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RESEARCH ARTICLE

Cognitive and biomechanical influences in pianists' finger tapping

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Abstract Movement sequences such as typing or tapping display important interactions among finger movements arising from anticipatory motion (preparing for upcoming events) and coupling (non-independence among fingers). We examined pianists' finger tapping for the influence of cognitive chunking processes and biomechanical coupling constraints. In a synchronization-continuation task, pianists repeatedly tapped four-finger sequences that differed in terms of the chunks that formed subsequences and in the transitions among physically adjacent or non-adjacent fingers. Chunking influenced intertap intervals, regardless of the particular fingers tapped; the final tap of each chunk was lengthened and less variable relative to other taps. The particular fingers tapped influenced peak finger heights, consistency of motion, and velocity–acceleration patterns, regardless of chunking. Thus, cognitive constraints influenced timing, whereas biomechanical factors influenced motion trajectories. These findings provide an important caveat for study of anticipatory motion by documenting the influence of biomechanical coupling on motion trajectories.

Keywords Tapping · Chunking · Coupling · Motion · Timing

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Introduction

In action sequences such as music and speech, movements that produce sequence elements are often influenced by the movements that generate surrounding elements. For example, when pianists perform music that begins with the same series of keystrokes but diverges mid-sequence, pianists' finger movements change one to two keystrokes before the point of divergence (Engel et al. 1997). Likewise, pianists' finger motions change in velocity and acceleration one to three events before a keypress (Palmer and Dalla Bella 2004) and violinists' fingers begin moving toward a string one event before its depression (Baader et al. 2005), suggesting that motion reflects planning of upcoming movements.

Finger movements in action sequences may also be constrained by biomechanical and/or neural factors that can contribute to lack of independence among neighboring fingers (Baader et al. 2005; Slobounov et al. 2002). Movement interactions among fingers within a hand that arise during force production tasks have been examined in terms of peripheral factors, including shared muscles and passive connections (Leijnse et al. 1993; Li et al. 1998) and in terms of central (neural) organization of fingers into a structural unit (Latash et al. 1998; see Li et al. 2000). These findings suggest that both peripheral and central factors contribute to performance on multi-finger tasks. Most of these studies, however, rely on force production tasks in which the timing goals of movement are less important. Findings from tasks that require fine temporal goals, such as Morse code tapping (Klapp 1977) or music performance (Meyer and Palmer 2003), suggest that the timing of movement sequences may be prepared independently of the muscle commands used to produce the timing (Summers 1981). We test here whether cognitive and biomechanical factors affect finger motion in a tapping task, which requires precise timing of movement goals.

One cognitive constraint that influences the timing of sequences is chunking, in which sequences of movements are organized into a hierarchy of subsequences (Rosenbaum et al. 1983; Sakai et al. 2004). Chunking has been observed in a variety of motor tasks in which participants produce movements under speeded response conditions, including serial reaction-time tasks (e.g., Koch and Hoffman 2000), 2 × *N* tasks (e.g., Sakai et al. 2003), and finger tapping tasks (Povel and Collard 1982; Rosenbaum et al. 1983). Chunks often correspond to changes in the structure of the sequence and are marked by longer latencies at the end of each chunk (Rosenbaum et al. 1983; Sakai et al. 2004). Povel and Collard (1982) had participants tap repetitions of the sequence (4 3 2 3 4 5) with the fingers of the right hand (1 = thumb). The sequential structure was designed to support chunking into two groups, (4 3 2) (3 4 5), and the produced intertap intervals reflected this structure: Longer intertap intervals occurred after the third and sixth elements. Furthermore, chunking occurred independently of the particular finger transitions required. When participants tapped a sequence with the same series of finger transitions but a different starting point (e.g., 3 2 3 4 5 4), the pattern of intertap intervals retained longer intervals after the third and sixth elements. Thus, participants' cognitive representations of chunks within the sequence, rather than the particular fingers used to produce those chunks, determined the timing of intertap intervals (Povel and Collard 1982).

Biomechanical constraints that influence interactions among finger movements include factors such as the soft tissues in the webs between fingers and connections between the tendons of the finger muscles (Schieber and Santello 2004). The partial dependencies among fingers are evidenced in force production tasks (e.g., Slobounov et al. 2002) and flexion/extension tasks (e.g., Hager-Ross and Schieber 2000; Li et al. 2004). Producing a force with one finger (the master finger) causes forces to be produced by the other fingers (slave fingers); this phenomenon has been termed force enslaving (Slobounov et al. 2002). Similarly, flexing and extending a given finger causes movement in other fingers (Hager-Ross and Schieber 2000; Li et al. 2004). In both tasks, the largest degree of enslavement occurs between the master finger and its physically adjacent fingers. Additionally, Finger 4 is most enslaved to the other fingers and Fingers 1 and 2 are least enslaved (Hager-Ross and Schieber 2000; Li et al. 2004; Slobounov et al. 2002). Together, these results suggest that coupling among fingers is likely to affect sequence production, particularly when the movement of Finger 4 and its physically adjacent fingers is considered.

The current study examined the influence of chunking and finger coupling on timing and motion in a finger tapping task with musically trained participants, who are experienced at producing timed sequences and practice musical exercises designed to reduce finger coupling. Participants tapped finger sequences that contained the same series of finger transitions but differed in terms of start position (starting finger) in the sequence. If timing or motion depends on biomechanical constraints, then changing the start position should alter sequence position effects as the finger producing each sequence position changes. If timing or motion depends on chunking (Povel and Collard 1982), then changing the start position should not alter the sequence position effects. We also examined whether Finger 4's motion (a highly coupled finger) prior to its tap depended on the motion of the preceding finger. If biomechanical constraints influence finger taps, then Finger 4's motion should differ depending on whether an adjacent or non-adjacent finger preceded it in the sequence.

