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A Forthcoming Key Press Can Be Selected While Earlier Ones Are Executed

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ABSTRACT. The possibility that a key press can be selected during execution of earlier key presses and the resulting pattern of interferences were investigated in this study. Subjects ($N = 26$) were required to press a series of keys, determined in advance, before they pressed a stimulus-dependent key. Response selection demands were manipulated by using spatially compatible and incompatible S-R mappings because S-R compatibility is well known to not disappear with practice. The longer time needed to select an incompatible key vanished when the choice key was preceded by two or four predetermined key presses. Only early in practice did the time to press the first and the choice key in a three-key sequence exhibit part of the compatibility effect. With limited practice, concurrent preparation in the three-key sequence was relatively slow and took longer than the time required for executing the fixed keys. These findings suggest that processes involved in execution are not affected by concurrent response selection and that one of the effects of practicing movement sequences is that later movements can be selected while earlier ones are being executed. This need not affect execution rate. Therefore, different degrees of concurrent processing are not always reflected in reduced execution rates.

Key words: concurrent processing, key pressing, movement sequences, practice effects

A main issue in research on human skills and human skill acquisition is how practice affects the way in which sequences of movements are produced. This issue is relevant for various real-world tasks, such as writing, typing, speaking, and controlling complex systems such as computers and cars. Early in practice, sequences may be produced by selecting and executing each element in the sequence one-by-one (e.g., Pew, 1974; Rosenbaum, Hindorff, & Munro, 1986; Van Donkelaar & Franks, 1991). With more practice, several elements are prepared in a single phase in which abstract information pertaining to the entire sequence is selected and retrieved from long-term memory and decoded into more specific instructions in a short-term motor buffer (Henry & Rogers, 1960; Rosenbaum, Inhoff, & Gordon, 1984; Sternberg, Monsell, Knoll, & Wright, 1978). Only then does execution start, which entails locating and retrieving information for each individual sequence element from the motor buffer.

It has become clear that skilled sequence production also may involve concurrent processing at various stages.[1] Evidence for concurrent processing in sequence production has been found in tasks as diverse as writing (Portier, van Galen, & Meulenbroek, 1990; Van Galen, Meulenbroek, & Hylkema, 1986), musical performance (Shaffer, 1976), typing (Salthouse, 1986), and sequential key pressing (Rosenbaum, Hindorff, & Munro, 1987; Semjen, 1992; Verwey, 1994). These studies suggest that information pertaining to later elements of a sequence can be transferred to the motor buffer (i.e., elements are still being programmed) while earlier ones are being executed and that the amount of such concurrent programming may increase with practice.

Even though the sequence as a whole may benefit from concurrent processing, execution of individual elements may be delayed. For example, in handwriting (Portier et al., 1990; Van Galen, 1991) and one-finger key pressing (Klapp & Wyatt, 1976; Verwey, 1993, 1994) the production rate of individual elements has been found to be affected by the presence of forthcoming elements. However, at least two studies have reported evidence for concurrent processing without prolonged interelement intervals (Garcia-Colera & Semjen, 1987, 1988). These studies suggest that at least some preparatory processes can con-

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cur with execution of earlier elements without affecting the rate of execution.

Under what circumstances preparatory processes can concur with ongoing execution without causing interference is an as yet unsettled question. Garcia-Colera and Semjen (1988) found that the effect of an accentuated tap on sequence production disappeared when the accentuated tap occurred later in the sequence. They proposed the *time-availability hypothesis,* which states that preparation for one element in the sequence (i.e., involving selection and programming) can concur with execution of earlier elements without affecting their rate of execution only when the execution takes enough time. So, as more elements precede the choice element concurrent preparation is less likely to affect sequence production. However, the validity of this hypothesis is still questionable because its empirical support was founded on a task in which subjects had to tap a single key about 7 times per second, a rate that may not be the highest possible. Perhaps at lower tapping rates capacity is left free for selecting the moment of increased tapping force. The time-availability hypothesis needs to be investigated in a paradigm with the highest production rates possible. Besides, the demands of tapping a single key may have been insufficient to demonstrate that effects of concurrent selection and interference with selection occur only with more difficult movement sequences.

The time-availability hypothesis does not indicate how much time concurrent preparatory processes require. Findings from studies of limited capacity models (Kahneman, 1973; Sanders, 1979, 1983; Wickens, 1984) suggest that either execution, preparation, or both require more time when a single limited capacity is tapped. Even when execution of a movement sequence is not affected by concurrent preparation for an ensuing movement, interference may still occur because preparation that concurs with execution may take longer than preparation that does not. This implies that the choice movement may not follow the sequence immediately even though sequence execution appears to take long enough to allow concurrent preparation. Alternatively, initiation may take longer when a fluent transition of the earlier part of the sequence to the choice element is preserved. Basically these notions are consistent with the time-availability hypothesis, but the limited capacity model adds the possibility that the choice movement or sequence initiation may be delayed even though execution of the earlier part of the sequence takes longer than preparation of the choice movement would take if it were performed alone. Because interference-free parallel processing is assumed to depend on practice (e.g., Broadbent, 1982; Detweiler & Schneider, 1991; Kahneman, 1973), capacity notions also suggest a major role of practice in the reduction of interference between simultaneous preparation and execution. In short, a movement that follows a sequence of movements can be prepared during execution of the sequence, but interference may occur because the earlier part of the sequence is executed more slowly or because preparation cannot be completed in time. With longer sequences or with practice interference may be reduced or absent.

