Interkey Timing in Piano Performance and Typing

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Abstract In typing, when the fingers executing two successive movements are on the same hand, the time between keystrokes is longer than when the fingers are on different hands. Biomechanical limitations of the hands are thought to account for this difference. The generality of this finding was explored by investigating skilled pianists' performance of two successive notes. Experiment 1 failed to find comparable differences in timing as a function of the hands involved. Experiment 2, employing both a piano production and a typing task, replicated the previous piano performance results, and revealed that the timing differences in typing were limited to letter sequences requiring fore-aft and lateral finger movements. Experiment 3 extended this finding to piano performance. Together, these findings clarify the nature of biomechanical constraints on skilled manual performance.

The ability of adults to coordinate hand and finger movements during skilled manual tasks is impressive, especially in the two prominent exemplars of such skill: typing and piano performance. Typically, a skilled typist produces between 60-80 words per minute, or approximately 5-7 keystrokes per second, with typing speed reaching up to about 200 words per minute (Gentner, 1983; Rumelhart & Norman, 1982). Piano performance can be even more rapid. Lashley (1951) noted that piano performance has the potential for 15 movements per second; others suggest that pianists routinely play up to 30 sequential notes per second over extended passages (Rumelhart & Norman, 1982).

Accordingly, the study of piano performance and typing can provide insight into processes of skilled manual motor control. By and large, the majority of such work has examined transcription typing, in which typists type short passages of prose. Analyses of the timing of typing, and of errors made during typing, provide a window onto the cognitive and motoric processes involved in this behaviour. One focal point in typing research involves the production of "digraphs," which are sequences of two different letters, identified with reference to the hands and fingers involved in their production. Two common classes of digraphs are two-hand (2H) and two-finger (2F) digraphs, which account for roughly 50% and 34% of English digraphs, respectively (computed using data in Solso, Barbuto, & Juel, 1979). A 2H digraph consists of two keystrokes typed by fingers from different hands; examples of 2H digraphs include "su" and "le." A 2F digraph consists of two keystrokes typed by different fingers from the same hand; examples of 2F digraphs include "li" or "dr."

Research investigating typing has uncovered timing phenomena related to the production of different digraph classes (cf., Rumelhart & Norman, 1982; Salthouse, 1986, for reviews). Using standard QWERTY keyboards, researchers have observed that the interkeystroke interval (IKI), or the time between the occurrence of the first and second keystrokes of the digraph, is shorter for 2H digraphs than for 2F digraphs (Fox & Stansfield, 1964; Gentner, 1982, 1983; Larochelle, 1983; Rumelhart & Norman, 1982; Salthouse, 1986), with approximately a 30-60 ms advantage for 2H digraphs. This greater speed in the execution of 2H digraphs has been interpreted in terms of constraints on the structure of the hands. Because the fingers on a hand are not fully independent, there is limited opportunity to prepare the second movement during the first movement of a 2F digraph. In contrast, the second movement of a 2H digraph can be prepared and initiated during the first movement, with this ability to overlap movements critical in affording faster production of these digraphs.

In a direct test of this biomechanical constraint explanation, Larochelle (1984) videotaped finger movements during typing, and found that in 2H digraphs the second movement was initiated about 30 ms prior to the first movement. In contrast, for 2F digraphs, the second movement was begun approximately 40 ms after the end of the first movement. Additional support for this biomechanical constraint idea comes from a study by Gentner (1983) in which beginner typists were taught to touch type. At the beginning of practice, the IKI for 2F digraphs was faster than for 2H digraphs, but this difference reversed by the end of practice, suggesting that typists learned to maximize the extent to which successive keystrokes were executed in an overlapping as opposed to serial manner.

In its strongest form, this explanation assumes that the timing of hand and finger movements results primarily (and possibly solely) from the mechanics of finger movements. One implication of this assumption is that the task environment plays little role, if any, in producing these differences. It is possible, however, that the task environment plays more of a role in determining digraph effects, with the demands of typing, which include producing sequential motor movements as quickly and as accurately as possible, providing limits on the timing and production of manual movements.

One way of testing these two possibilities (biomechanical constraints vs task environment) is through examining the timing of hand and finger movements in skilled manual domains that place somewhat different constraints on performers. One obvious candidate is the motor control involved in piano performance. If the digraph effects found in typing truly reflect constraints arising from the biomechanical structure of the hands, then similar findings should be observed in piano performance. In contrast, although piano performance and typing are related in that they use the same physical system for productions (i.e., hands and fingers), the demands of piano performance diverge from typing. Although typing places a premium on speed, this is of less importance in piano playing, in which temporal and rhythmic precision are critical. Moreover, piano performance, unlike typing, necessitates a mixture of simultaneous and successive keystrokes, occurring both within a hand and between the two hands, providing pianists with more experience in overlapping finger movements than typists. Given such differences, if the digraph effects found in typing rely in any way on aspects of the task environment or goals of performance, then these digraph differences should be negligible in piano performance.

Although previous research on piano performance has examined issues of timing (Clarke, 1985; Mackenzie, Van Eerd, Graham, Huron & Wills, 1986; Mackenzie & Van Eerd, 1990; Palmer, 1989a, 1989b; Shaffer, 1981, 1982; Shaffer, Clarke, & Todd, 1985; Sloboda, 1983, 1985; Todd, 1985) and errors during performance (Palmer, 1992; Palmer & van de Sande, 1993), the detailed goals of this work diverge from the current questions in that they reflect concerns more intrinsic to the nature of musical structure and performance. For example, some work (e.g., Mackenzie & Van Eerd, 1990; Shaffer, 1981, 1982) has explored rhythmic consistency and/or precision as a function of repeated performances of a single piece of music, or the rate of performance. Other work (e.g., Clarke, 1985; Mackenzie et al., 1986; Palmer, 1989a, 1989b; Shaffer et al., 1985; Todd, 1985) has examined deviations from mechanical regularity as a function of musical structure or the expressive intentions of a performer. As with typing, both the timing and error data indicate the structure of the mental representations assumed to be operative during musical comprehension and production.

Mackenzie and Van Eerd (1990) provide the most relevant data on interkey timing in their research on rhythmic precision in the performance of piano scales. In this work, pianists performed ascending and descending major scales at a variety of tempos, and in different hand combinations (i.e., one hand alone, both hands in parallel motion, and both hands in contrary motion). Their most pertinent results concern analyses of the IKI, with these authors finding that IKI varied with note position, or the fingers performing these notes, with such variations reflecting biomechanical limitations involved in moving fingers and shifting hand positions. Such results imply that basic biomechanical factors constrain piano performance, and that they can be indexed via analysis of timing parameters of piano production. Unfortunately, because these studies examined IKIs only for successive notes played within a hand, this work does not address whether IKIs vary as a function of two finger movements by a single hand, relative to finger movements across the two hands.

