Practicing a Structured Continuous Key-Pressing Task: Motor Chunking or Rhythm Consolidation?

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ABSTRACT. An experiment is reported on the effects of extensive practice in a task in which subjects \((N = 36)\) pressed a succession of nine keys with nine separate fingers, each key press in response to a corresponding stimulus. The order of the key presses remained constant over practice. Key-pressing cycles followed each other without interruption. A stimulus was usually presented immediately upon depressing the previous key, but in the structured conditions, a stimulus was preceded at either two (the 45 group) or three (the 33 group) positions by a 750-ms response-stimulus interval (RSI). This partitioned the sequence into three response groups for subjects in the 333 condition and into two response groups for subjects in the 45 condition. On occasion, all subjects performed in the unstructured condition, in which RTs were zero. Interkey times in this condition clearly reflected the position of the 750-ms RSI in the structured conditions. This suggests that motor chunks developed in the structured conditions were also used in the unstructured condition. Rhythm-based control, as proposed by Summers (1975), was rejected as an explanation for this effect because group-start/within-group ratios exceeded 2:1 and because the theory of rhythm-based control could not predict intervals in the unstructured 45 condition. Unstructured within-group intervals were slower than structured within-group intervals, which effect was more pronounced in the 333 than in the 45 condition. Also, the initial element of the unstructured four-key group was faster than the initial element of the unstructured three-key group. These and other findings (a) accord with the notion that in unstructured sequences preparing a forthcoming response group concurs with the execution of the preceding group and (b) suggest that shorter group are more slowed by concurrent preparation for the forthcoming group than are longer groups.

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

Practice is generally viewed as a major determinant of proficient motor performance. The classic notion is that the execution of movement sequences is constructed from the combining of elementary, sometimes innate, motor patterns or chunks (e.g., Book, 1908; Keele, 1986; Lashley, 1951; Miller, Galanter, & Pribram, 1960; Paillard, 1960). The reason for executing movement sequences as a concatenation of isolated chunks lies probably in the storage and retrieval efficiency associated with chunks (see, e.g., Jones, 1981; Newell & Rosenbloom, 1981; Restle, 1970). Yet, despite the persistence of this notion it is still insufficiently clear what exactly determines the development of motor chunks and their typical properties. Sternberg, Knoll, and Turock (1990) listed various features that may indicate that motor chunks are being used. One feature is that intervals separating successive component actions should be longer across than within chunk boundaries (e.g., Adams, 1984; Reason, 1979; Shaffer, 1976). Another feature concerns invariant execution of a chunk, which implies that intervals within chunks should be relatively constant (e.g., Gentner, 1987; Terzuolo & Viviani, 1980).

One of our purposes in the present study was to examine whether chunking develops in a multifinger key-pressing task when a timing structure is imposed during practice. This paradigm was developed by Summers and colleagues (Summers, 1975; Summers, Sargent, & Hawkins, 1984), who carried out several experiments in which nine keys had to be pressed with nine fingers in response to stimuli that were presented in nine spatially compatible locations. The stimuli were presented in a fixed order and at an experimenter-determined rate.

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Summers's interest concerned how the timing and sequencing aspects of motor skills are integrated. When a single sequence had been completed, it was immediately produced again so that subjects continuously cycled through the nine key presses. In one condition (the 511 condition in Summers, 1975), the sequence was structured in that it contained three response groups. Each response group started with a 500-ms response-stimulus interval (RSI) that preceded the stimulus to the first key press of the group, whereas two 100-ms RSIs preceded the stimuli to the second and third key presses. Following extensive practice, the subjects were instructed to reproduce the sequence as fast as possible in an unstructured condition without RSIs and without any requirement to adhere to the original timing structure. The results showed that the timing structure was maintained during 10 subsequent blocks of unstructured cycles: Responses to stimuli that had been preceded by a 500-ms RSI in the structured practice condition were about twice as slow in the unstructured condition than were the remaining responses in the unstructured condition.