Method

Participants

One male and eleven female pianists, ranging in age from 18 to 36 years ($M = 23.3$, $SD = 4.85$), were recruited from the McGill community for this study. All participants had at least 7 years of experience playing the piano, $M = 13.67$, range = 7–23 years, and all but one were right-handed.[1] Experienced pianists were asked to participate so as to maximize potential for finger independence and to ensure familiarity with tapping 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

Four 4-finger sequences with no repeating finger movements were created, labeled "normal" sequences in

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[1] The pattern of results did not change when the left-handed participant was dropped from analysis; therefore, analyses included all 12 participants.

Table 1; fingers are numbered from 1 to 5 starting with the thumb. All sequences were shifted to change the finger that began the sequence, labeled "shifted" sequences in Table 1. Within each sequence, Finger 4 was preceded by either a physically adjacent finger (top two rows of Table 1) or by a non-adjacent finger (bottom two rows of Table 1). The sequences were constrained such that the serial position of Finger 4 was balanced across the sequences. Each sequence was presented as a set of four finger movements to be tapped repeatedly, forming a 64-tap sequence; participants were expected to chunk the sequences into four-tap chunks.[2]

Equipment

The three-dimensional motion of each finger was recorded with Optotrak's (Northern Digital Inc., Waterloo, ON, Canada) infrared-emitting diodes (IREDs) at a sampling rate of 200 Hz. Optotrak's active sensors measure the trajectory of motion with a precision of 0.1 mm at high sampling rates (Pettito et al. 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.

Design and procedure

Normal and shifted versions of each of the four sequences were presented to each participant in a within-subjects design. Four pseudo-random trial orders of the eight stimuli were created with the following constraints: a trial containing a normal pattern occurred before the trial consisting of its shifted equivalent half of the time, and a normal pattern and its shifted equivalent never occurred successively. Each participant was randomly assigned to one of the orders across two blocks of eight trials each.

Table 1 One cycle of each sequence

Preceding finger	Normal	Shifted
Physically adjacent	$(\underline{3}\ 4\ 2\ 1)$ $(2\ 1\ \underline{5}\ 4)$	$(1\ \underline{3}\ 4\ 2)$ $(4\ 2\ 1\ \underline{5})$
Non-adjacent	$(3\ \underline{1}\ 4\ 5)$ $(4\ 3\ 5\ \underline{2})$	$(\underline{1}\ 4\ 5\ 3)$ $(3\ 5\ \underline{2}\ 4)$

The finger preceding Finger 4 is underlined and four-tap subsequences are enclosed in parentheses

Pianists were asked to tap the four-finger patterns on a tabletop with the right hand, the dominant hand in piano performance tasks (Palmer and 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 piano key as indicated by a sheet of paper on the tabletop. A metronome was sounded at 400 ms per interonset interval 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 12 cycles (48 taps) at the pace set by the metronome. Each trial contained three repetitions of the 16 cycles of the sequence. Participants therefore tapped each stimulus cycle 48 times within each of two blocks over the course of the experiment. Participants also completed a questionnaire about their musical backgrounds. Participation in the experiment took approximately 1 h, and participants received a nominal fee.

Data analysis

The first and last continuation tapping cycles were dropped from analysis; a total of 120 fingertaps from each trial (three stimulus repetitions) were included in both the timing and motion analyses. Finger tap onsets were determined from the kinematic data based on the first change from negative to positive velocity that occurred after the first large decrease in finger height (indicating movement toward the table) below a threshold of 20% of the maximum finger height. Intertap intervals (ITIs) were defined as the time interval (ms) from one finger tap (defined here as event onset) to the next. 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 and Palmer 2002; Zelaznik et al. 2002). Further timing analyses were conducted on the detrended values.

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[2] We hypothesized that participants might subdivide the 4-tap chunks into two 2-tap subsequences because isochronous patterns are sometimes produced as strong and weak beats, indicated by the lengthening of every second intertap interval (e.g., Nagasaki 1987). Neither accuracy nor precision measures indicated that the 4-tap chunks were subdivided.

Occasional missing values in the three-dimensional motion data (less than 1% of all samples) due to occlusion factors were replaced using linear interpolation. The three-dimensional data were low-pass filtered using a second-order Butterworth filter with a cutoff frequency of 10 Hz. 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. Analyses of the finger motion trajectories were conducted with functional data analysis techniques (Ramsay and Silverman 2005). B-splines were chosen to fit the discrete data as it contained non-periodicities. Order 6 splines were fit to the second derivative (acceleration) of the motion data. Twenty splines were applied per fingertap, creating a 4:1 ratio of data observations to splines. The data were smoothed using a roughness penalty on the fourth derivative ($\lambda = 10^{-11}$, within 0.00001 of the generalized cross-validation estimate; Ramsay and Silverman 2005), which allowed for control of the smoothness of the second derivative.