The basic issue addressed in this article is the extent that practice and sequence length affect interference-free concurrent selection of a movement following a fixed sequence. Study of this issue is interesting because information can be gleaned on how people link movement sequences in real-world behavior and on the possibility of using timing data to show transitions between fixed sequences (see, e.g., Sternberg, Knoll, & Turock, 1990). The effect of stimulus-response (S-R) compatibility of the last key press in a sequence on earlier key presses that were independent of the imperative stimulus was examined. S-R compatibility is particularly appropriate to use in investigating this issue because it is generally acknowledged to be a pure selection effect that does not affect other processing stages (Sternberg, 1969; see Sanders, 1990, for an elaborate overview), and it does not disappear with practice (Dutta & Proctor, 1992; Fitts & Seeger, 1953). The latter is important because the disappearance of the compatibility effect with longer sequences or with practice can then be attributed to interference-free concurrent selection. A basic assumption in the paradigm is that the fixed part of the sequence is prepared in advance of the imperative signal and that the S-R compatibility manipulation does not affect the way in which the previous key presses are executed. Proof for this assumption may be derived from the presence of the sequence length effect on initiation time (i.e., the complexity effect), which is usually found with integrated sequence production (Henry & Rogers, 1960; Sternberg et al., 1978).

Various types of results can be expected when this paradigm is used. When the stimulus-dependent key is not selected during sequence execution but before or after execution of the fixed part of the sequence (i.e., serial rather than concurrent selection), the entire compatibility effect should appear in the time used for initiating the sequence or in the interval preceding the choice key. The first of these options was actually anticipated by Inhoff, Rosenbaum, Gordon, and Campbell (1984), but they did not test it. On the other hand, concurrent selection is indicated by a reduction or disappearance of the compatibility effect. For a remaining compatibility effect, two patterns of interference can be distinguished. First, concurrent processing may delay execution of the fixed key presses. This may indicate that processes involved in execution are hampered by concurrent selection. Second, the intervals preceding sequence initiation and the interval preceding the choice key may be prolonged while the fixed key presses are not affected. This would suggest that execution itself is not hindered but preparation for the choice key requires more time than is available during execution of the fixed key presses. Finally, to accurately evaluate effects of S-R compatibility on the various phases of sequence production, I analyzed separately pressing and movement times (e.g., Kerr, 1978; Laszlo & Livesey, 1977).

Method

Tasks

A trial started with a written instruction on a screen to press the *home* key, that is, the [5] key in the center of the keypad on a regular PC-AT keyboard (Figure 1). Pressing the [5] replaced the instruction by a plus sign (+) at the center of a 1.3- × 1.4-cm square located in the middle of the screen. The plus functioned as fixation point, and the combination of plus and square started a nonaging foreperiod that was always stopped after 4 s. A nonaging foreperiod is one in which the likelihood of a stimulus lessens as the foreperiod lengthens. This assures that subjects cannot anticipate the moment of stimulus arrival (see Gottsdanker, Perkins, & Aftab, 1986, for a detailed discussion). At the end of the foreperiod the square was positioned with its midpoint 6 cm either to the left or to the right of the fixation point (+), which subtended a visual angle of about 5°. The square disappeared from the screen as soon as the home key was released. Subjects responded to the repositioning of the square with a sequence of either one, three, or five key presses, depending on the condition.

In the *one-key condition,* the response consisted of releasing the home key and pressing and releasing either the [4] or the [6] key. The response in the *three-key condition* consisted of pressing either [8 5 4] or [8 5 6] in about half of the blocks and [2 5 4] or [2 5 6] in the other half. Which of these two sequence pairs was produced was determined randomly in advance of each trial block. Two pairs of sequences were used to reduce orthogonal compatibility effects (Weeks & Proctor, 1990) and to minimize the possibility that separate motor chunks would develop that would include the stimulus-dependent response. In that case, the compatibility effect might not occur because the chunk would be selected as a whole. Likewise, the *five-key condition* consisted of [8 5 2 5 4] and [8 5 2 5 6] on about half of the blocks and [2 5 8 5 4] and [2 5 8 5 6] on the remaining blocks, which also was randomly determined in advance of each block. Thus, only the last key in the three- and five-key conditions was stimulus-dependent. The keys were pressed in rapid succession after the right index finger released the home key. The subjects were instructed to minimize the time between releasing the home key and depressing the last key in the sequence. Depression of any further key yielded an error.