The primary goal of this project was to explore the importance of biomechanical and task environment constraints on skilled manual activity. Towards this end, these experiments examined interkey timing during piano performance, relating such productions to the interkey timing results typically observed in typing tasks. Again, if differences in digraph productions result primarily from biomechanical constraints, then similar findings should arise in piano performance. In contrast, divergent results from those typically found in typing would indicate a role for more contextual factors.

Experiment 1: 2F Versus 2H Dyads During Piano Performance

Experiment 1 represents an initial exploration of this issue by having trained pianists perform a musical analogue to a "digraph typing" task (Bosman, 1993, 1994). The digraph typing task involves presenting letter pairs (digraphs) on a computer screen and asking subjects to type these digraphs as quickly and as accurately as possible. Bosman (1993) has found that this task reveals differences in IKI as a function of digraph class. For use with musical stimuli, we presented pairs of sequential musical notes, or dyads, on a computer screen, and asked pianists to perform these dyads as quickly and as accurately as possible; this task will be called the "dyad playing" task.

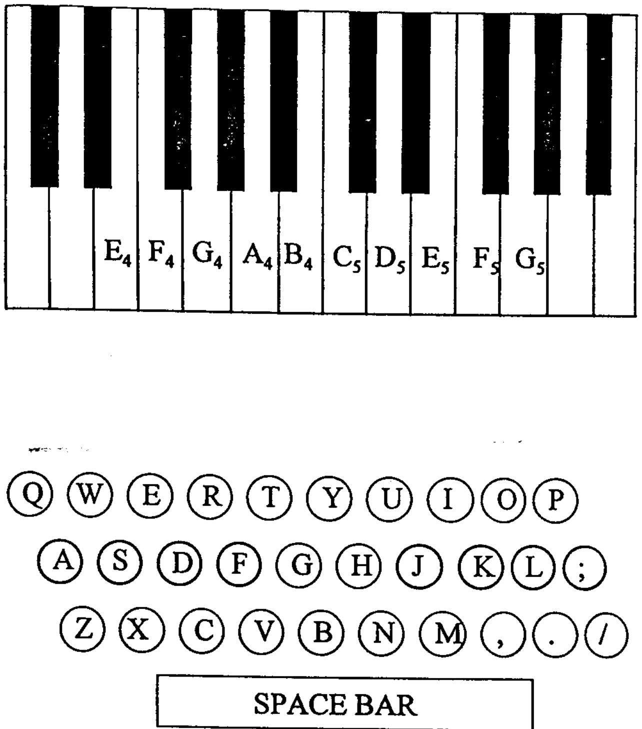

Figure 1. Schematic diagrams of the piano and standard QWERTY keyboards. The musical the notes to be played by the left and right hands are shown, as are the position of fingers on the homerow for left and right hands.

Why would we use this dyad playing task, as opposed to a more natural production task? One reason is that, unlike transcription typing, the ability to play at first sight, or "sight-read," an extended passage of music is a skill in which musicians vary greatly. In practical terms, the dyad playing task reduces sight-reading demands to a minimum, making it equally applicable to most pianists. Second, presenting pianists with minimalistic musical passages, such as dyads, effectively eliminates expressive and/or artistic concerns. Although not a consideration in typing, musical sequences are often performed expressively; unfortunately for our purposes, expressive intentions have a significant impact on the timing of performances (see Palmer, 1989a). Finally, the dyad playing task provides multiple possible dependent measures. The first measure is the already discussed interkeystroke interval (IKI). A second measure involves the time between the appearance of the to-be-performed stimulus and the first keystroke, or the initial latency. Previous research in typing (Bosman, 1993, 1994; Sternberg, Monsell, Knoll, & Wright, 1978) suggests that these measures are sensitive to different stages of motor control, with initial latencies indexing preparation of motor performance, and IKI assessing execution processes. Research by Sternberg et al. (1978, p. 142, Figure 5A) has found that typists take longer to initiate the production of letter strings requiring alternating hand movements, relative to letter strings requiring only a single hand, with these differences most pronounced for strings of three letters or more.

It is also of interest to examine the timing of the musical dyads as a function of left vs right hand performance, looking for evidence of hand asymmetries in production. Previous research on piano performance (MacKenzie & Van Eerd, 1990) has found significant hand asymmetries in piano productions, with pianists' emphasizing the right hand more than the left hand in terms of the amount of overlap between notes and note intensity. Accordingly, it is possible that the timing of the production of simple musical dyads will vary systematically as a function of left vs right hand performance.

METHOD

Subjects

Eight trained pianists took part in Experiment 1. They had been playing the piano for an average of 16.6 years, had received formal instruction for an average of 10.4 years, and were currently playing the piano for an average of 6.9 hours per week. All pianists had achieved at least grade 8, Royal Conservatory of Music ranking (mean RCM level = 9.1), and were right-handed. All subjects were either paid, or received course credit in an introductory psychology class, for participating.

Apparatus and Stimulus Materials

All stimuli were generated by an IBM-PC 286 compatible computer, displayed on a 14" VGA monitor, and consisted of pairs of musical notes displayed on a musical staff. Ten notes were used, with five of these notes played by the left hand and five played by the right hand. The notes performed by the left hand consisted of the five white keys ranging from E_4 (equal tempered tuning = 330 Hz) to B_4 (494 Hz); the notes played by the right hand consisted of the five white keys ranging from C_5 (523 Hz) to G_5 (784 Hz); Figure 1 presents a schematic piano keyboard, with the stimuli labeled.

The musical staff consisted of a treble clef and five lines — together this display was approximately 6.0 cm long and 2.2 cm high, and appeared in the center of the computer screen. The musical notes appeared side by side on the staff, separated by approximately 1.9 cm. For convenience in programming, all notes appeared as open ovals with stems (half notes). The notes to be played by the left hand had downward stems; the notes to be played by the right hand had upward stems.

Pianists played these notes on a Yamaha DX7 synthesizer, which has an unweighted, velocity-sensitive keyboard. The harmonic structure of the voice used by the DX7 approximated that of a piano, with each tone having about a 15-ms rise to peak amplitude, a gradual decay over the length of the tone until its release, followed by an approximately 80-ms fall to zero amplitude. All tones were amplified by a Peavey KB60 amplifier. The DX7 synthesizer was connected to the same IBM-PC that controlled the presentation of stimulus notes, using a Roland MPU-401 MIDI interface. The internal clock of the IBM-PC calculated all timing measures. This clock had a 1 ms resolution, with the resolution of the MPU-401 at plus or minus 2 ms. The computer recorded the time at which the stimulus originally appeared on the monitor, as well as the onsets and offsets of both keystrokes.