To determine whether timing and motion depended on the sequence position of the tap or the finger used to produce the tap, we analyzed influences of shifting the start position of the sequence separately for sequence position and tapping finger (cf. Povel and Collard 1982). Shifting the start position of the sequence changes the sequence position in which a given finger taps; therefore, analyses of shifting manipulations must be conducted separately for sequence position and tapping finger.[3]

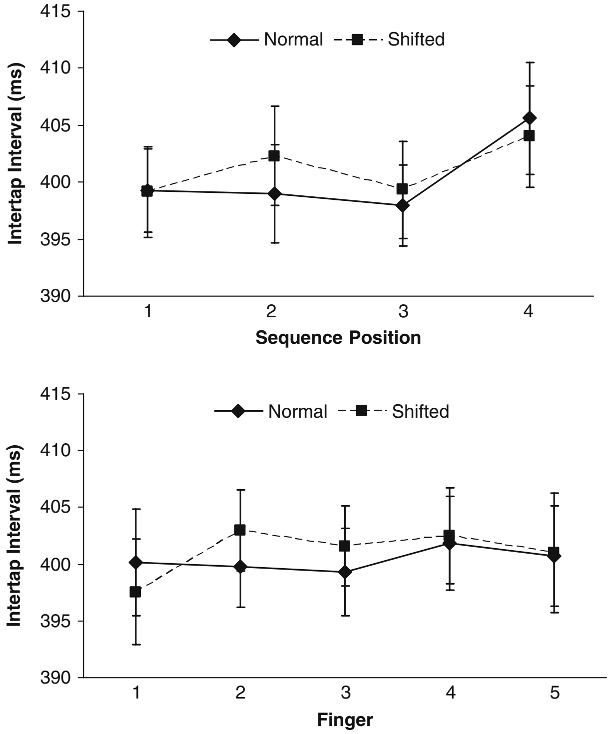

Fig. 1 Mean ITIs (±SE) by sequence position and by finger tapped at beginning of ITI

Results

Intertap intervals

The mean ITI (=400.75 ms) was equivalent to the metronomic rate of 400 ms. The mean ITIs for normal and shifted sequence types are presented in Fig. 1. The top half of the figure shows the mean ITIs by sequence position, and the bottom half shows the ITIs by finger. If the timing of the taps depended on the sequence positions of the taps rather than the particular fingers used to produce them (as in Povel and Collard 1982), then the ITIs should be consistent across normal and shifted sequences when analyzed by sequence position. An analysis of variance (ANOVA) on the ITIs by sequence position and sequence type (normal, shifted) revealed only a significant main effect of sequence position, $F(3,\ 33) = 4.60$, $P < 0.01$, and no interactions. Post-hoc tests revealed that the duration of the fourth sequence position (the end of the cycle) was significantly longer than the durations of the first and third sequence positions (Tukey's HSD = 4.99, $P < 0.05$). There were no effects of finger used on the ITIs. Thus, the timing data replicated Povel and Collard's (1982) findings that sequence position transcended particular fingers in ITIs and that a longer intertap interval occurred at the end of each stimulus cycle.

The variability of the intertap intervals also indicated that timing depended on the sequence position of the tap rather than the finger used to produce the tap. The coefficient of variation (CV) for each repetition within each trial, defined as the standard deviation divided by the mean ITI, differed significantly by sequence position, $F(3,\ 33) = 6.64$, $P < 0.01$, as shown in the top half of Fig. 2. The timing of the first and fourth sequence positions was less variable than that of the other sequence positions (Tukey's HSD = 0.0025, $P < 0.05$). The CVs did not differ between fingers, as shown in the bottom half of Fig. 2, and there was no interaction with sequence position. In sum, sequence

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[3] Additional analyses directly tested for interactions between finger and sequence position (these analyses do not allow direct tests of the normal/shifted factor) on each dependent variable: intertap interval, coefficients of variation, peak amplitude, time of peak amplitude, and Procrustes correlations. Those analyses yielded the same patterns of results: either sequence position or finger affected timing or motion, with no interactions.

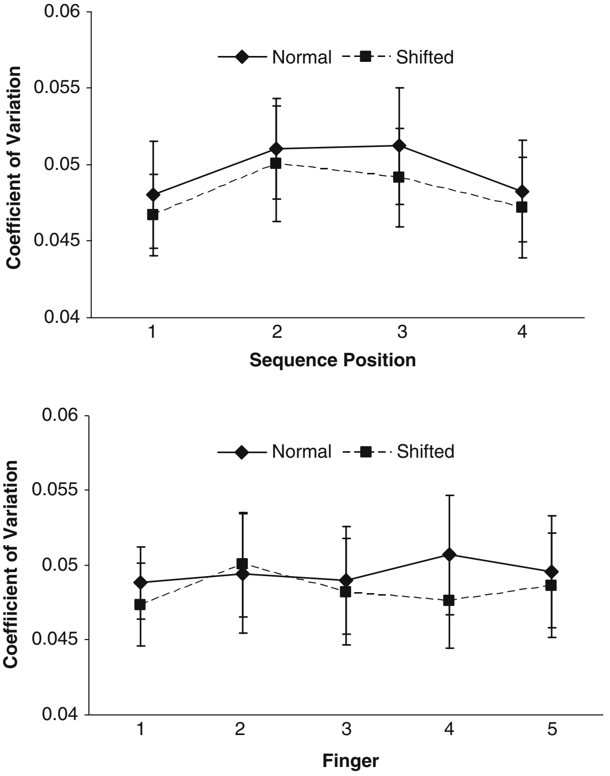

Fig. 2 Mean CVs (±SE) by sequence position and by finger tapped at beginning of ITI

position influenced the timing of participants' tapping more than did the finger used to produce a tap. Thus, cognitive constraints rather than biomechanical constraints influenced the timing of intertap intervals.

Motion trajectories

Finger motions were examined in terms of finger position, velocity, and acceleration in the *z*-plane (height above the table). Figure 3 shows the position, velocity, and acceleration curves for one participant's Finger 4 motion during two tapping cycles of the 4 3 5 2 sequence. The top panel shows the smoothed position curve and the bottom two panels show the corresponding velocity and acceleration curves. The vertical lines mark the arrival time of each tap; for example, event 5 marks the time at which Finger 4 made contact with the table and event 6 marks the time at which Finger 3 tapped. One event region corresponds to the interval between two successive taps or vertical lines, equivalent to an ITI. The data in each event region were interpolated to contain 80 equally spaced observations. The position, velocity, and acceleration curves were thus aligned (co-registered) across finger trajectories in terms of the arrival time of the finger producing each tap.