Summers proposed that relative timing becomes an integral part of the motor program representation. He argued that the long intervals were about twice as long as the short ones because of a "natural" tendency to adhere to 1:1 or 2:1 ratios. These ratios are stable because rhythms are symmetrical, hierarchical structures of time patterns in which basically all elements in the output occur at equal time intervals (Martin, 1972). When the number of events in a sequence deviates from a power of two, subjects would insert "blank" elements—that is, covert sequence elements—at appropriate points to represent the sequence as a binary tree with equal intervals between successive elements (also see Keele & Summers, 1976). Insertion of a blank leads to the 2:1 ratio. Therefore, rapid and continuous execution of the 511 sequence, without the need to adhere to the timing structure, yields the observed 2:1:1 ratio for each group of three key presses because a blank is inserted at the position of the 500-ms RSI during practice, so a binary tree representation consisting of four elements is used. This would have the effect that, with practice, the rhythm of these types of key-pressing sequences consolidates.

Summers (1975) used a model for explaining his data that was developed for rhythm production at submaximal rates. The suggestion that performance in the rapidly executed unstructured condition relies on the same clock-like triggering mechanism that is asserted for relatively slow rhythm production is not necessarily valid. The interkey times in the unstructured sequence might have been determined by the duration of the processes involved in producing the responses in the appropriate order. Summers's (1975) finding, then, that the original timing structure returned in the unstructured condition could suggest that the timing structure in the structured condition had partitioned the sequence into separate motor chunks. These became robust in the course of practice and were also used when not explicitly required in the unstructured condition. This chunking hypothesis presumes hierarchical sequence execution (Sternberg et al., 1990), in that chunks of key presses are selected and programmed as a whole at a higher level, whereas at a lower level individual key presses of the chunk are retrieved and executed from a motor buffer (Henry & Rogers, 1960; Sternberg, Monsell, Knoll, & Wright, 1978). Our main purpose in the present experiment was to test the merits of the hypothesis that imposing a timing structure in Summers's (1975) type of task governs the development of motor chunks rather than induces a natural rhythm.

The chunking hypothesis implies that the 2:1 ratio observed by Summers (1975) in the unstructured condition was merely incidental. The ratio would actually depend on practice. The impact of chunking would increase with practice because subjects tend to select and program the chunk more and more as a whole prior to its initiation. The times between successive keys within a response group would decrease more with practice than the time preceding a response group because programming load would gradually shift to the start of the response group, and this shift has the effect that the ratio increases. Accordingly, we investigated whether the ratio of times preceding and within response groups in the unstructured condition exceeds 2:1.

The second purpose of this study concerned the possibility that preparation of a response group may overlap with execution of the earlier response group. These preparatory processes appear to involve various subprocesses, such as response selection (Verwey, 1995), motor programming (Garcia-Colera & Semjen, 1987, 1988; Rosenbaum, Hindorff, & Munro, 1987; Van Donkelaar & Franks, 1991; Verwey, 1995), and unpacking (Verwey, 1993, 1994). The extent of concurrence depends on factors like practice, execution rate, and the number of units in the preceding sequence (Canic & Franks, 1989; Hultsijn & Van Galen, 1983; Verwey, 1995). This could imply that, in the present task, preparation of a response group may occur in parallel with execution of the preceding group. This would probably delay execution of the preceding response group (Portier, Van Galen, & Meulenbroek, 1990; Verwey, 1995). Hence, response groups may be executed more slowly in the unstructured than in the structured condition because the absence of pauses in the unstructured condition may cause preparation of the forthcoming response group to occur during execution of its predecessor.

In the present experiment, the predictions derived from the chunking hypothesis were tested in Summers's (1975) type of key-pressing task. To decide whether concurrent preparation in the unstructured condition slows response groups, we removed Summers's (1975) 100-ms RSIs in the structured condition; within structured and unstructured response groups, the stimuli at these positions were presented immediately upon pressing the earlier key. To ascertain that individual response groups were well separated during practice in structured, we used 750- rather than 500-ms intergroup RSIs. In the 333 condition, subjects practiced a sequence, or cycle, in which the long RSIs were located.
so that there were three groups of three key presses each (RSI order: 750-0-0-750-0-0-750-0-0 ms). In the 45 condition, another group of subjects practiced the same sequence, which now contained two long RSIs partitioning the sequence into a four- and a five-key group (750-0-0-0-750-0-0-0-0-0 ms). Occasionally, all subjects carried out blocks with unstructured cycles in which all RSIs were zero. Hence, no timing structure was imposed in unstructured.

