piano performance tasks (Palmer & van de Sande, 1993; Peters, 1985), in a synchronization-continuation paradigm. In each trial, participants were presented with the written four-finger sequence to be tapped and they practiced tapping it until they could produce it from memory. Participants were instructed to tap with each finger falling within the width of a white piano key as indicated by a sheet of paper on the tabletop. The metronome was sounded and participants synchronized their tapping for four cycles of the stimulus pattern (16 taps). Then the metronome stopped and the participants continued tapping for another twelve cycles (48 taps) at the pace set by the metronome. Each trial contained three repetitions of this task. Participants therefore tapped each sequence cycle 48 times within each of three blocks over the course of the experiment. Participants also completed a questionnaire about their musical backgrounds. The session took approximately one hour, and participants received a nominal fee.

Data Analysis

The synchronization cycles and the first and last continuation cycles were dropped from analysis, leaving 10 cycles per trial; a total of 120 finger taps from each trial (4 taps x 10 cycles x 3 repetitions) were included in both the timing and motion analyses. Finger tap onsets were determined from the raw kinematic data based on the finger's peak acceleration, which occurred when the finger was stopped by contact with the table. Thin lines in Figure 1 show the position, velocity, and acceleration curves for one participant's Finger 4 motion during two tapping cycles of the 3 1 4 5 sequence. The vertical lines mark the arrival time of each tap as determined from peak acceleration in the raw data; for example, event 7 marks the time at which Finger 4 made contact with the table and event 6 marks the time at which Finger 1 tapped. Intertap intervals (ITIs) for each finger were defined as the time interval (ms) from the preceding finger's to the critical finger's contact with the table (from event 6 to event 7 in Figure 1). Because some performances showed a tendency to speed up over a 16-cycle repetition, the ITIs were adjusted for linear tempo drift by adding the mean ITI to the residuals from a regression of ITI on sequence position, as in previous synchronization-continuation tapping studies (e.g., Pfordresher & Palmer, 2002; Zelaznik, Spencer, & Ivry, 2002). Further timing analyses were conducted on the detrended values.

The motion analyses focus on finger motion in the z-plane (height above the tabletop), as the tapping patterns required little movement in the x- and y-planes. Occasional missing values in the three-dimensional motion data (less than 0.01% of all samples) due to occlusion factors were replaced using linear interpolation. Analyses of the finger motion trajectories were conducted with functional data analysis techniques (Ramsay & Silverman, 2005). B-splines were chosen to fit the discrete data; spline functions are commonly used to fit motion data which are not strictly periodic (Ramsay, 2000; Ramsay, Munhall, Gracco, & Ostry, 1996; Ramsay & Silverman, 2005). Order 6 splines were fit to the second derivative (acceleration) of the motion data using a 4:1 ratio of data observations to splines. The data were smoothed using a roughness penalty on the fourth derivative ($\lambda = 10^{-13}$, within .00001 of the generalized cross-validation estimate; Ramsay & Silverman, 2005), which allowed for control of the smoothness of the second derivative. Thick lines in Figure 1 show the smoothed position, velocity, and acceleration curves superimposed over the raw data. The smoothed data were interpolated to create 80 equally spaced data points between successive finger tap onsets; the acceleration curves were

aligned (co-registered) across fingers and rates in terms of the arrival time of the finger producing each tap.

Results

Intertap intervals

ITIs were very close to prescribed metronome rates (mean fast ITI = 245.71 ms (prescribed = 250 ms); medium ITI = 397.40 (prescribed = 400 ms); slow ITI = 544.33 ms (prescribed = 550 ms)), but significantly shorter than the prescribed rate for each rate, $ts > 13.75$, $ps < .01$. Shortening of ITIs during the continuation phase of the synchronization-continuation task is consistent with previous findings in tapping (Flach, 2005) and was not due to systematic shortening of any particular ITI within the cycle. The mean signed ITI error, defined as (observed – expected) / expected ITI (the same as "constant error," Schmidt & Lee, 1999), was analyzed by rate (fast / medium / slow), critical finger (Finger 2 / 4), and preceding finger (adjacent / non-adjacent). The mean percent ITI error is shown in Figure 2 for each rate, finger, and adjacency condition. An analysis of variance (ANOVA) indicated shorter ITIs than expected when the taps were produced by Finger 4, $F(1, 15) = 15.41$, $p < .01$, and when they were preceded by a physically adjacent finger, $F(1, 15) = 25.25$, $p < .01$. There was no main effect of rate on timing error. There was a rate by adjacency interaction, $F(2, 30) = 13.54$, $p < .01$, and the three-way interaction between rate, adjacency, and critical finger was also significant, $F(2, 30) = 4.98$, $p < .02$. The difference between adjacent and non-adjacent preceding fingers was only significant at the fast rate (Tukey's HSD = 2.50, $p < .05$), as shown in Figure 2. Thus, ITIs preceding a finger tap were less accurate (shortened) when biomechanical constraints were imposed by an adjacent preceding finger and by the dependence of the critical finger, with larger effects occurring at the fast rate.