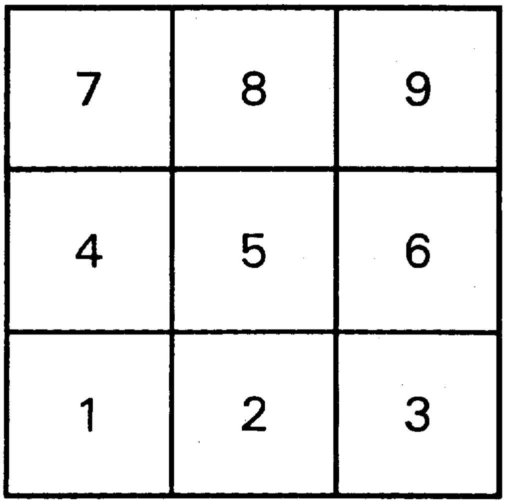

FIGURE 1. Spatial layout of the keypad used for the key pressing sequences.

S-R mapping was varied between conditions. In the *compatible condition,* a square shifting to the right required subjects to press the key located to the right of the home key, that is, the [6] key, and a square shifting to the left required them to depress the key located left of the home key, that is, the [4] key. In the *incompatible condition,* this mapping was reversed. The *sequence length condition* determined whether the choice key was pressed immediately or only after pressing previous keys.

Analyses and Design

Three sets of time data were used. First, T_1 indicated the time between stimulus presentation and onset of the first key press. T_2, T_3, T_4, and T_5 indicated the respective interkey-interval times. For example, T_2 indicated the time between onset of the first and onset of the second key press. So, T_2 indicated the time needed to prepare and to subsequently move to the second key. The second set of time data, pressing time, involved the duration of a particular key press and was defined as the time between on- and offset of a key press (denoted by T_{p1} through T_{p5}). For instance, T_{p1} indicated the interval between stimulus onset and release of the home key,[2] and T_{p2} the period that the first key was depressed (and the second was prepared). Finally, movement times T_{m1} through T_{m5} indicated the time between releasing a key and pressing the next key. So, for each of the T_xs ($1 \leq x \leq 5$), the following equation holds: $T_x \leq\ = T_{px} + T_{mx}$.

Subjects performed 15 experimental sessions, 7 sessions on Day 1 and 8 sessions on Day 2. A session included two blocks, each consisting of 74 trials, the first 4 of which were considered practice and were excluded from analyses. S-R compatibility was varied within subjects in that half of the subjects first performed a compatible and then an incompatible block in each session and the other half first an incompatible and then a compatible block. In each of these groups, half of the subjects were randomly assigned to the three-key condition, the other half to the five-key condition. All subjects had one-key response blocks in Session 2, 6, 9, and 13. The number of one-key sessions was limited to four because this condition was aimed only at verifying that a possible reduction of the compatibility effect on sequence production could not be attributed to disappearance of the compatibility effect per se.

Basically, the data were analyzed with a mixed 2 × 2 × 11 (Compatibility × Sequence Length × Session) design for the multikey conditions and a 2 × 2 × 4 (Compatibility × Sequence Length × Session) design for the one-key condition. Sequence length was included in the one-key condition to check for differences between the performances of subjects who pressed three and five keys. To test whether the compatibility effect differed in one- and multikey conditions, I used a 2 × 2 × 2 × 4 (Condition [one- vs. multikey] × Sequence Length × Compatibility × Session) design. The four one-key sessions and the average of the multikey sessions immediately preceding and following the respective one-key sessions were included in the analysis.

Subjects

In total, 26 right-handed students (20 women and 6 men) from Utrecht University participated as subjects. They all received Dfl. 90 for their participation. A bonus of Dfl. 20 was given to the 3 subjects in the three- and in the five-key group who had the fewest errors but still responded rapidly. Four subjects were removed from the analyses, 1 because her fingernails obstructed key pressing, 1 because he had participated in a comparable study and was already highly skilled, and 2 because they had high average error percentages (16 and 23%). Twenty-two subjects remained, 11 in each sequence length group.

Procedure

Thirteen subjects visited the Institute on two consecutive mornings and 13 on two consecutive afternoons. On the 1st day, written instruction was handed out that briefly introduced the tasks and explained the way the computer had to be controlled. After some additional oral instructions, subjects were introduced to the task during a training session consisting of four 15-trial blocks. The first two blocks included a compatible and an incompatible one-key condition, the third and fourth block consisted of compatible and incompatible three- or five-key response conditions, depending on the subject's sequence length assignment. Next, they performed seven experimental sessions, including two one-key sessions. On Day 2 the subjects performed the ensuing eight sessions, two of which included the one-key condition.

Both the morning and the afternoon subjects were split into two groups of 6 or 7, each with 3 or 4 subjects from each length condition. These two groups worked alternately: When one group was working, the other group relaxed in a separate room. This resulted in a 15-min work and rest schedule for each subject.