Conditions

There were two conditions in this study, corresponding to the combination of hands used to play the stimulus notes. In the 2F condition, the notes were played by different fingers on the same hand, either left or right. For each hand there were five stimulus notes, producing 25 possible stimulus dyads per hand. Because our interest was in examining the timing of notes played by different fingers (either within the same hand or between the two hands) the 5 notes involving a repetition of the same finger (e.g., E_4 followed by E_4) were eliminated. This left 20 stimulus dyads per hand, for a total of 40 stimulus dyads. In the 2H condition, the stimulus notes were played by one finger from each of the hands (e.g., E_4 followed by C_5). Again, five stimulus notes for each hand produced 25 stimulus dyads with the left hand playing the first note and the right hand playing the second note, and 25 stimulus dyads with the reverse order, producing 50 stimulus dyads in all. Together, the 40 2F and 50 2H dyads constituted a single block of trials, with all pianists receiving a different random order for each block of trials.

Procedure

All pianists were seated at the DX7 keyboard, and were told that they were participating in a study examining the performance of short passages of music. At the beginning of each trial, a musical staff and treble clef would appear on the computer screen, followed by two notes. The pianists' task was to play these notes as quickly and as accurately as possible, making sure to perform these notes successively, rather than simultaneously. Pianists were cautioned that although the notes would appear on the screen as half-notes (open ovals) this was done for convenience in computer programming, and that they should play these notes as quickly as they could. Pianists were also told that there would be five notes played by the left hand, and five notes played by the right hand, notated by the downward or upward stems of the notes as well as by labels attached to the piano keyboard itself. To make this task comparable to standard touch-typing, in which the hands are placed in the homerow position (the middle row of the typing keyboard), the pianists' fingering for each note was constrained, such that each finger was uniquely associated with the production of a single note. Thus, the note E_4 was always to be played by the little finger of the left hand, F_4 was to be played by the ring finger of the left hand, B_4 to be played by the thumb of the left hand, C_5 to be played by the thumb of the right hand, G_5 to be played by the little finger of the right hand, and so on. Although pianists found this limitation unusual, none reported difficulty in adopting this constraint.

Following these instructions, pianists placed their hands on the piano keyboard, and the experimenter hit a key on the computer keyboard to initiate a block of trials. After a 2s delay the musical staff appeared on the computer monitor, followed 1s later by the notes to be played. Following the release of the second performed note, the computer monitor blanked, and there was a 2s delay before the occurrence of the musical staff signaled the beginning of the next trial. As described earlier, a single block consisted of 90 trials, with subjects completing four such blocks. The entire first block of trials was considered practice, to allow pianists to adjust to the timing of experimental trials, to the feel of the DX7 key-board, and to adapt to the constraint imposed on their fingering of the different notes. The experimenter was pre-sent during the entire first block of trials to caution pia-nists about the use of inappropriate fingering, as well as to answer questions. Each block took approximately 7 - 8 minutes, with pianists allowed to take breaks between blocks as they wished. After completing all blocks, the purpose of this study was explained, and pianists completed a questionnaire concerning their musical background. The entire experiment took approximately 45 - 60 minutes.

RESULTS AND DISCUSSION

The two primary dependent measures in this study were the initial latency to produce the first keystroke, and the interkeystroke interval (IKI). In calculating these measures, all trials on which an error in production occurred, such as playing two notes by one finger, or playing the wrong note were removed. Averaging across the three blocks, there was a mean of 6.6% errors, with individual subject error rates ranging from 1.5% to 10.4%. Analyses of error rates failed to reveal any significant differences across the three blocks of trials, $F(1,14) = 1.66$, nor as a function of condition, $F(1,7) = 0.18$.

Mean initial latency and IKI measures were calculated[1]

[1] Because of concerns about skewed distributions, research in typing typically employs medians rather than means for analyses; in contrast, the current manuscript analyzed means. This was primarily because examination of the latency and IKI measures failed to reveal consistent evidence of strongly positively skewed distributions, and previous research on musical production has typically examined means rather than medians. Note, though, that although they are not

TABLE 1
Means (In ms) and Standard Deviations for Initial Latencies and Interkeystroke Intervals (IKIs) as a Function of Hand and Condition in Experiments 1 - 3.

	Initial Latency				IKI			
	Left Hand		Right Hand		Left Hand		Right Hand	
	2F	2H	2F	2H	2F	2H	2F	2H
Experiment 1								
Mean	763	794	666	790	122	134	116	118
SD	96	99	92	125	37	48	32	38
Experiment 2								
Mean	799	870	688	849	167	169	158	170
SD	145	179	102	141	49	61	45	68
Experiment 3 – White Key Dyads								
Mean	751	773	651	790	142	139	136	137
SD	197	235	124	214	46	49	51	54
Experiment 3 – Black Key Dyads								
Mean	878	883	798	856	143	144	134	142
SD	287	312	208	260	55	48	55	57
Experiment 3 – Mixed Key Dyads								
Mean	864	804	784	823	158	144	149	138
SD	272	231	192	222	51	52	51	52

and examined using three-way analyses of variance (ANOVAs), with the within subject factors of condition (2F vs. 2H), block (block 1, block 2, or block 3), and hand (left vs right). For this last factor, initial latencies were coded relative to the hand playing the first note of the dyad, while IKIs were coded in terms of the hand performing the second note of the dyad. The analysis of the initial latencies revealed a main effect of condition, with 2H dyads (M = 792 ms, SD = 112) initiated more slowly than 2F dyads (M = 715 ms, SD = 105), $F(1,7) = 50.1$, $MS_e = 2887.2$, $p < .001$, and a main effect of hand, with dyads beginning with the left hand (M = 779 ms, SD = 98) initiated more slowly than dyads beginning with the right hand (M = 728 ms, SD = 126), $F(1,7) = 22.1$, $MS_e = 2758.3$, $p < .005$. The only other significant result involved the two-way interaction between condition and hand, $F(1,7) = 13.3$, $MS_e = 3883.6$, $p < .01$. The means and standard deviations for 2F and 2H dyads, as a function of hand, are shown in Table 1, and demonstrate that the difference between 2F and 2H conditions was more pronounced for the right hand than for the left hand.

The critical ANOVA examined IKI, using the same factors as for initial latencies. In contrast to the research on transcription typing, there was no difference in IKIs for 2F (M = 119 ms, SD = 34) and 2H (M = 126 ms, SD = 44) dyads, $F(1,7) = 0.99$. In fact, the only noteworthy results produced by this analysis were marginally significant main effects of block, with decreasing IKIs across blocks (Ms = 138, 118, and 111 ms, SDs = 41, 35, and 37, for blocks 1 to 3, respectively), $F(2,14) = 3.1$, $MS_e = 2112.1$, $p = .078$, and hand, with right hand IKIs (M = 117 ms, SD = 35) slightly faster than left hand IKIs (M = 128 ms, SD = 43), $F(1,7) = 3.9$, $MS_e = 684.8$, $p = .088$. Means and standard deviations for the IKIs are also shown in Table 1.

These initial analyses contain a number of results of interest. First, in sharp contrast to research on typing, there was no difference in IKI as a function of whether the two notes to be performed required a single hand (2F) or both hands (2H).[2] The most obvious implication of this

systematically presented in this manuscript, analyses of median values were also performed. By and large, the pattern of results produced in analyses of medians did not differ from those of the means.