Motion trajectories

Figure 3 shows mean acceleration trajectories at each rate for Finger 2 (top half of each panel) and Finger 4 (bottom half) during their taps, which occurred at 0 ms, and during the preceding finger's tap (marked by the solid vertical line at 250, 400, or 550 ms before the critical finger's tap). To determine when the finger trajectories differed across conditions, a functional ANOVA (Ramsay et al., 1996; Ramsay & Silverman, 2005) was conducted on the critical finger's acceleration by rate, critical finger (2 or 4), and preceding finger adjacency[1]. There were main effects of rate (critical $F(2, 30) = 8.77$, $p < .001$), critical finger (critical $F(1, 15) = 16.59$, $p < .001$), and preceding finger adjacency (critical $F(1, 15) = 16.59$, $p < .001$), and interactions between rate and critical finger (critical $F(2, 30) = 8.77$, $p < .001$), rate and preceding finger adjacency (critical $F(2, 30) = 8.77$, $p < .001$), and critical finger and preceding finger adjacency (critical $F(1, 15) = 16.59$, $p < .001$). The three-way interaction was also significant (critical $F(2, 30) = 8.77$, $p < .001$).

Of most interest was the three-way interaction between rate, critical finger, and preceding finger adjacency. The horizontal brackets in Figure 3 indicate where the differences in preceding finger adjacency reached significance within each critical finger and rate (critical q for Tukey's HSD = 7.15, $p < .001$). The adjacency of the preceding finger tap influenced critical finger acceleration trajectories during both the preceding finger's and the critical finger's taps. At the

fast rate (Figure 3, top panel), both critical fingers showed greater changes in acceleration during the preceding finger's tap when they were preceded by a physically adjacent finger than when they were preceded a non-adjacent finger. This difference was larger and encompassed more of the trajectory for Finger 4. During the critical finger's tap, only Finger 4 showed smaller changes in acceleration when it was preceded by a physically adjacent finger than when it was preceded by a non-adjacent finger. The same pattern of differences was seen at the medium and slow rates (Figure 3, middle and bottom panels), although differences between adjacent and non-adjacent preceding fingers were smaller and encompassed relatively less of the (longer) intertap intervals. In sum, acceleration trajectories were influenced by the biomechanical constraints imposed by an adjacent preceding finger and by the independence of the critical finger, with larger effects occurring at the fast rate.

Similarity between trajectories

The mean acceleration trajectories of Fingers 2 (top graph) and 4 (bottom graph) and of the physically adjacent preceding finger (dashed lines) are shown in Figure 4 for the fast rate. The figure illustrates that acceleration changes in the preceding finger's motion as it approached the table (a large negative peak followed by a large positive peak around 250 ms) were followed by smaller but similar changes in the critical finger's acceleration. To measure this similarity, we calculated the correlation between the preceding finger's acceleration and the critical finger's acceleration during the preceding finger's tap, defined as beginning when the preceding finger's movement toward the table reached 3% of its maximum negative acceleration and ending when positive acceleration fell to 3% of its maximum (marked by the dashed vertical lines in Figure 4). Lag-n correlations between preceding and critical finger trajectories were calculated over a lag of 0 - 120 ms; the average lag of maximum correlation was 24.19 ms and did not differ across rates ($p > .05$). Figure 5 shows the mean values of the maximum correlations by critical finger and preceding finger adjacency. As expected, the trajectories of critical and preceding fingers were most highly correlated when the preceding finger was adjacent, $F(1, 15) = 46.12$, $p < .01$. There was also a significant interaction of critical finger and adjacency, $F(1, 15) = 8.61$, $p = .01$, indicating greater differences between adjacent and non-adjacent preceding finger conditions for Finger 4 than for Finger 2 (Tukey's HSD = 0.25, $p < .05$). There was no main effect or interaction with rate. Thus, trajectories were more similar when the biomechanical constraints were imposed by an adjacent preceding finger and when the critical finger was less independent, regardless of the rate at which sequences were produced.