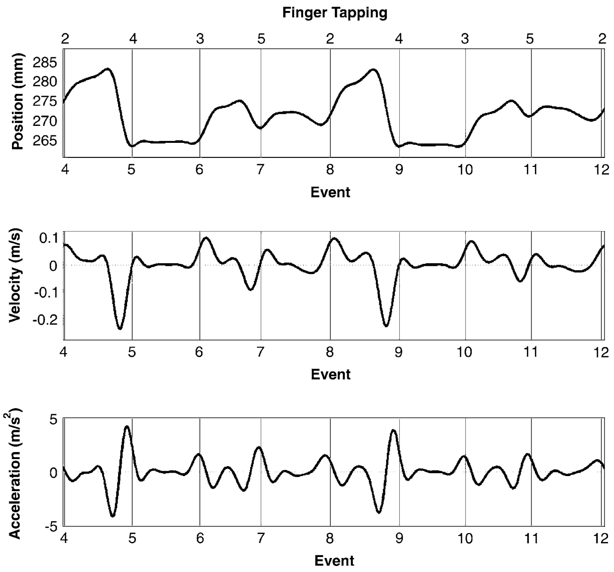

Fig. 3 Position on *z*-plane (height), velocity, and acceleration of Finger 4 during eight taps in one participant's trial for a 4 3 5 2 finger sequence. *Top panel* Smoothed position curve. *Middle panel* Velocity. *Bottom panel* Acceleration

Peak amplitude

Each finger's maximum amplitude before its tap, one measure of anticipatory movement in piano performance (Palmer 2006; Palmer and Dalla Bella 2004), was identified in terms of its height (mm) and time (ms) before the finger's contact with the table.[4] Figure 4 shows the average peak finger height for normal and shifted sequence types. The top half of the figure shows the mean peak height for each sequence position, and the bottom half shows the mean peak height of each finger. The sequence position effects show an interaction with sequence type, F (3,33) = 21.91, $P < 0.01$, suggesting that peak finger heights were not consistent across shifts in start position. As the bottom half of the figure illustrates, the tapping finger had a significant effect on peak height, F (4, 44) = 5.68, $P = 0.01$, with no effects of sequence type or interaction. The peak height of Finger 1 was significantly smaller than that of the other fingers (Tukey's

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[4] Sometimes a finger's peak amplitude in the event region immediately before another finger's tap exceeded that of its peak amplitude in the event region immediately before its own tap. Because fingers' motion was influenced by previous finger taps, we report analyses for each finger's peak amplitude in the event region before its own tap. When we conducted peak amplitude analyses using global (computed over the two prior event regions) peak amplitudes, the same pattern of results (main effects of finger, and sequence position by sequence type interactions) emerged.

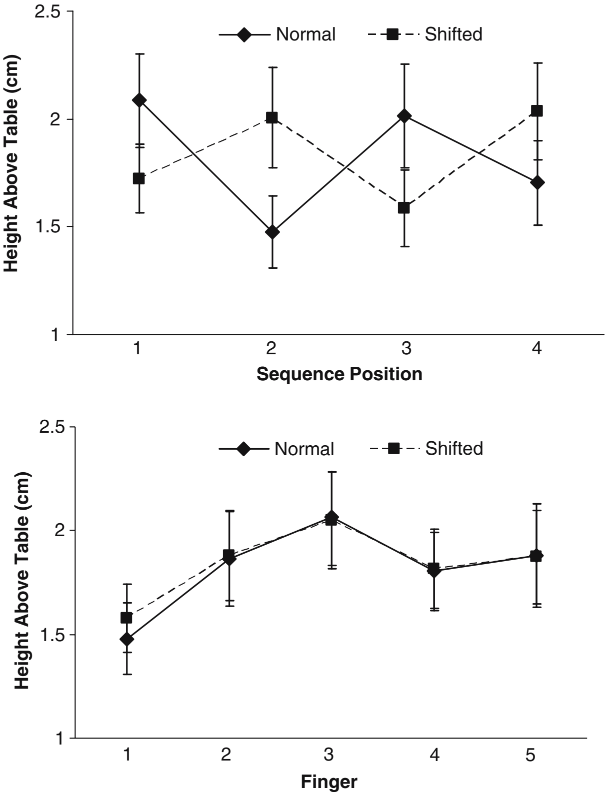

Fig. 4 Mean peak amplitude of finger above the table (±SE) by sequence position and finger, for normal and shifted sequence types

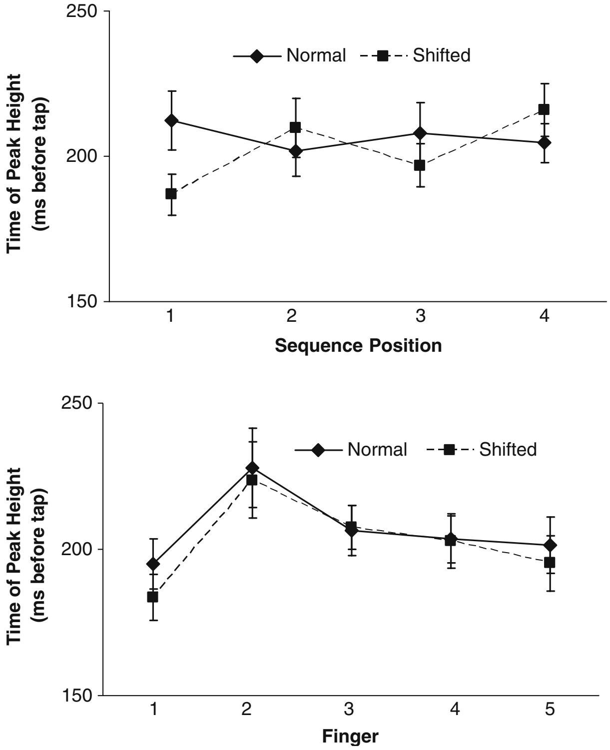

Fig. 5 Mean time of peak amplitude before the tap (±SE) by sequence position and finger, for normal and shifted sequence types

HSD = 0.32, $P < 0.05$). These results suggest that mean peak amplitude depended on the finger used rather than the sequence position of the tap.