[2] Because the two movements in this study were executed successively, there is the possibility the two influence one another, with, for example, a trade-off between the two movements, such that a fast initial latency would be associated with a slow IKI. If such a relation existed, this might mask differences in timing as a function of 2F vs 2H conditions. One way of assessing this possibility is to examine each timing measure (e.g., IKI) using the other timing measure (e.g., initial latency) as a covariate. A pair of analyses took this tack,

finding is that it is task environment, and not biomechanical factors, that constrain timing in skilled manual activity. Second, the finding of longer initial latencies for the 2H than for the 2F condition suggests that the preparation involved in having to coordinate the activity of two hands takes longer than that for only one hand. Finally, the differences in initial latencies as a function of hand coincide with previous research in piano performance (e.g., MacKenzie & Van Eerd, 1990) that found a right hand advantage in piano productions. It is possible that because piano music tends to emphasize the right hand relative to the left, pianists have either learned to favor this hand, or have better motor control in this hand. However, it is also possible that the observed hand asymmetries resulted from the fact that our subjects were exclusively right-handed; unfortunately, it is not possible to disentangle these two alternatives in the present experiment.

Experiment 2: 2F and 2H Dyads/Digraphs During Piano Performance/Typing

Although Experiment 1 suggests that it is task environment and not biomechanical limitations that constrain manual performance, this interpretation is not yet warranted. One potential alternative to this idea is that pianists simply have a different form of motor control than do typists, with their motor control reflecting the necessity of performing both simultaneous and successive finger movements; such an alternative leaves open the issue of biomechanical limits on manual performance. Another concern is a difference in the to-be-produced stimulus. The musical dyads of Experiment 1 differ from typical digraphs in that the dyads did not require finger movements away from and towards the body; hence, these dyads are most similar to digraphs located exclusively on the homerow of the typing keyboard. The homerow in typing (shown in the bottom of Figure 1) is defined as the row containing the keys "a", "s", "d", "f", "g", "j", "k", and "l". Touch typists position their hands on the homerow while typing, and use the homerow as the reference point for executing all keystrokes. Obviously the presence of fore-aft finger movements is clearly relevant to the issue of whether biomechanical factors or task environment constrains skilled manual performance. Finally, a methodological concern is that pianists in Experiment 1 were restricted in their choice of fingering for the musical dyads. Although done to enhance comparability with the typing literature, such a restriction is unusual in piano performance, and virtually all of the pianists commented on this novelty. It is possible that this unusual limitation altered pianists' more typical motor control.

Experiment 2 examined these issues by having pianists who were also touch-typists participate in both types of tasks. If pianists generally differ in their motor control, then the interkey timing of motor performance will be similar across the two specific tasks. However, if digraph typing effects arise due to task environment, then typing, but not piano performance, should show these differences. Similarly, the importance of the (biomechanical) factor of fore-aft finger movements was examined by analyzing latency and IKI measures separately for digraphs drawn exclusively from the homerow versus digraphs not based solely on the homerow. Finally, the effect of restricting finger choice was assessed by removing the limitations on fingering: Pianists used whatever finger they wished to strike a key, provided they retained the distinction between left and right hand notes.

METHOD

Subjects

The final sample of subjects consisted of eight trained pianists who were also touch typists. Four additional subjects participated, but their data were not included because of excessively high error rates (> 10%) in either the digraph typing or dyad playing task. None of these subjects participated in Experiment 1. Mean errors for the dyad playing task were 6.0% and 9.0% for 2F and 2H conditions, and 10.2% and 9.5% for 2F and 2H conditions of the digraph typing task. In terms of their musical background, the remaining participants had been playing the piano for an average of 14.6 years, had received formal instruction for an average of 12.0 years, and were currently playing the piano an average of 6.4 hours per week. All pianists had passed at least grade 8 RCM (mean RCM level = 9.1). Seven of the subjects were right-handed, and one subject was left-handed. The participants had been typing for an average of 8.1 years, with a self-reported average typing speed of 60.1 net words per minute, and an actual typing speed of 56.8 net words per minute (see below). Four of the eight participants had held jobs requiring them to type, and seven of the eight subjects were currently typing for three hours or less per week (M = 1.1 hrs per week); the remaining subject was currently typing for 40 hours per week. All subjects were either paid or received course credit in an introductory psychology class for participating.

Dyad Playing Task

Apparatus, stimuli, and conditions. The experimental

comparing 2H and 2F conditions for the latency residuals, after removing the effect of IKI, and the IKI residuals, after removing the effect of latency. Both of these analyses produced virtually identical ANOVA results to those reported in the text. Although not reported here, similar covariate analyses were conducted for the data of Experiments 2 and 3, with identical results: Controlling for the effects of one variable (e.g., IKI) did not change the pattern of results for the other variable (e.g., initial latency).

apparatus employed was identical to that of Experiment 1. The stimuli performed by each hand were the same as in Experiment 1, consisting of multiple blocks of 40 2F stimuli and 50 2H stimuli.

Digraph Typing Task

Apparatus. All subjects completed the typing tasks using a standard QWERTY keyboard attached to the IBM-type 286 computer. The computer monitored and recorded the timing of all keypresses. All stimuli appeared in the center of the 14" VGA monitor attached to the computer.

Stimuli. Two sets of digraphs were created, home-row digraphs and non-home row digraphs. The home row digraphs consisted entirely of letters located on the home row of the QWERTY keyboard (i.e., a, s, d, f, g, h, j, k, l). The non-home row digraphs could contain letters that were located on the home row, but could not consist of two consecutive letters located on the home row. Figure 1 also presents a schematic of the typing keyboard, with the home-row position of fingers for the left and right hands notated. Both sets of digraphs were drawn from the set of digraphs legally occurring in English.

Homerow stimuli. The home-row digraphs consisted of 21 2F and 21 2H digraphs for a total of 42 digraphs. To make the 2F and 2H digraphs as comparable as possible, the two digraph sets were matched on digraph frequency. For the 2F digraphs, mean frequency was 3391.6 (SD = 8016.4); for the 2H digraphs, mean frequency was 3630.8 (SD = 8299.6). Frequency data represent occurrence per million words, and were obtained from Solso, Barbuto, & Juel, 1979.

The 2F and 2H digraphs were selected using the following method. From the set of all home row digraphs, the digraphs beginning with a particular character were identified (i.e., all of the digraphs beginning with a, s, and so on) Once the subset of digraphs beginning with a particular character was identified, 2F and 2H digraphs were selected in pairs so that the finger typing the second letter of the digraph was the same across the 2F and 2H digraph. For example, the 2F digraph "af" was paired with the 2H digraph "aj" because in both instances the second letter is typed by the index finger. For each letter appearing on the home row, all such pairs of 2F and 2H digraphs were selected.