Preceding finger's influence on critical finger's trajectory

We also examined the impact of the preceding finger's acceleration on the critical finger's acceleration in terms of the amount of change in critical finger acceleration following the preceding finger's trajectory. The amount of change was defined as the difference between the first minimum and subsequent maximum in the critical finger's acceleration (marked by vertical arrows in Figure 4) following the onset of the preceding finger's movement toward the table as defined above. Figure 6 shows the mean amount of change at each rate by critical finger and by preceding finger adjacency. Critical finger acceleration changes were larger for Finger 4 than Finger 2, $F(1, 15) = 42.67$, $p < .01$, when the preceding finger was adjacent, $F(1, 15) = 68.92$, $p < .01$, and at faster rates, $F(2, 30) = 5.19$, $p < .05$. There were significant interactions between critical finger and rate, $F(2, 30) = 9.19$, $p < .01$, adjacency and rate, $F(2, 30) = 15.90$, p

< .01, and adjacency and critical finger, $F(1, 15) = 38.44$, $p < .01$; the three-way interaction was also significant, $F(2, 30) = 8.42$, $p < .01$. Post-hoc comparisons indicated that differences between adjacent and non-adjacent preceding fingers were largest for Finger 4 at the fast rate (Tukey's HSD = 1.05, $p < .05$). Thus, an adjacent preceding finger had the greatest influence on Finger 4's motion at the fast rate, indicating that the biomechanical constraints imposed by an adjacent preceding finger depended on both the (in)dependence of the critical finger and the rate of sequence production.

Correlations between motion and timing error

Finally, we examined the relationship between the critical fingers' timing error and the influence of preceding finger trajectories on critical fingers' trajectories. Correlations were calculated between the mean signed timing error and mean acceleration change for each 10-cycle repetition. Amount of acceleration change in the critical finger's trajectory correlated negatively with timing error at each of the three rates, $ps < .001$; greater acceleration change was associated with shorter ITIs. An ANOVA on the correlations within participants revealed that correlations were higher at the fast rate (mean $r = -.41$ across participants) than at the medium and slow rates (mean rs = . -.15 and -19, respectively), $F(2, 30) = 6.62$, $p < .01$, and when the preceding finger was adjacent ($r = -.17$) than when it was non-adjacent ($r = -.14$), $F(1, 15) = 12.29$, $p < .01$. Thus, timing error and acceleration change increased with the biomechanical constraints imposed by a preceding finger, with the largest correspondence occurring at the fastest rate.

Differences among preceding fingers

To ensure that the results were consistent across preceding fingers, the analyses were repeated while excluding the thumb, whose connections to Finger 2 differ from connections between adjacent fingers both biomechanically and with respect to common motor unit inputs (Lang & Schieber, 2003; Schieber & Santello, 2004). This reanalysis controlled for the adjacent preceding finger: the same finger (Finger 3) preceded both critical fingers' motion. Only half of the original sequences were included in these analyses (which reduced statistical power): those in which Finger 3 was the adjacent preceding finger (for both critical fingers) and those in which Finger 2 was the non-adjacent preceding finger for critical finger 4 and vice versa. Overall, the pattern of results with this limited data set was similar to the results from the full data set; Finger 4 showed shorter intertap intervals, greater similarity to the preceding finger's acceleration, and more acceleration change when the preceding finger was adjacent than when the preceding finger was non-adjacent, and differences between adjacency conditions were smaller for Finger 2. Functional ANOVAs indicated the same significant trajectory regions as in the full analysis; correlations between timing error and acceleration change increased when the thumb was excluded from analysis, consistent with the expectation that the thumb's motion would be more independent of either coupled finger.

Discussion

Biomechanical and sequential constraints imposed by interdependencies among fingers influenced both timing and motion in a sequential finger tapping task. Pianists tapped sequences in which a more or less independent finger (Finger 2 or 4) was preceded by a finger to which it was more or less coupled (physically adjacent or non-adjacent), at each of three rates. Motion

trajectories produced by the less independent Finger 4 and preceded by a more coupled finger showed more influence of the preceding finger's motion and resulted in more timing error (shorter intertap intervals). Increased influence of the preceding finger's motion was correlated with increased timing error for the critical finger's tap. These effects were strongest at faster tapping rates. We discuss the ramifications of these interactions of motion and timing below.