Similar results were found in terms of the time of maximum amplitude of each finger before table contact. Figure 5 shows the mean time of peak amplitude before table contact by sequence position (top half) and by finger (bottom half) for each sequence type. The top half of Fig. 5 shows a significant sequence position by sequence type interaction, $F(3, 33) = 5.65$, $P < 0.01$. As the bottom half of the figure illustrates, this effect was due primarily to differences across fingers, $F(4, 44) = 4.03$, $P < 0.01$, as well as a main effect of sequence type, $F(1, 11) = 6.66$, $P < 0.03$, but no interaction between the two. Peak amplitude was reached earlier for Finger 2 than for Fingers 1 and 5 (Tukey's HSD = 27.18, $P < 0.05$). Peak amplitude occurred slightly earlier on average for normal sequences ($M = 206.84$ ms) than for shifted sequences ($M = 202.56$ ms). As with the height of peak amplitude, these findings suggest that time of peak amplitude depended on the finger tapping rather than on the sequence position of the tap.

Finally, we calculated the correlation between the height and time of peak amplitude to determine whether fingers that reached greater heights also reached peak amplitude earlier. The correlation between height and time of peak amplitude across participants and fingers was small, $r = -0.107$, $P < .01$, and accounted for less than 2% of the variance. In sum, analyses of both the height and the timing of peak amplitude suggest that peak amplitude depended primarily on which finger was tapping; thus, biomechanical constraints but not cognitive constraints influenced peak amplitude measures.

Velocity and acceleration trajectories

Motion trajectories were first analyzed in terms of phase-plane plots of velocity (x-axis) by acceleration (y-axis) for each event region (ITI), as shown in Fig. 6 for one participant's Finger 4 motion during eight taps of the normal (4 3 5 2) and shifted (3 5 2 4) sequence types. 'Finger about to tap' indicates which finger approached the table during the event region; the dot indicates the end of the event region (when the finger tapped the table). The figure shows that motion trajectories were highly consistent across repetitions of event regions and across normal and shifted sequence types, suggesting that the trajectories depended on finger transitions within the sequence rather than on how the sequence was chunked. A Procrustes similarity metric,

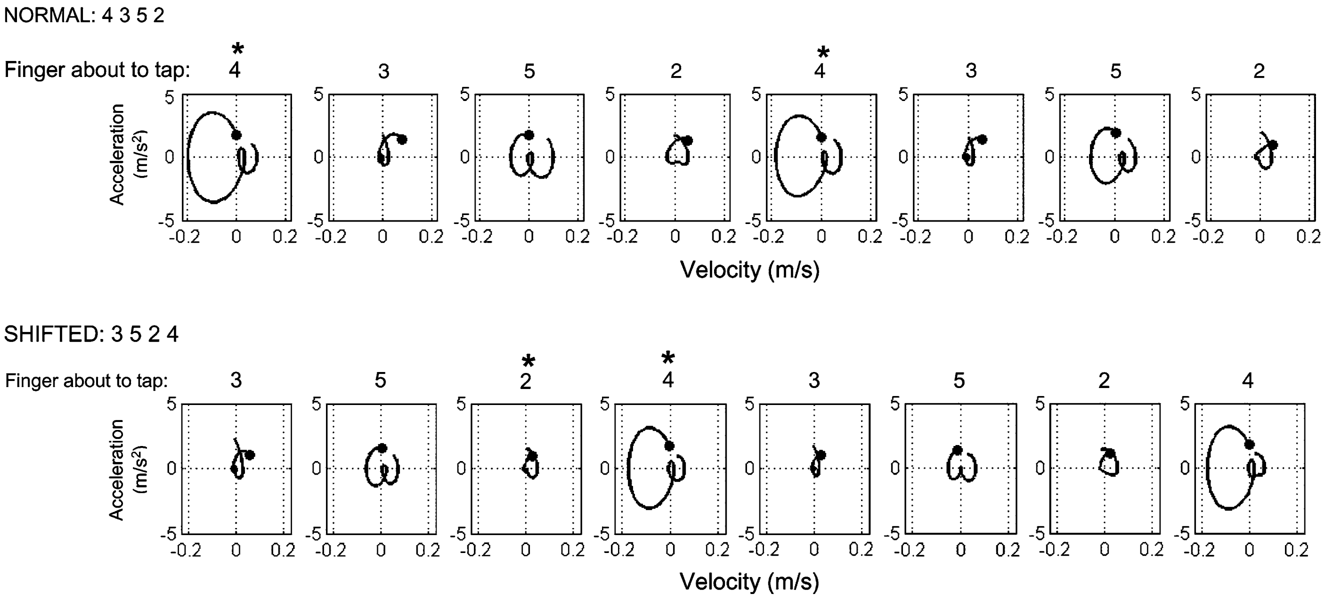

Fig. 6. Velocity-acceleration phase-plane plots of one participant's Finger 4 motion during eight taps of the normal and shifted versions of the 4 3 5 2 sequence. 'Finger about to tap' indicates which finger was approaching the table during each event. *Solid dots* denote the end of each event region

which determines a normalized linear transformation of the points in one event region to best conform them to the points in the other event region, ranging from 0 (minimal similarity) to 1 (maximal similarity), was computed for each finger's trajectories. The average correlation between a finger's motion during a given event region and its motion during other occurrences of the same event region within a trial (the two starred event regions in the top half of Fig. 6) was high, $r = 0.75$, $P < 0.01$. The average correlation between a finger's motion during a given event region and its motion during other event regions (the two starred event regions in the bottom half of Fig. 6) was lower, $r = 0.42$, $P < 0.01$. This difference was significant, $F(1, 11) = 1015.03$, $P < 0.01$, and did not differ between normal and shifted sequence types.