It was expected that the timing structure in the 333 sequences would determine the duration of the unstructured response times in a way similar to that reported by Summers (1975) for his S11 condition. Although the present RSIs in the structured conditions were 750 ms rather than Summers's (1975) 500 ms, and the 100-ms within-group RSIs were removed, the natural rhythm hypothesis still predicts that ratios between response times in the unstructured condition should be either 1:1 or 2:1 for individual subjects. Only if different partitioning patterns occur across subjects could the average ratios be between 1:1 and 2:1. Yet, they should never exceed 2:1. The 45 sequence was used because the natural rhythm hypothesis cannot predict in what way it will be executed. According to the rhythm hypothesis, several options are conceivable. For instance, the entire sequence might be represented by a binary tree or separate groups might be represented by binary trees. As a consequence, subjects are likely to adopt different tree representations, so that after averaging across subjects, we would expect no specific structure in unstructured sequences.

The chunking hypothesis, on the other hand, predicts that the original timing structure will be reflected in the response times of both the unstructured 333 and 45 conditions. The ratio between response time preceding an unstructured response group and that within an unstructured response group need not reach asymptote at 2:1. Instead, it should gradually increase with practice and may exceed 2:1.

In short, subjects continuously cycled through the same series of nine key presses. Each key was pressed with a different finger, and each key press was given in response to a corresponding stimulus. Subjects usually performed in the structured conditions in which the RSI at three (333 condition) or at two (45 condition) positions amounted to 750 ms, whereas the remaining RSIs were 0 ms. The merits of the chunking hypothesis and of the natural rhythm hypothesis were tested in the unstructured condition in which all RSIs were zero and which was performed occasionally in the course of practice. The rhythm hypothesis is corroborated when (a) a pattern of response times in the unstructured 45 condition is found that deviates from the structured time pattern and (b) the group-start/within-group ratio in 333 is 2:1 or, because of individual differences, between 1:1 and 2:1. However, this ratio may never exceed 2:1—neither when averaged across subjects nor when averaged for individual subjects. In contrast, motor chunking is supported when (a) in the unstructured 333 and 45 sequences long response times are observed at the positions of the 750-ms

RSIs in the structured sequences. (b) When the group-start/within-group ratio exceeds 2:1, this would offer further support for motor chunking. Concurrent preparation is suggested when (c) within-group response times are longer in unstructured than in structured sequences.

**Method**

**Subjects**

Subjects were 36 paid students (initially 15 males and 21 females) from Utrecht University. Eighteen subjects were randomly assigned to each of the two structure conditions. They were paid 90 Dutch guilders for participation. Six subjects in each group received a bonus of 25 guilders. Four subjects were replaced (3 males and 1 female): one because of illness, 2 because of data loss, and 1 because of extremely poor performance. They were replaced by 4 other subjects (2 males and 2 females).

**Tasks**

A block started with a written instruction to position the left little finger, ring, middle, and index fingers on the z, d, f, and g keys of an ordinary PC keyboard and the right thumb, index, middle, ring, and little fingers on the space bar, j, k, l, and / keys, respectively. These assignments were chosen so that each finger could easily press a separate key (Figure 1). The computer screen displayed white outlines of nine squares in the same spatial arrangement as the assigned keys. The task started when one of the nine squares became homogeneously green as if a light had been turned on. Subjects responded by pressing the corresponding key, whereupon the green content disappeared as if the light had been turned off. After a predetermined response–stimulus interval (RSI) one of the other eight squares turned green, which was again followed by pressing the corresponding key. In this way a sequence of nine key presses was carried out in which each of the nine keys was pressed once. Only the moment of key depression was registered, not the moment of its release, and keys could be released after ensuing ones had been depressed. Immediately upon completion of the nine-key sequence, the next cycle started, which involved the same sequence of nine key presses.