Non-homerow stimuli. The non-home row digraphs were created using the procedure employed by Bosman (1993, 1994), and consisted of 30 2F and 30 2H digraphs. The two digraph sets were matched on digraph frequency, with a mean frequency for 2F digraphs of 10343.6 (SD = 8409.4), and for 2H digraphs of 11525.0 (SD = 8797.2). In addition, within each digraph class, each letter in the alphabet appeared an equal number of times in the first and second position within a digraph. Within digraph class and position, an equal number of letters were typed by the left and right hand. To achieve this, it was necessary to repeat some of the letters typed by the right hand because the layout of the QWERTY keyboard is such that 15 characters are typed by the left hand, and 11 by the right. The letters U, I, O, and P, were repeated because they are each typed by a different finger on the right hand. One repetition of all letters, plus an additional repetition of U, I, O, and P, in every position, and in every digraph class, resulted in 30 2H and 30 2F digraphs.

Assessment of typing skill. Typing skill was assessed using Paragraph 6 from Form F of the Nelson-Denny Reading Test. This paragraph contains 1398 keystrokes. Prior to typing the skill passage, each subject warmed up by typing a passage taken from Reader's Digest that was approximately 500 keystrokes in length.

Procedure

All subjects were told that they were participating in a study comparing piano performance and typing. The instructions and procedure for the dyad playing task were identical to those of Experiment 1, except that there was no constraint in their choice of fingering for the intervals, so long as pianists retained the left vs right hand distinction outlined in Experiment 1. All other experimental details (stimulus presentation, timing of trials) were identical to Experiment 1.

In the digraph typing task, subjects first completed the warm-up and skill passages, and then began the digraph typing task. To familiarize subjects with the typing task, 10 practice trials were completed, with the practice stimuli randomly chosen to contain an equal number of 2F and 2H digraphs. The experimental trials consisted of three blocks of 102 trials, with each block containing one repetition of the entire stimulus set. Each subject had a different random ordering of both practice and experimental trials. While performing the task, subjects sat with their hands in home row position, and initiated each trial by pressing the space bar with their thumb. A fixation cross appeared in the middle of the screen 1s after the space bar was pressed, and remained on for 500 ms. The stimulus replaced the fixation cross, and remained on until a response was made. Subjects were instructed to type the digraph as quickly as possible without making errors. The entire experimental session, including both dyad performance and digraph typing tasks, took approximately 75 - 90 minutes.

RESULTS AND DISCUSSION

Experiment 2 was analyzed in a manner comparable to that of Experiment 1. First, all production errors were removed. In the dyad playing task, averaging across the three blocks of trials, there was a mean of 4.1% errors,

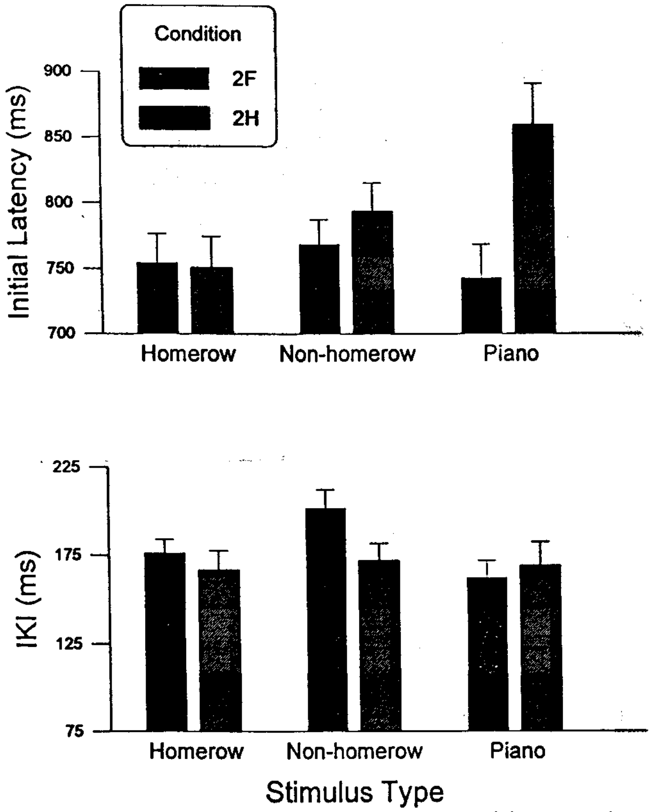

Figure 2. Means and standard errors for the initial latency and IKI measures, as a function of stimulus type and condition, in Experiment 2. Homerow and non-homerow stimuli refer to the digraph typing task; piano refers to the dyad piano task.

with individual subject rates ranging from 1.1% to 7.0% errors. For the digraph typing task, there was a mean of 4.6% errors across blocks, with individual subject rates ranging from 0.5% to 9.0% errors. Analyses of errors failed to reveal significant differences as a function of 2F versus 2H conditions for the dyad playing task, $F(1,7) = 1.58$, or the digraph typing task, $F(1,7) = 0.0$.

For the dyad playing task, initial latency and IKI values were calculated for each of the blocks of trials as a function of condition (2F versus 2H). For the digraph typing task, initial latency and IKI were computed separately for the homerow and non-homerow stimuli. These measures for the piano and typing tasks were then directly compared in a pair of three-way ANOVAs, with the factors of task (piano, homerow typing, or non-homerow typing), condition (2F vs. 2H), and block (blocks 1, 2, or 3). For the analysis of initial latencies, there were main effects of block, $F(2,14) = 7.9$, $MS_e = 1518.6$, $p < .01$, with decreasing latencies as a function of increasing block, and a main effect of condition, $F(1,7) = 25.4$, $MS_e = 3013.3$, $p < .002$, with longer latencies in the 2H condition relative to the 2F condition. Most interestingly, however, was a significant two-way interaction between task and condition, $F(2,14) = 20.18$, $p < .001$; this interaction is shown graphically in Figure 2. Subsequent t-tests revealed that 2H stimuli led to increased initial latencies relative to 2F stimuli in the dyad playing task, $t(7) = 5.71$, $p < .01$, and for the non-homerow stimuli of the digraph typing task, $t(7) = 2.48$, $p < .05$. In contrast, there was no difference between 2H and 2F conditions for the homerow stimuli of the digraph typing task, $t(7) = 0.32$.

The three-way ANOVA on the IKI measures revealed a main effect of block, $F(2,14) = 14.0$, $MS_e = 273.7$, $p < .001$, with IKIs decreasing across blocks, along with a significant task by condition interaction, $F(2,14) = 10.1$, $MS_e = 405.1$, $p < .005$; this interaction is also shown graphically in Figure 2. None of the other main effects or interactions were significant. T-tests revealed that the dyad playing task and the homerow stimuli failed to produce a difference between conditions, $t(7) = 0.65$, and $t(7) = 1.10$, respectively. In contrast, for the non-homerow stimuli, IKIs for 2F stimuli exceeded those for 2H stimuli, $t(7) = 3.28$, $p < .05$. Thus, only for the non-homerow stimuli did the typical digraph typing effect occur, with 2F digraphs having a larger IKI than 2H digraphs.