We next examined whether the consistency of a finger's motion immediately before its tap differed by finger or by sequence position. For each finger, we calculated Procrustes correlations between the finger's motion trajectory during its tap and its motion trajectories during its other taps within a trial (the two starred event regions in the top half of Fig. 6, which illustrate the motion of Finger 4, the first sequence position in the stimulus pattern, immediately before its tap). The average Procrustes correlations shown in Fig. 7 thus indicate the consistency of motion trajectories across repeated finger taps. The mean correlations are shown in Fig. 7 by the sequence position of the tap (top) and by the finger tapping (bottom). The top of the figure shows a significant sequence position by sequence type interaction, $F(3, 33) = 3.51$, $P < 0.05$, indicating that the consistency of motion trajectories at each sequence position changed with shifts in the start position of the sequence. The bottom of the figure shows that trajectory consistency depended on which finger was tapping, $F(4, 44) = 4.53$, $P < 0.01$, and was not affected by sequence type or the interaction. The motion of Finger 2 was less consistent than that of the other fingers (Tukey's HSD = 0.023, $P < 0.05$). Thus, consistency of motion trajectories depended on which finger was tapping rather than on the sequence position of the tap, suggesting that biomechanical constraints had a greater influence on motion trajectories than did cognitive constraints.

To determine where the finger trajectories differed across conditions, we conducted two functional ANOVAs (Ramsay and Silverman 2005) on Finger 4's velocity and acceleration trajectories over the two event regions (800 ms) before its tap. Figure 8 shows the mean velocity and acceleration trajectories (top and bottom panels, respectively) of Finger 4 for the four conditions of preceding finger (physically adjacent or non-adjacent) by sequence type (normal or shifted). Finger 4's tap occurred at time 0, the preceding finger's tap occurred at 400 ms, and the finger tap two events before Finger 4 occurred at 800 ms. The brackets along the bottom of each panel indicate the regions in which the main effect of adjacency and interaction with sequence type in the ANOVA reached significance [threshold $F(1, 11) = 9.65$, $P < 0.01$]. The main effect of sequence type did not reach significance at any point.

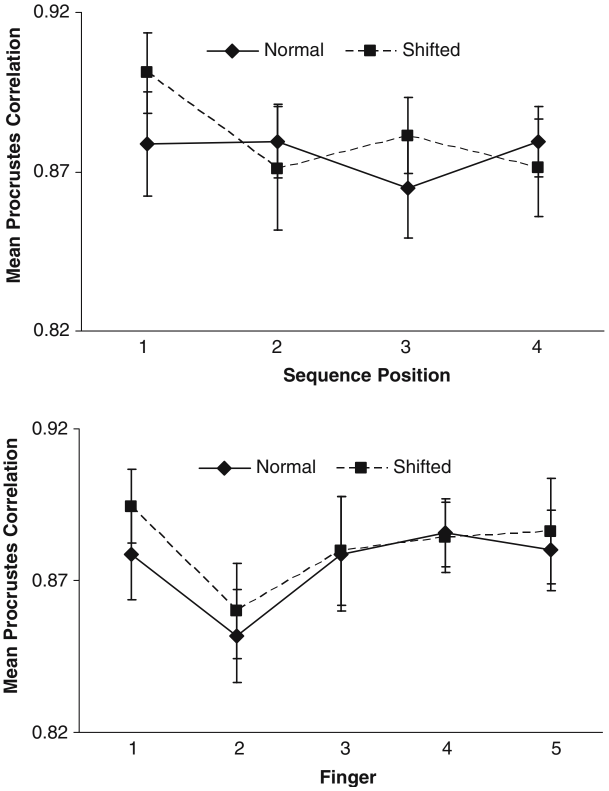

Fig. 7 Mean Procrustes correlations (±SE) between finger velocity-accelerations for the fingertaps within each trial, by sequence position and by finger

As Fig. 8 shows, Finger 4’s motion differed depending on whether a physically adjacent or non-adjacent finger preceded it, particularly in the 150 ms interval before its own tap and before the tap preceding it. Finger 4’s motion was relatively unaffected by shifting the start position of the sequence.

The 150–0 ms interval before Finger 4’s tap shows that when the preceding finger was physically adjacent to Finger 4, Finger 4’s motion showed less change in velocity and acceleration. When the preceding finger was not physically adjacent to Finger 4, Finger 4’s motion showed greater changes in velocity and acceleration. Thus, the influence of physically adjacent fingers’ taps on the motion of Finger 4 was evident immediately before Finger 4’s tap. Physically adjacent fingers also influenced Finger 4’s motion during the preceding finger’s tap. The insets of Fig. 8 show the mean trajectories of the preceding finger over 800–400 ms before Finger 4’s tap (the event region during which the preceding finger tapped). A comparison of the motion of the preceding finger and the motion of Finger 4 during the 550–400 ms before Finger 4’s tap reveals that the motion of Finger 4 closely resembled the motion of the preceding finger, only when the preceding finger was physically adjacent to Finger 4. Procrustes similarity analyses comparing the velocity-acceleration trajectories of Finger 4 during the 550–400 ms before its tap with the velocity-acceleration trajectories of the preceding finger over the same time span confirmed that the trajectories were more similar when the preceding finger was physically adjacent (mean $r = 0.83$) than when it was not (mean $r = 0.61$). An ANOVA on the Procrustes similarity metric indicated a significantly higher correlation for physically adjacent fingers, $F\,(1, 11) = 61.31$, $P < 0.01$, and no differences due to sequence type or interaction. In sum, the large effects of adjacency along with the relatively small effects of sequence type suggest that the motion of Finger 4 was primarily influenced by the motion of the fingers to which it is coupled rather than by how the sequence was chunked.