Each block of trials started with a written instruction on the screen about which stimuli could be expected and which keys had to be pressed. A sequence of key presses in one trial was considered wrong when an incorrect key was pressed or when the order was incorrect. In addition, the sequence was considered erroneous when the interval between ensuing key presses (i.e., T_x) took more than 1,500 ms. In case of an error or slow response, subjects were informed immediately after the trial about the kind of error they had made. Intertrial times were about 1,600 ms, the first 1,000 ms of which were reserved for presentation of error messages.

Following a block of 74 trials, performance feedback was displayed in terms of the average time between stimulus onset and the moment of pressing the last key divided by the number of keys in the sequence, and in terms of the error proportion. An additional message stating that the subject had been too slow was given when, in the experimental sessions, the average time for releasing subsequent keys exceeded 350 ms. When more than five errors occurred (i.e., more than 8%) at a particular block, subjects were informed that they had made too many errors. There was a 23-s interval between the two blocks in each session.

Apparatus

The experiment was conducted on seven identical IBM AT compatible (386) computers with NEC Multisync VGA 3D color monitors. Stimulus presentation and response collection were controlled through Micro Experimental Laboratory software ([MEL]; Schneider, 1988). This software package was specially developed for running PC-based experiments. The warning stimulus was presented at the center of the screen. At a typical viewing distance of about 65 cm, the square subtended a visual angle of approximately 1°. The stimuli were presented in bright white on a black background and were viewed under normal room illumination. The response keys were part of the keypad of a normal AT-like keyboard (BTC). Input delays as measured by MEL ranged between 10.6 and 13.4 ms for the keys used. Although MEL can measure times with 1-ms precision by reprogramming the internal timer, variances caused by these keyboard delays add approximately 19 ms to the error variance (see Segalowitz & Graves, 1990, for a derivation). With large numbers of trials, this is considered acceptable (Segalowitz & Graves, 1990). The distance between ensuing keys in a sequence was always 2.0 cm.

Six or 7 subjects were simultaneously tested in separate sound-attenuated 2.4- × 2.5- × 2-m rooms. Each subject sat in front of a table on which a keyboard and a computer monitor were positioned and was monitored by a video camera. To enable subjects to attain an optimal, nontiring hand position and to assure that they pressed the key similarly (i.e., that they moved only the wrist, hand, and index finger), I required them to rest their underarm on a wooden armrest (4.6 cm height, 9.6 cm wide, and 35 cm length) that was raised 2 cm at the side of the keyboard.

Results

The influence of spuriously long response times was removed by excluding trials in which T_1 exceeded 700 ms in the one- and three-key conditions and 900 ms in the five-key condition or trials in which interresponse times T_2 through T_5 exceeded 300 ms. These cutoff values were derived from a T + 3 *SD* criterion in the first two sessions. In total, less than 2% of all trials were removed by this procedure. Analyses of variance (ANOVAs) were performed on average times and arcsine-transformed error percentages per session.

One-Key Condition

Error rates averaged less than 2% across trials and showed no significant effects.

Compatibility Effects

The average compatibility effect in all four one-key sessions amounted to 44 ms (compatible, 348 ms; incompatible, 392 ms), $F(1, 20) = 187.5, p < .001$. The compatibility effect emerged in depression times (33 ms) as well as in movement times (11 ms); T_{pl} = 261 and 294 ms, $F(1, 20) = 120, p < .001$; T_{ml} = 87 and 98 ms, $F(1, 20) = 49.2, p < .001$. The compatibility effect tended to decrease with practice, from 52 ms in the first one-key session to 45 ms, 40 ms, and 40 ms in the later one-key sessions (see Figure 2), $F(3, 60) = 2.4, p < .08$. Further analyses showed that this reduction concerned key depression and not movement: The compatibility effect in T_{pl} decreased from 41 ms in the first one-key session to 28 ms in the last two one-key sessions, $F(3, 60) = 3.8, p < .05$, whereas the compatibility effect in T_{ml} remained at about 11 ms, $F(3, 60) = 0.2$.

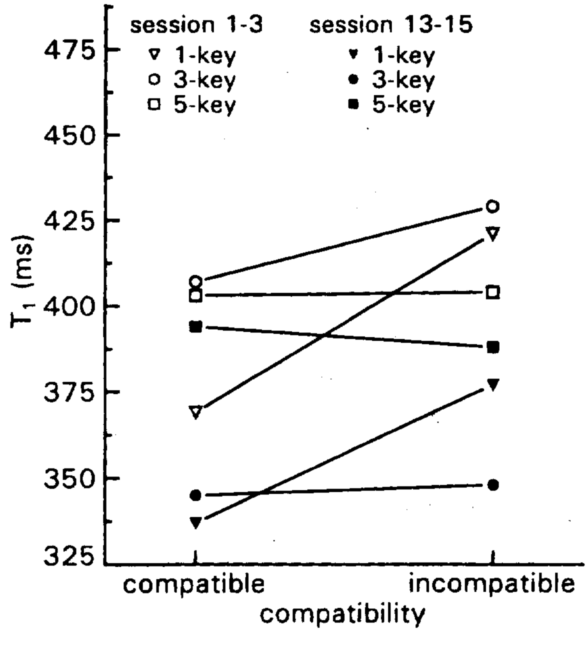

FIGURE 2. T_1 as a function of compatibility, sequence length, and session.