Influence of biomechanical and sequential constraints on motion and timing

The influence of biomechanical (finger independence) and sequential (preceding finger) constraints on finger motion replicates previous findings (Hager-Ross & Schieber, 2000; Li, Dun, Harkness, & Brininger, 2004) and extends them beyond individual finger movements to sequences of timed finger movements. Loehr and Palmer (2007) showed that when the preceding finger was physically adjacent (compared to non-adjacent), Finger 4 showed less change in its acceleration during its own tap and more change during the preceding finger's tap. Loehr and Palmer's (2007) findings were measured only at one tapping rate (400 ms/tap); the current results extend these findings to show that the degree of influence is greatest at fast rates. The current results also extend previous findings to show that Finger 2's motion is less influenced by the adjacency of the preceding finger than Finger 4's motion; in particular, Finger 2's motion during its tap is not affected by preceding finger adjacency.

Finger independence and preceding finger adjacency also influenced timing accuracy, despite pianists' high level of skill at producing accurately timed sequences (Palmer, 1989; Pfordresher & Palmer, 2002; Repp, 1995) and years of practice designed to overcome finger coupling constraints (Jerde et al., 2006). Timing was therefore not independent of the biomechanical and sequential constraints imposed by the effectors used to produce the timing. Finger differences in the impact of biomechanical constraints on acceleration trajectories may explain finger differences in timing accuracy. It is possible that Finger 2 produced more accurate timing than Finger 4 because its motion is relatively independent of the preceding finger's motion, particularly over the interval leading up to its contact with the table. The current study documented timing differences for intertap intervals measured from the preceding finger's tap to the critical finger's tap (i.e., over the interval leading up to the critical finger's tap). Loehr and Palmer (2007), who measured the interval following the critical finger's tap, did not find timing differences between fingers for the one tapping rate reported in their study. Timing differences may be evident only for the interval leading to table contact because this interval is more important to determining onset accuracy than the interval following table contact (both intervals are measured relative to the onset of the critical finger's tap). Acceleration trajectories are also less likely to differ between fingers after table contact, when the finger's motion is highly constrained by having just made contact with the table.

Theoretical and practical implications

Biomechanical and sequential constraints influenced both timing accuracy and finger accelerations; increased influence of sequential constraints on acceleration was associated with increased timing error (shorter intertap intervals). In particular, the preceding fingers' motion led to changes in the critical fingers' motion which were then associated with decreased timing accuracy. These findings suggest that at least some portion of timing error arises from properties of the motion trajectories used to produce the timing (the degree to which motion is influenced

by other fingers' motion). Doumas and Wing (2007) argued that a lack of correlation between the timing and velocity of finger movements in a bimanual tapping task is consistent with the view that timing is centrally specified and independent of motion trajectories. The correlations reported in the current study, in contrast, indicate that timing was not independent of finger accelerations, particularly at faster production rates. These findings are more consistent with the dynamical systems view in which timing emerges from the dynamics of motion (Kelso, 1995; Schöner, 2002; Turvey, 1990). In addition, the current findings suggest that timing is not independent of movement trajectories that occur between discrete events (finger taps).

Rate-dependent changes in motion trajectories and their relationship with timing are also consistent with a dynamical systems view. The interactions of motion with rate reported here are consistent with previous findings that motion trajectories change across rates (Balasubramian et al., 2004; Diedrich & Warren, 1998) and that the timing of motion components does not scale with rate (Gentner, 1987). It is possible that timing may exhibit more independence from motion in sequences that are near preferred tapping rates; the slower rates, which demonstrated the most independence of timing and motion, were near tappers' preferred tempo of approximately 400-600 ms/tap (Fraisse, 1982; Pfordresher & Palmer, 2002; van Noorden & Moelants, 1999). A greater independence at slower rates also coincides with the fact that pianists are often advised to practice fast passages of music at slower rates and gradually increase to the desired performance speed. The current results are also consistent with findings that the influence of finger constraints on timing increases with rate in evenly timed musical tasks (MacKenzie & Van Eerd, 1990); when pianists perform musical scales, onset intervals between tones differ depending on which fingers are used to produce the tones, and these differences become more pronounced as tempo increases. Rate-dependent changes in timing may be a result of the increased impact of biomechanical and sequential constraints on motion trajectories and timing accuracy that occurs as rate increases.