Discussion

Cognitive factors (chunking) and biomechanical constraints (finger coupling) influenced timing and motion, respectively, in a finger tapping task. Pianists, experienced at producing timed finger movements, tapped sequences that had the same set of finger transitions but differed in terms of starting point in the sequence (chunking). Timing, measured by intertap intervals, and motion, measured by position, velocity, and acceleration finger trajectories, were both accurate and consistent, perhaps due to the experienced nature of the pianists. The mean and variability of intertap intervals revealed influences of chunking in the finger tapping task, whereas the velocity and acceleration trajectories revealed influences of finger coupling.

Effects of cognitive constraints

The implied chunking of finger sequences affected the mean intertap intervals and their variability, each of which depended on the sequence position of the tap rather than the particular finger used to produce it. Mean intertap intervals and coefficients of variation suggested that participants chunked the sequences into groups of four and tended to produce longer, more consistent durations for the last item in the group than for the other items in the group. This is consistent with previous research indicating that intervals occurring at ends of groups are lengthened relative to other intervals (Palmer 1997; Povel and Collard, 1982; Rosenbaum et al. 1983). This effect was independent of the particular fingers used to produce the items; thus, the timing of sequence elements transcended the effectors used to generate those elements. This independence is

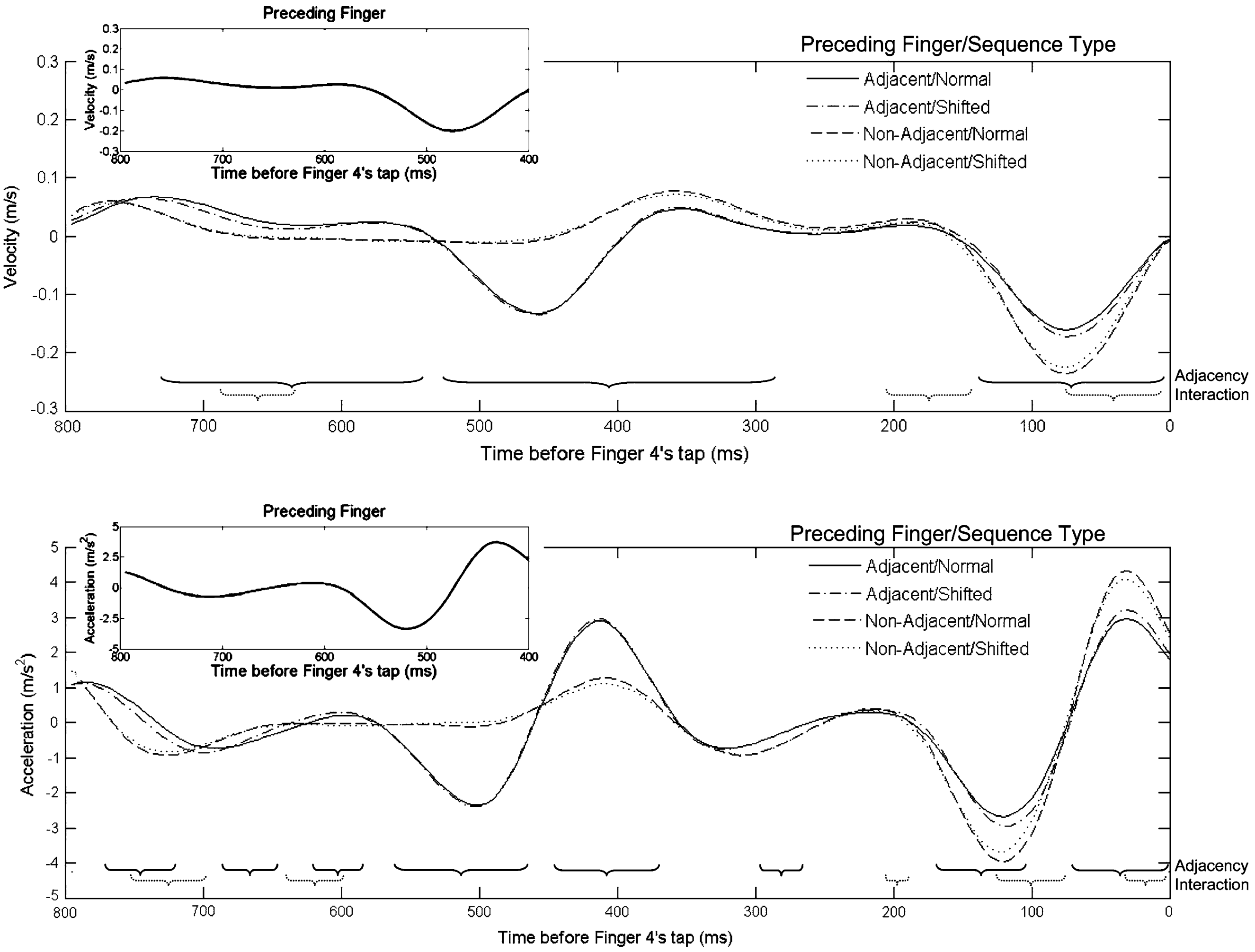

Fig. 8 Mean velocity and acceleration trajectories (*top* and *bottom panels*, respectively) for Finger 4 during two taps prior to its tap, by preceding finger (physically adjacent/nonadjacent) and sequence type (normal/shifted). *Solid brackets* beneath trajectories indicate the regions over which the main effect of adjacency reached significance at $P < 0.01$; *dashed brackets* indicate a significant adjacency by sequence type interaction. *Insets* Mean velocity and acceleration trajectories of the preceding finger during the tap (800–400 ms) prior to Finger 4's tap

important for an ability to transfer learning and generalize across situations, and is consistent with pianists' ability to transfer their knowledge of how to perform a melody from one hand to another (Meyer and Palmer 2003; Palmer and Meyer 2000).