Three- and Five-Key Conditions

Again, error analysis showed no significant effects. Average error percentage amounted to 3.6%.

Compatibility Effects on Sequence Duration

To test whether compatibility affected the total duration of the sequence, I added all interkey intervals (three-key sessions $T_1 + T_2 + T_3$; five-key sessions $T_1 + T_2 + T_3 + T_4 + T_5$) and subjected the sums to a Compatibility × Sequence Length × Session ANOVA. Besides main effects of sequence length, $F(1, 20) = 80, p < .001$, and session, $F(10, 200) = 12, p < .001$, there was a main effect of compatibility, $F(1, 20) = 8.4, p < .01$, indicating an average compatibility effect of 13 ms. The compatibility effect amounted to 18 ms (725 − 707 ms) in three-key sessions and 8 ms (1,121 − 1,113 ms) in five-key sessions, but this difference was not substantiated by a Compatibility × Sequence Length interaction, $F(1, 20) = 1.2, p > .25$. Planned comparisons of the compatibility effect on three- and five-key sequences showed that the effect was significant in three-key sequences, $F(1, 20) = 7.9, p < .01$, but not in five-key sequences, $F(1, 20) = 1.6, p > .20$. The compatibility effect did not appear to lessen with practice; that is, the Compatibility × Session interaction did not reach significance, $F(10, 200) = 0.9$. A Condition (one- vs. multikey) × Group (three- vs. five-key) × Compatibility × Session ANOVA showed that the compatibility effect was smaller in the multikey than in the one-key sessions, $F(1, 20) = 50.7, p < .001$. The Condition (one- vs. multikey) × Compatibility × Session interaction, which would indicate that the reduction with practice was different in one- and multikey conditions, was not significant, $F(3, 60) = 0.5$.

Compatibility Effects on T_1

Averaged across multikey sessions, T_1 exhibited a compatibility effect of 8 ms, (385 − 377 ms), $F(1, 20) = 5.1, p < .05$. The Compatibility × Session interaction did not reach significance, suggesting that the compatibility effect lasted with practice, $F(10, 200) = 1.3, p > .20$. In the Condition (one- vs. multikey) × Sequence Length × Compatibility × Session ANOVA, the compatibility effect was found to be smaller in the multikey than in the one-key condition, $F(1, 20) = 84.0, p < .001$.

Subsequent analyses showed that the compatibility effect in T_1 amounted to 8 ms in depression times, (T_{pl} = 263 vs. 271), $F(1, 20) = 5.6, p < .05$, and was absent in movement times, $F(1, 20) = 0.3$. Again, no differences in depression and movement times were found between three- and five-key sequences, $Fs(1, 20) = 1.5$ and 0.9, respectively, $ps > .20$. The 2 × 2 × 2 × 4 ANOVA confirmed that the compatibility effect in depression times as well as in movement times was significantly greater in one-key sequences (34 vs. 7 ms), $F(1, 20) = 33.2$, $p < .001$, than in multikey sequences (12 vs. 0 ms) $F(1, 20) = 18.3$, $p < .001$.

In Figure 2, one can see that the compatibility effect on T_1 in the three-key condition on Day 1 (409 − 386 = 23 ms) was larger than it was on Day 2 (average compatibility effect was 353 − 348 = 5 ms), and larger than the compatibility effect in the five-key condition on Days 1 and 2 (average compatibility effect, 402 − 395 = 7 and 384 − 384 = 0 ms, respectively). However, this was not supported by a significant Length × Compatibility × Session interaction in the T_1 analysis, $F(10, 200) = 0.6$. Close examination of the data suggests that this interaction did not reach significance because T_1 in the five-key condition was quite noisy in the Day 1 sessions. Yet, a marginally significant Length × Compatibility × Session interaction, $F(10, 200) = 1.8$, $p < .07$, was found in the T_{pl} analysis, indicating that in the three-key condition the average compatibility effect of 22 ms on Day 1 (22, 17, 31, 27, and 11 at subsequent Day 1 sessions) reduced remarkably to about 3 ms on Day 2 (4, 3, 2, 6, 0, and 2 ms at subsequent Day 2 sessions), whereas the compatibility effect in T_{pl} of the five-key condition did not change at all with practice (averages on Day 1 and 2 were both 4 ms). The compatibility and practice effects found in the various conditions and the levels of significance obtained by planned comparisons (not discussed in the text) are presented in Table 1.