Conclusions

In sum, timing accuracy was affected by biomechanical and sequential constraints on finger motion in trained pianists' tapping, although timing error was small; the relationship between timing and motion was stronger at faster rates. These results suggest that the timing of sequence elements depends on the motion trajectories used to produce them and indicate that neither motion nor the relationship between motion and timing is invariant across changes in rate. Rate-dependent effects on timing and motion may also contribute to failures of rate invariance found in music performance. Finally, these findings highlight the need to examine the sequential context of movements when assessing the relationship between timing and motion.

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Author Note

Footnotes

[1]The functional ANOVA compared smoothed acceleration curves sampled at 120 equally spaced intervals beginning before the preceding finger tapped the table (halfway between the preceding finger's tap and the tap that preceded it) and ending with the critical finger's tap. This analysis yielded an *F*-value as a function of time for each main effect and interaction. Effects were deemed significant when they exceeded the threshold *F*-value for the corresponding degrees of freedom. A conservative threshold of $p < .001$ was used to adjust for the multiple comparisons (Loehr & Palmer, 2007; Vines, Krumhansl, Wanderley, & Levitin, 2006).

Figure Captions

Figure 1. Raw and smoothed position (height; top panel), velocity (middle panel), and acceleration (bottom panel) curves for one participant's Finger 4 motion during two tapping cycles of the 3 1 4 5 sequence. Vertical lines mark the arrival time of each tap.

Figure 2. Mean ITI error ([observed – expected] / expected ITI; + *SE*) for each rate by critical finger and preceding finger adjacency.

Figure 3. Mean acceleration trajectories of each critical finger during its own and the preceding finger's tap, when preceded by an adjacent or non-adjacent finger, at the fast (top panel), medium (middle panel), and slow rates (bottom panel). Brackets beneath trajectories indicate regions where differences between adjacency conditions reached significance at $p < .001$.

Figure 4. Mean acceleration trajectories of each critical finger and the physically adjacent preceding finger at the fast rate. Dashed vertical lines indicate the beginning and end of the preceding finger's movement toward the table. Arrows indicate the first minimum and subsequent maximum in the critical finger's acceleration following the onset of the preceding finger's movement toward the table.

Figure 5. Mean correlations (+ *SE*) between preceding and critical finger trajectories, by critical finger and preceding finger adjacency.

Figure 6. Mean critical finger acceleration change (+ *SE*) following the preceding finger's tap, by critical finger and preceding finger adjacency for each rate.

Table 1

One cycle of each sequence. The critical finger is in bold italics and the finger preceding

it is underlined.

	Critical Finger Coupling	
Preceding Finger	Finger 4 (Strong)	Finger 2 (Weak)
Physically Adjacent	<u>3</u> *4* 2 1	<u>3</u> *2* 4 1
	1 2 <u>5</u> *4*	3 <u>1</u> *2* 5
Non-Adjacent	3 <u>1</u> *4* 5	*2* 3 5 <u>4</u>
	4 3 5 <u>2</u>	1 4 <u>5</u> *2*

(A) FAST

Preceding Finger
Adjacent
Nonadjacent

ITI Error (%)

Finger 2   Finger 4

(B) MEDIUM

ITI Error (%)

Finger 2   Finger 4

(C) SLOW

ITI Error (%)

Finger 2   Finger 4

Preceding Finger's Tap↓   Critical Finger's Tap↓

(A) FAST

Preceding Finger
— Adjacent
-- Nonadjacent

Finger 2
Acceleration (m/s²)

Finger 4

375   250   125   0

(B) MEDIUM

Finger 2
Acceleration (m/s²)

Finger 4

600   400   200   0

(C) SLOW

Finger 2
Acceleration (m/s²)

Finger 4

825   550   275   0
Time before critical finger's tap (ms)

(A) FAST

Preceding Finger
Adjacent
Nonadjacent

Acceleration Change (m/s^2)

Finger 2   Finger 4

(B) MEDIUM

Acceleration Change (m/s^2)

Finger 2   Finger 4

(C) SLOW

Acceleration Change (m/s^2)

Finger 2   Finger 4