Effects of biomechanical constraints

The influence of biomechanical constraints was evidenced in pianists' finger motion trajectories. Both the height and time of maximum finger amplitudes varied by finger rather than by sequence position; velocity–acceleration trajectories were more consistent across fingers than across sequence positions. Coupling influences on finger motions were evident in the motion of Finger 4, the least independent of the fingers. Finger 4's motion more closely resembled the preceding finger's motion when the preceding finger was physically adjacent than when it was not, particularly during the 150 ms before a tap. These results are consistent with findings that physically adjacent fingers cause more unintended force production (Slobounov et al. 2002) and flexion/extension movement (Hager-Ross and Schieber 2000; Li et al. 2004) in other fingers than do non-adjacent fingers, particularly for Finger 4. In the current study, the goal of Finger 4 (to tap the table at a particular time) was constant across the finger taps that preceded Finger 4; thus, the biomechanical constraints of the preceding finger influenced the motion of Finger 4 toward its goal. Further research is needed to determine whether the anticipatory motion of other, less coupled fingers is similarly influenced by biomechanical constraints.

In the current study, finger heights reached peak amplitude on average 204 ms (approximately one-half of an intertap interval) before each tap. Engel et al. (1997) found similarly that anticipatory finger movements diverged up to 500 ms before the point of divergence in two melodies that shared the same initial sequence of finger movements. Palmer and Dalla Bella (2004) reported peak finger heights one to three events (200–800 ms) before each piano keypress, across a range of performance rates. The current study differed from Palmer and Dalla Bella (2004) and Engel et al. (1997) in terms of both the task (tapping versus piano performance) and the production rate (Engel et al. 1997, did not control rate; Palmer and Dalla Bella 2004, altered the rate). It is possible that less anticipatory motion is required in simple repetitive sequences performed at a single rate. Our findings suggest that peak finger amplitudes may reflect finger coupling; the prior finger's tap may influence the motion trajectory and the resulting peak amplitude of the current finger's tap in ways that reflect coupling rather than anticipatory movement. Future research will need to address whether peak finger amplitudes that occur more than one event prior to the finger's arrival at a key or on the table reflect anticipatory motion or an influence of coupling among fingers.

Timing versus motion in tapping tasks

Chunking and finger coupling differentially influenced the timing and motion of pianists' tapping. This finding may be due to participants' goals in performing the tapping task. As in music performance, the timed tapping task required temporal precision in pianists' finger taps on the table but did not require spatial precision beyond the width of piano keys. Furthermore, the synchronization-continuation paradigm required participants to maintain the pace initially set by the metronome. Both the accuracy and precision of participants' taps were high; participants' coefficients of variation for intertap intervals approached those of pianists performing isochronous melodies (Pfordresher and Palmer 2002), and did not change between fingers. These findings are consistent with previous research in which timing accuracy was preserved despite changes in finger motion trajectories. Balasubramaniam et al. (2004) had participants produce repeating single finger flexion/extension movements with a metronome under different instructions: flexing in synchrony, extending in synchrony, and flexing in syncopation (midway between metronomic beats). The instructions influenced finger trajectories in the degree of asymmetry between movements in the flexion and extension phases of the movement cycle. Furthermore, the degree of asymmetry correlated with temporal accuracy on the phases of the movement cycle but not with temporal accuracy of the entire flexion/extension cycle (similar to intertap intervals measured in the current study). Thus, these findings indicate that the relationship between timing and motion may differ as a function of the particular task goals.

Task goals are known to influence time-limited movement planning; people alter their behavior in anticipation of task demands (Rosenbaum et al. 2001). Music performance tasks differ from traditional timing or movement tasks; for example, they require the optimization of temporal precision under complex movement constraints. In contrast, most laboratory tasks are constructed to optimize performance on one dimension (timing or motion) under conditions that simplify the other dimension. In addition, music performance requires a varying sequence of movements that are produced with different effectors; most laboratory tasks tend to measure single-effector movements, such as reaching or grasping objects with one hand (e.g., Meulenbroek et al. 2001), or a series of movements, such as tapping, that relies on one or two effectors (fingers) (e.g., Balasubramaniam et al. 2004). Future work will address how the relationship between timing and motion variables changes when spatial goals in addition to temporal goals are prioritized, as in violinists' finger placement on particular string locations (Baader et al. 2005).

Conclusions

In sum, cognitive constraints and biomechanical factors differentially influenced pianists' production of finger tapping sequences. Chunking influenced the timing of intertap intervals, whereas finger coupling influenced motion trajectories. When participants optimized timing accuracy under conditions that allowed variability in motion trajectories, the chunking manipulation influenced the timing but not the motion. These findings are consistent with the view that, given appropriate task constraints, participants control the timing of events while allowing motion trajectories to vary (Balasubramaniam et al. 2004; Shaffer 1982). The findings also provide an important caveat for studies of anticipatory motion in finger tapping; motion in advance of a finger's tap may be influenced by finger coupling in addition to anticipatory goals.

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