Compatibility Effects on T_2 to T_5

Separate ANOVAs on interkey intervals T_2 to T_5 (T_2 and T_3 ANOVAs included sequence length as a factor; T_4 and T_5 ANOVAs did not) did not show significant compatibility effects on T_2, T_4, and T_5. Only the ANOVA on T_3 showed a Compatibility × Length interaction, indicating a minor compatibility effect in three-key T_3s (5 ms);

TABLE 1
Effects of Compatibility and Practice on Pressing, Movement, and Total Interkey times (in ms)

	T_1		T_2		T_3		T_4		T_5		Total	
	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
One key												
Compatibity												
p[a]	38***	29***									39***	29***
m	10***	11***									10***	11***
p + m	48***	40***									48***	40***
Practice[b]												
p	26***											
m	12***											
p + m	38***											
Three keys												
Compatibity												
p	21**	3	−3	3	2	3					21*	8
m	2	2	0	1	3	0					5	3
p + m	23**	5	−3	4	5*	3					25*	12
Practice[c]												
p	59***		2		15*							
m	13		6		9***							
p + m	72***		8		24***							
Five keys												
Compatibity												
p	4	4	1	0	0	3	2	4	1	2	9	13*
m	3	−3	0	−3	0	−2	1	1	0	−1	5	−8
p + m	7	0	1	−2	0	1	3	5	1	1	12	5
Practice												
p	20		1		6		4		10*			
m	− 7		−5		8***		0		12**			
p + m	13		−5		14**		4		22***			

[a] m = movement time, p = pressing time, p + m = total (interkey) time. [b] Obtained by subtracting times from the last one-key session from those in the first one-key session. [c] Obtained by subtracting times from the last two multikey sessions from those in the first two multikey sessions.
$*p < .05$; $**p < .01$; $***p < .001$.

which was not found in five-key T_3s (0 ms), $F(1, 20) = 4.7$, $p < .05$. Analyses of movement and pressing intervals showed a minor compatibility effect on T_{p3}, $F(1, 20) = 6.2$, $p < .05$, which amounted to 2 ms in both sequence length conditions.

Multikey Execution Versus One-Key Preparation Times

$T_{m1} + T_2 + T_{p3}$ in the three- and $T_{m1} + T_2 + T_3 + T_4 + T_{p5}$ in the five-key conditions were averaged over the sessions before and after each one-key session and were compared with T_{p1} found in the one-key sessions, to test whether slowed sequence production in the incompatible conditions could be attributed to limited time availability. A Condition (one- vs. multikey) × Sequence Length × Compatibility × Session ANOVA showed a main effect of condition, indicating that the summed intervals in the multikey sequences were longer than T_{p1} in the one-key conditions, $F(1, 20) = 331$, $p < .001$. Planned comparisons confirmed that this difference was significant for both sequence length conditions: three-key group (summed intervals = 363 ms, T_{p1} = 286 ms), $F(1, 20) = 12.4$, $p < .01$; five-key group (summed intervals = 756 ms, T_{p1} = 269 ms), $F(1, 20) = 492$, $p < .001$. The absence of a significant Condition (one- vs. multikey) × Session interaction, $F(3, 60) = 0.6$, suggests that the difference between the summed intervals and T_{p1} in the one-key condition did not change over sessions. On Day 1 alone, when compatibility effects were found in the three-key sequence, the average execution times for the fixed keys in the compatible and incompatible three-key sequence were also longer than the time required for preparation in the one-key condition: compatible ($T_{m1} + T_2 + T_{p3}$ = 375 ms, T_{p1} = 274 ms), $F(1, 20) = 21.45$, $p < .001$; incompatible ($T_{m1} + T_2 + T_{p3}$ = 378 ms, T_{p1} = 315 ms); $F(1, 20) = 6.6$, $p < .05$.

Remaining Effects on T_1

In the first session, T_1 in the five-key condition was equal to T_1 in the three-key condition (both = 429 ms), which effect could be attributed to the slow T_1 in the incompatible three-key condition (three-key sequence, compatible = 418 ms, incompatible = 439 ms; five-key sequence, compatible = 435 ms, incompatible = 424 ms). With practice, T_1 in the three-key condition decreased faster and more than T_1 in the five-key condition, ending up with T_1s of 391 ms and 347 ms in the last two sessions. This resulted in a Sequence Length × Session interaction, $F(10, 200) = 3.3$, $p < .001$, but not a significant three-way interaction with compatibility, $F(10, 200) = 0.6$.