A subsidiary analyses examined the dyad piano latency and IKI measures as a function of right versus left hand performance.[3] Data for both 2H and 2F conditions were divided into separate groups based on the hand involved in productions, and coded as in Experiment 1. Both measures were examined using two-way ANOVAs, with the factors of condition (2F vs 2H) and hand (right vs left). The means and standard deviations for these values are also shown in Table 1. The only significant effects were found for the initial latencies, with the 2F condition producing shorter latencies than the 2H condition, $F(1,7) = 32.5$, $MS_e = 3321.7$, $p < .002$, and the right hand producing shorter latencies than the left hand, $F(1,7) = 10.6$, $MS_e = 3297.7$, $p < .05$. Moreover, a significant condition by hand interaction, $F(1,7) = 20.85$, $MS_e = 757.3$, $p < .005$, suggested that the difference between these conditions was more pronounced for the right hand than for the left hand.

In terms of the dyad playing task, this study strongly replicates Experiment 1, with no observable differences in IKI as a function of 2H versus 2F conditions, but a strong difference in initial latencies between the two conditions. The findings of the digraph typing task provide a mixture of known and new results. Although this study produced the typical digraph typing effect for IKIs, with 2H digraphs executed more quickly than 2F digraphs, this result is qualified by the fact that it was exclusive to non-homerow

[3] Because one of the subjects was left-handed in this study, the analyses described in this section were also conducted coding the data in terms of dominant versus non-dominant hand. These analyses did not differ appreciably from a coding of right versus left hand. To maintain comparability with Experiment 1, the results in this section will be discussed in terms of right versus left hand.

digraphs. Homerow digraphs failed to produce any difference in IKI as a function of 2H versus 2F conditions, a result that, to our knowledge, has not been reported in the literature.

The fact that digraph typing of homerow letters and the dyad playing task produced similar IKI results provides renewed support for a biomechanical explanation, and suggests that is the simultaneous coordination of fore-aft with lateral finger movements that produces differences in IKI during skilled manual activity. It also leads to the prediction that if pianists were to coordinate fore-aft and lateral movements during productions they too would show increased IKIs for 2F versus 2H dyads. This prediction was tested in Experiment 3.

Experiment 3: 2F and 2H Homerow and Non-homerow Dyads

Experiment 3 examines whether coordinating lateral finger movements simultaneously with fore-aft movements on the same hand leads to increased IKIs in piano performance. To assess this possibility, the stimulus dyads of Experiment 3 included both white and black keys, with the white keys on the piano considered analogous to homerow stimuli in typing, whereas the black keys are analogous to non-homerow stimuli. Given the large physical distance between keys on the piano keyboard, however, the easiest way to strike multiple black notes is to move the hand away from the body before producing the first finger movement, and then perform the interval. Accordingly, whether the dyad consists of two white keys ("white key dyads"), two black keys ("black key dyads"), or one white key and one black key ("mixed dyads") should have varying effects on latencies and IKIs. Black key dyads should produce longer initial latencies than either white key or mixed dyads, given that the forward movements occur prior to striking of the first note. Because the fore-aft movement can occur prior to the lateral movements, however, neither white key nor black key dyads should produce an IKI difference between 2H and 2F stimuli. In contrast, mixed dyads necessitate integrating fore-aft and lateral movements simultaneously, and should therefore produce longer IKIs for 2F relative to 2H dyads.

METHOD

Subjects

Eight trained pianists took part in the current study. None of these subjects took part in either Experiments 1 or 2. These participants had been playing the piano for an average of 14.2 years, had received formal instruction for an average of 11.8 years, and were currently playing the piano for an average of 3.2 hours per week. All pianists had passed at least grade 8 RCM (mean RCM level = 9.2), and were right-handed. One additional subject was run, but her data were discarded because of high error rates (14.0% and 12.7% errors in 2F and 2H conditions), and excessively high initial latencies (approximately 2000 ms), due to excessively poor music-reading skills. All subjects were either paid, or received course credit in an introductory psychology class for participating.

Apparatus and Stimulus Materials

All visual stimuli were generated using the same equipment as in Experiments 1 and 2. For this experiment, 16 notes were chosen as stimuli, with 8 notes played by the left hand and 8 notes played by the right hand. The notes played by the left hand consisted of the five white and three black keys ranging from E_4 to B_4; the notes played by the right hand consisted of the five white and three black keys ranging from C_5 to G_5 (see Figure 1). Black keys were notated by placing a sharp sign ("#") in front of the appropriate note. To accommodate the occurrence of sharp signs, the musical staff was increased in length to 9.2 cm. All other aspects of the stimulus and response gathering apparatus were the same as in previous studies.

Conditions

This experiment again contained both 2F and 2H conditions. In the 2F condition, there were 8 notes played by either hand, producing 64 possible dyads for each hand. As in previous studies, the 16 dyads requiring a repetition of the same finger (e.g., E_4 followed by E_4, or $D\#_5$ followed by $D\#_5$) were eliminated, leaving 112 stimulus pairs in total for the 2F condition. In the 2H condition, all possible note combinations across the two hands were included, resulting in 128 stimulus pairs. These 240 stimuli constituted a single block of trials, and were presented to pianists in a different random order for each block of trials.

Procedure

The procedure of Experiment 3 mimicked that of the earlier experiments, with the following additions and/or omissions. Pianists were informed that some notes would appear with sharp signs and other notes would not, and that only notes with sharp signs directly in front of that note should be performed as such. Some intervals, such as $F\#_4$ to F_4, could be performed by pianists sliding a single finger from the first note, which is on a black key, to the second note, which is on a white key. Pianists were warned against this practice, and asked to make sure that they did not use the same finger twice to produce an interval. Pianists were allowed the same freedom in fingering as in Experiment 2.