Remaining Effects on T_2 to T_5

An overview of the various interval durations at the first and last sessions appears in Figure 3. Several main effects of session were found: T_3, T_4, and T_5 all decreased with practice. Average values in the first and last two sessions were 180 and 161 ms for T_3, $F(10, 200) = 11.6$, $p < .001$; 186 and 182 ms for T_4, $F(10, 100) = 2.3$, $p < .05$; and 184 and 162 ms for T_5, $F(10, 100) = 6.9$, $p < .001$. T_3 tended to be smaller in the three- than in the five-key sequence, 160 and 175 ms, respectively, $F(1, 20) = 3.3$, $p < .09$, and T_3 tended to lessen more with practice in the three-key condition than in the five-key condition (three-key, from 176 to 152, five-key, from 184 to 170 ms), $F(10, 200) = 1.7$, $p < .09$. All practice effects were caused by depression as well as movement times. Analyses of depression times showed practice effects on T_{p3} (10 ms), $F(1, 20) = 6.2$, $p < .05$, on T_{p4} (3 ms), $F(10, 100) = 2.3$, $p < .05$, and on T_{p5} (10 ms), $F(10, 100) = 3.6$, $p < .001$. Movement time analyses revealed practice effects on T_{m3} (9 ms), $F(10, 200) = 6.0$, $p < .001$, and on T_{m5} (12 ms), $F(10, 100) = 2.3$, $p < .05$. The only main effect of sequence length was encountered on T_{m3}, where the time for moving to the third key was 13 ms faster with a three-key sequence than with a five-key sequence, $F(1, 20) = 5.1$, $p < .05$.

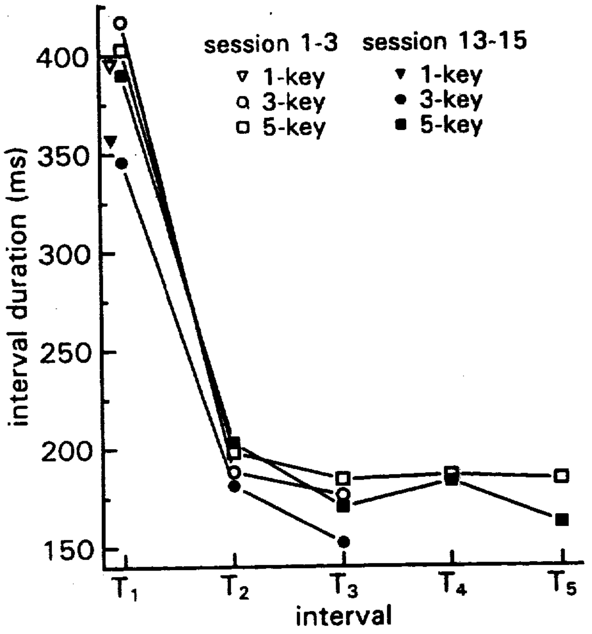

FIGURE 3. Interval durations as a function of interval, sequence length, and session, and pooled over compatibility.

Multivariate planned comparisons were carried out to find whether the decrease with practice (first two vs. last two sessions) was different for the various interkey intervals. In the three-key condition T_3 decreased more than T_2, $F(1, 20) = 20.8$, $p < .001$. In the five-key condition, T_2, which increased with practice, differed from the decreasing T_3 and T_5, $Fs(1, 20) = 29.6$ and 20.1, respectively, $ps < .001$, and was marginally different from the slightly reducing T_4, $F(1, 20) = 3.0$, $p < .10$. The decrease of T_3 exceeded the T_4 decrement, $F(1, 20) = 5.2$, $p < .05$, but not the T_5 decrement, $F(1, 20) = 2.3, p > .10$. Finally, T_4 reduced less with practice than T_5, $F(1, 20) = 42.6, p < .001$.

Summary of the Results

Clear compatibility effects were found in the one-key condition. The effect emerged in the time the home key was depressed (T_{p1}) and the time for moving toward the choice key (T_{m1}). The compatibility effect in depression time decreased with practice, but in movement time the effect did not change. In the multikey sequences the compatibility effect was virtually absent. The times required for executing the fixed part of the sequences (estimated in the three-key sequences by $T_{m1} + T_2 + T_{p3}$ and by $T_{m1} + T_2 + T_3 + T_4 + T_{p5}$ in the five-key sequences) were significantly longer than the time for releasing the home key (T_{p1}) in the one-key condition. Yet, a significant compatibility effect was obtained in the three-key sequence at Day 1, which was mainly caused by depressing the home key and, to a lesser extent, by the last interkey interval. The key pressing rate of the fixed keys in both sequences was not affected by compatibility. The data derived after subjects had some practice showed complexity effects in the compatible conditions and in the incompatible multikey conditions. Interkey times decreased with practice, with the exception of T_2. T_3 and T_{m3} appeared smaller and T_3 tended to lessen more with practice in the three-key than in the five-key sequence. Multivariate comparisons showed that the interval preceding the last key in both sequences decreased more with practice than those preceding the earlier keys, but in the five-key sequence the difference between T_3 and T_5 did not reach significance.

Discussion

This experiment was primarily designed to assess the effects of sequence length and practice on the possibility of selecting a forthcoming key press during execution of previous key presses and to investigate whether sequence execution is hampered by such concurrent response selection. Despite the more complex keying task and the requirement that it be performed at the highest speed possible, the results are largely in agreement with those of Garcia-Colera and Semjen (1988) in that concurrent selection occurred: The compatibility effect, which was clearly demonstrated in the one-key condition, was virtually absent in the multikey sequences. The finding that concurrent response selection developed with practice in movement sequences is consistent with recent models of writing (e.g., Van Galen, 1991) and key pressing (Rosenbaum et al., 1987) and does not support the notion that sequences are always prepared as a whole before execution starts (Inhoff et al., 1984; Rosenbaum et al., 1984; Sternberg et al., 1978). Whether other processes involved in preparing the choice key (e.g., motor programming, parameter setting, and motor initiation; Van Galen & Teulings, 1983) affected execution of the fixed keys cannot be determined from the present data because these other processes are assumed to be unaffected by the compatibility manipulation (Sanders, 1990). The present findings corroborate the notion that practice with movements sequences may operate not only by increasing the amount of concurrent programming (e.g., Portier et al., 1990; Semjen & Gottsdanker, 1990) but also by the development of concurrent selection of forthcoming movements. The results show that different demands of response selection need not affect concurrent sequence production. This implies that variations of concurrent processing load in sequence production cannot always be inferred from interval prolongation and, hence, that interval data may not always indicate the transition from one movement sequence to the next.

With limited practice, initiation of the three-key sequence and, to a minor extent, the interval preceding the choice key were affected by compatibility of the choice key. This suggests that with little practice some subjects selected the last key in the three-key sequence before the fixed keys were initiated, as also anticipated by Inhoff et al. (1984), and/others did so after the fixed part of the sequence had been completed. Apparently preparation for the choice key could not entirely concur with execution of the fixed keys. As this was not found in the earlier sessions of the five-key condition where selection load was the same, preparation of the choice key in the three-key sequence appears to have required more time than was available during execution of the fixed key presses. Note that the delayed preparatory process is not necessarily response selection. If, for example, only programming the last key in the three-key condition slowed down, the longer time needed to select an incompatible response may still have caused the observed compatibility effects. The absence of a compatibility effect on earlier key presses in the three- and five-key sequences supports the version of the time-availability hypothesis that assumes that execution is not hindered by concurrent selection. Practice seems not to be a necessary requirement for interference-free concurrent response selection in that the greater availability of time associated with longer sequences may compensate for limited practice.

These data suggest that multiple capacity models (Sanders, 1979; Wickens, 1984) are suitable to describe concurrent response selection in skilled sequence production because those models assume that response selection and execution tap different capacities and, hence, do not interfere. The usefulness of multicapacity models for concurrent processing in sequence production is further corroborated by the finding that with practice the interval preceding the last key press became clearly shorter than those preceding earlier key presses. This effect occurred independently of the compatibility manipulation. In itself, this confirms earlier results. Verwey (1994) advanced the notion that, with practice, a key pressing movement can be unpacked from the motor buffer while the preceding key press is being executed. However, this would delay the preceding key press. Because no key follows the last one, this one is not delayed by concurrent unpacking, and, hence, a relatively fast last key press suggests concurrent unpacking of earlier keys. The observation in the present study that the last key press became faster than earlier ones (also see Verwey, 1993) indicates that a single limited capacity feeds unpacking and execution processes. This is consistent with the multicapacity models (Sanders, 1979; Wickens, 1984), which state that typical motor processes tap the same limited capacity. Thus, the possibility of using multicapacity notions for describing patterns of interference between concurrent processes in skilled sequence production is supported by (a) the absence of interference between simultaneous selection of a forthcoming element in the sequence and execution of earlier elements and (b) the relatively fast last key press.

The complexity effect, which is usually interpreted as evidence for integrated sequence production (Henry & Rogers, 1960; Sternberg et al., 1978; Verwey, 1994), was found in the present study, in that compatible and incompatible five-key sequences were initiated more slowly than three-key sequences. This is significant in that it supports the assumption in the introductory comments that the fixed part of the sequence was prepared and executed as a whole irrespective of the compatibility of the last key. Sequence performance on a one-by-one basis would not have yielded the complexity effect.

In conclusion, the present study shows that the last key press in a sequence can be selected while earlier ones are being executed. With practice or with longer sequences, this does not affect execution of the sequence. This has ramifications for the possibility of inferring concurrent processing from interval prolongation. With only limited amounts of practice and shorter sequences, initiation of the sequence and the interval preceding the choice element may be affected by demands of response selection. This suggests that with limited practice concurrent preparation is slower than preparation that does not concur with execution. For real-world tasks these findings suggest that people may decide what to do next while performing a movement sequence without adverse effects on producing that sequence.

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NOTES

1. Because part of the evidence for concurrent processing comes from findings of reduced execution rates, concurrent processing is considered to be a more appropriate term than parallel processing, which suggests interference-free processing.
2. In some studies, this interval is referred to as RT.

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