There were also minor changes in the structure of the experimental session. First, because of the increased length of a block of trials, the number of initial practice trials was

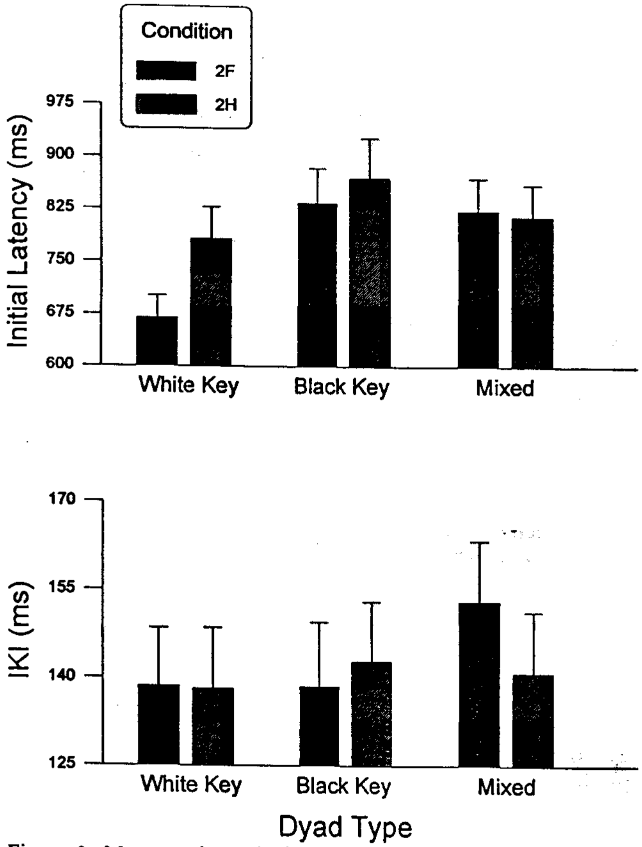

Figure 3. Means and standard errors for the initial latency and IKI measures as a function of dyad type and condition, in Experiment 3. White key dyads contain two white notes, black key dyads contain two black notes, and mixed dyads contain one white and one black note.

decreased from a complete block to a randomly chosen subset of 50 trials. Second, the time between the occurrence of the musical staff and the subsequent interval was decreased to 500 ms, and the time from the disappearance of the musical staff at the end of a trial to the beginning of the next trial was decreased to 250 ms. Despite the increased number of trials, a single block of trials took approximately 7 - 8 minutes. Not counting the practice stimuli, pianists completed three blocks of trials, with the entire session taking about 45 - 60 minutes.

RESULTS AND DISCUSSION

Initial data processing involved removing all production errors. Averaging across blocks, there was a mean of 5.8% errors, with subjects' average error rates ranging from 2.9% to 9.2%. An ANOVA revealed that error rates differed significantly, $F(1,7) = 5.9, p < .05$, with 2F stimuli producing more errors (6.3%) than 2H stimuli (5.0%). However, error rates for both conditions were at the same general levels as in the earlier studies.

Initial latency and IKI values were calculated for all trials, and were explored in a series of four-way ANOVAs, with the factors of condition (2F vs 2H), dyad type (white key, black key, or mixed dyad), *block* (block 1, 2, or 3), and hand (left vs right). For the initial latencies, the only significant main effect was for dyad type, $F(2,14) = 12.0$, $MS_e = 25926.7, p < .002$, with black key dyads producing the longest initial latencies ($M = 852$ ms, $SD = 268$), white key dyads resulting in the shortest initial latencies ($M = 741$ ms, $SD = 201$), and mixed dyads producing intermediate latencies ($M = 819$ ms, $SD = 229$). This ANOVA also uncovered a significant dyad type by condition interaction, $F(2,14) = 5.32, MS_e = 9691.7, p < .05$; this interaction is shown graphically in Figure 3. Replicating the results of Experiments 1 and 2, initial latencies for 2H stimuli exceeded those for 2F stimuli; extending these previous studies, this difference was most pronounced for white key dyads, weaker for black key dyads, and absent for mixed dyads. The only other significant result was the interaction between condition and hand, $F(1,7) = 18.6$, $MS_e = 8218.0, p < .005$, with the right hand producing a large difference in initial latencies between 2F and 2H conditions, whereas the left hand produced essentially comparable initial latencies between the conditions. Means and standard deviations for the initial latency (and IKI) values of the different hands, as a function of dyad type and condition (averaged across block) appear in Table 1.

The ANOVA on the IKI measures revealed a significant main effect for dyad type, $F(2,14) = 9.2$, $MS_e = 208.1$, $p < .005$, with white key dyads producing the shortest IKIs ($M = 138$ ms, $SD = 50$), followed by black key dyads ($M = 141$ ms, $SD = 53$), and finally by mixed dyads ($M = 147$ ms, $SD = 51$). There was also a significant main effect of hand, $F(1,7) = 8.1, MS_e = 266.8, p < .05$, with IKIs for dyads in which the right hand played the second note shorter than dyads in which the left hand played the second note. Finally, and of primary interest, was the significant dyad type by condition interaction, $F(2,14) = 8.1$, $MS_e = 221.2$, $p < .005$. This interaction, shown in Figure 3, reveals that 2F stimuli resulted in longer IKIs than 2H stimuli for mixed dyads, $t(7) = 2.63$, $p < .05$. In contrast, IKIs did not vary as a function of condition for either white key, $t(7) = 0.14$, or black key, $t(7) = 1.12$, dyads. As initially suggested, coordinating the movement of two fingers on the same hand with simultaneous fore-aft finger movements leads to increased IKIs.

A subsequent analysis directly compared the IKI values from the current experiment with the IKI values of the digraph typing task of Experiment 2. If the critical distinction between 2F and 2H digraphs/dyads truly involves performing successive movements requiring simultaneous fore-aft and lateral movements, then there should be a comparable pattern of results across the studies. For this analysis, IKI values for both white and black key dyads were grouped together; because these dyads do not require fore-aft movements during their execution, they were treated as analogous to homerow digraphs. In contrast, because the mixed dyads do require fore-aft and lateral movements, they were assumed analogous to the non-homerow digraphs. IKI values from the two studies were compared in a three-way ANOVA, with the factors of condition (2F vs 2H), digraph/dyad type (homerow vs non-homerow), and experiment (Experiment 2 vs Experiment 3). This analysis revealed main effects of condition, $F(1,14) = 7.4$, $MS_e = 330.7$, $p < .02$, with 2F stimuli slower than 2H stimuli, and digraph/dyad type, $F(1,14) = 30.0$, $MS_e = 68.4$, $p < .001$, with homerow stimuli executed faster than non-homerow stimuli. In keeping with our earlier analyses, there was a significant condition by digraph/dyad-type interaction $F(1,14) = 26.4$, $MS_e = 45.0$, $p < .001$, with non-homerow stimuli showing a difference in IKI as a function of 2F vs 2H conditions (*Ms* = 177 vs 156 ms, *SDs* = 55 vs 50, respectively), but no difference between 2F and 2H conditions for homerow stimuli (*Ms* = 157 vs 154 ms, *SDs* = 46 vs 47, respectively). Finally, and most tellingly, there was no three-way interaction between these factors, $F(1,14) = 0.87$, indicating that the differences between 2F and 2H conditions for homerow vs non-homerow stimuli were comparable across both typing and piano tasks.

General Discussion

Under certain conditions, musical intervals requiring two finger movements on the same hand take longer to execute than intervals requiring movements by fingers on different hands. Such a finding is analogous to that found in the typing of 2F versus 2H digraphs. The fact that piano performance and digraph typing produce equivalent patterns of results supports the explanation that one of the critical underlying factors on motor control in these situations involves the biomechanical organization of the hands. In contrast, there is little support for the idea that interkey timing results from contextual constraints arising from the specific goals of the task environment (e.g., the demands of typing or piano performance).

The current experiments also significantly clarify this result in finding that it is the specific movements of the fingers in relation to one another than underlies this difference. Two finger movements by the same hand produce slower execution times only when they require simultaneous integration along lateral and fore-aft body axes. When only lateral movements are required (such as with homerow digraphs or white key dyads) or the fore-aft movements can be performed prior to the lateral movements (such as with black key dyads) this difference disappears. Given the rather intuitive nature of this effect, it is somewhat surprising that research in typing has overlooked this constraint. Instead, typing research has focussed on cognitive factors, such as letter pair and/or word frequency (see, Salthouse, 1986, for a review), or investigated theoretical issues related to the existence of motor programs and/or templates (e.g., Terzuolo & Viviani, 1980; Viviani & Laissard, 1996). Clearly, however, basic biomechanical constraints play a fundamental role in skilled manual performance, and accordingly, merit further investigation.

One intriguing difference between the production of musical intervals and the typing of digraphs was the evidence that initial latencies to produce musical intervals increased when these intervals required both hands, relative to only a single hand, a result in keeping with previous research on typing (Sternberg et al., 1978). Before much is made of this finding, it is important to remember that the current project did not find any evidence for this difference in initial latencies in digraph typing (see Experiment 2), a finding that also has empirical support (Bosman, 1993). Fortunately, reconciling our results with Sternberg et al. (1978) is not problematic. Close inspection of their findings reveals that the latency differences in typing primarily occurred for sequences of three or more letters; differences for two letter strings, which are most analogous to the digraph typing task, were small at best. Moreover, Sternberg et al.'s (1978) task differed from the current study in that their work employed a simple reaction time procedure in which typists received advanced warning of the letter strings to be typed, and executed these movements when instructed. In contrast, the digraph typing task requires participants to perceive and organize the to-be-produced digraph, plan and prepare the movement, and finally to execute the movement.

What underlies the observed differences in initial latencies in the dyad playing task? One possibility involves the physical distance on the piano keyboard or spatial separation of the stimulus note heads on the computer screen, with 2F dyads systematically closer together than 2H intervals. Although not formally reported, a series of analyses of all three experiments examined the impact of such factors on latency values, and failed to find any compelling evidence that such factors could account for the observed initial latency differences. Unfortunately, it is not possible to fully dismiss this possibility. Because of the necessity of notating right versus left hand notes in a musically common way, notes for the right hand contained upward stems, whereas notes for the left hand contained downward stems. Although this difference does not change the actual distance between notes on the computer screen, it does produce differences in the overall visual array, potentially varying scanning of the display, and hence differences in latencies. Subsequent work could examine this issue either by monitoring eye movements during this task, and relating this information to latencies, or by employing the paradigm used by Sternberg et al.

(1978), in which subjects see the to-be-produced information prior to being given a signal to produce these movements.

Although the current studies strongly suggest that biomechanical factors play an important role in constraining the timing of skilled manual performance, contextual factors clearly have an impact on interkey coordination, as shown by the prevalence of frequency effects in typing (see Salthouse, 1986, for a review). Thus, a complete model of skilled manual performance must differentiate the situations in which biomechanical and more cognitive factors operate, as well as defining the relative contributions of each component. Moreover, such findings must be generalized across different skill domains, such as piano performance and typing. In this regard, subsequent work on piano performance seems warranted, with future studies investigating the role of contextual factors such as note frequency, as well as exploring contexts such as continuous piano performance. Overall, this work will provide a fuller account of the roles of both biomechanical factors and specific task constraints, as well as the inter-relation of the two, on skilled manual activity.

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Sommaire

L'aptitude des adultes à coordonner les mouvements de la main et des doigts lors d'exercices manuels spécialisés est fascinante, particulièrement dans les deux exemples évidents de la dactylographie et du jeu de piano. Dans ces deux domaines, l'analyse du temps d'exécution et des erreurs commises nous ouvre une fenêtre sur les processus cognitifs et moteurs associés à de telles activités manuelles spécialisées.

Une étude de la transcription à partir d'un dictaphone a permis d'observer que le temps requis pour produire une chaîne de deux lettres (digramme) diffère selon les combinaisons de mains et de doigts utilisés. Cette étude a permis de constater que le temps écoulé entre la première et la deuxième touche (l'« intervalle intertouche ») augmente lorsque le digramme exige des mouvements de deux doigts de la même main (digrammes 2D) par rapport à des mouvements de doigts des deux mains (digrammes 2M). Cette différence a été interprétée comme une limite biomécanique de la structure des mains, les digrammes 2D offrant moins de possibilités de chevauchement des mouvements à cause du manque d'indépendance des doigts de la même main.

Trois expériences ont permis de vérifier le caractère général de cette explication. Lors d'activités manuelles spécialisées, nous avons minuté les mouvements des doigts en imposant différentes contraintes aux exécutants : des pianistes. Au cours de la première expérience, des pianistes qualifiés ont exécuté deux notes musicales successives (« dyades » musicales), exigeant soit deux mouvements de la même main (dyades 2D), soit deux mouvements des deux mains (dyades 2M). Les dyades étaient composées de toutes les combinaisons possibles des touches blanches du clavier, de E_4 à G_5. Les analyses de l'intervalle intertouche ont révélé qu'il n'y avait pas de différence entre les conditions 2D et 2M, une constatation contredisant les résultats de recherches sur la dactylographie et l'explication biomécanique mentionnée plus haut.

La deuxième expérience a permis de comparer les intervalles intertouches du piano et de la dactylographie chez un groupe de pianistes qui étaient également des dactylos qualifiés. L'analyse des données d'exécution au piano a permis de constater que les résultats correspondaient à ceux de l'expérience précédente; pas de différence dans l'intervalle intertouche quelle que soit la condition. L'analyse des résultats de la dactylographie a révélé que l'intervalle intertouche des stimuli 2D était plus grand que celui des stimuli 2M, mais seulement lorsque les digrammes comportaient une combinaison de mouvements latéraux et longitudinaux. Les stimuli ne comportant pas de mouvements longitudinaux (digrammes ne se trouvant pas dans la rangée d'appui) n'ont pas produit de différences dans l'intervalle intertouche.

La troisième expérience a permis d'approfondir ces conclusions en comparant l'intervalle intertouche dans les dyades musicales exigeant des mouvements latéraux et longitudinaux non concurrentiels. Conformément aux résultats de la deuxième expérience, les dyades exigeant des mouvements longitudinaux et latéraux ont produit des intervalles intertouches plus longs lors des stimuli 2D par rapport aux stimuli 2M. Par contre, il n'y a pas eu de différence d'intervalle intertouche dans les dyades n'exigeant pas de tels mouvements. Dans l'ensemble, ces expériences suggèrent que la structure biomécanique des mains limite le minutage intertouche et l'exécution manuelle spécialisée tout en expliquant les conditions précises (la coordination des mouvements longitudinaux et latéraux par exemple) associées à de telles limites.