The RSIs in the structured conditions were fixed for either subject group in that the long and zero intervals

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![Figure 1](attachment:layout_of_letter_keys_on_ordinary_PC_keyboard.jpg) **FIGURE 1.** Layout of the letter keys on an ordinary PC keyboard. Underlined keys and the space bar were operated by nine different fingers. Indices denote location numbers that are used in the text to indicate response order.
always occurred at the same positions of the sequence. Subjects in the 333 condition practiced with RSIs: 750-0-0-750-0-0-750-0-0 ms (750 ms between R0 and S1, 0 ms between R1 and S2, and between R2 and S3, etc.). Subjects in the 45 condition practiced the same key-pressing sequence with the RSI sequence 750-0-0-750-0-0-0-0-0 ms. In the unstructured condition all RSIs were 0 ms, rendering the same task for all subjects.

The same basic sequence was used for all subjects, but each of the nine keys functioned as a starting key for 2 subjects of a group. For example, when the stimulus locations were designated 1 through 8 for the fingers from left to right and the right thumb was designated 9, one sequence was 5 9 1 7 4 2 6 8 3 (see Figure 1). This sequence was also used by Summers (1975) and was carried out by 2 subjects of each group. Two other subjects of each group executed 9 1 7 4 2 6 8 3 5, and so forth. In this way, all response times had all between-hands and within-hand transitions. This is important because they are known to affect the time between subsequent key presses (Kornblum, 1965; Kornbrot, 1989).

Procedure

On the first day, a written instruction was handed out to the subjects that briefly introduced the task and the way the computer had to be controlled. We instructed subjects to type as fast and accurately as possible so that their scores at the end of each block would be maximized. They were told that the 6 highest scoring subjects of each group would earn a bonus. All individual blocks were also preceded by a written instruction on the computer monitor, which indicated the sequence to be pressed and, when appropriate, that no long RSIs would occur.

Each subject carried out seven sessions on two consecutive mornings or afternoons. In total, 36 subjects took part; they were assigned to six groups of 6 subjects. Within each group, 3 subjects had the 333 condition and 3 subjects had the 45 condition. On each morning or afternoon, two groups were tested in alternation. While one group was tested, the other group relaxed in an adjacent room. This resulted in a 15-min rest and test schedule for each subject.

All 14 sessions consisted of four blocks of cycles. The fourth block of Sessions 1, 3, 5, 8, 10, and 12 had unstructured sequences; all other blocks involved structured sequences. A block had 30 cycles. Each cycle included one sequence of nine key presses, which followed the preceding nine-key-press cycle immediately. Blocks were separated by a 20-s break.

During a block of cycles, the keys were always pressed in a fixed order. Hence, the subjects soon knew which key to press next. In structured sequences, this had the effect that they could press the key before the 750-ms RSI had elapsed and the stimulus had been presented. When this happened, a "too early" message was presented. An error message also occurred when an incorrect key was pressed or when no key was pressed at all during a 3,500-ms interval. In these three situations, key-pressing continued only after the correct key had been pressed.

Each block was followed by display of a score, which ranged from 0 to 100 points. The score consisted of a weighted combination of speed and accuracy. The score depended on keying speed in such a way that higher scores both early and late in practice were still reflected. Accuracy affected scoring in that subjects were "punished" with reduced scores for low and high error rates: Below 3% and over 6% errors, the score was reduced by a fixed amount, and the reduction was even larger when errors exceeded 10%. Error rates less than 3% evoked the instruction to increase keying speed—unless the response time was below 100 ms—whereas error rates of more than 10% elicited the instruction to reduce errors. Response times or error scores were not displayed.

Apparatus

The experiment was conducted on seven identical IBM AT-compatible (386) computers with NEC Multisync VGA 3D color monitors, one of which was used as a spare. Stimulus presentation and response collection were controlled through Micro Experimental Laboratory software (MEL; Schneider, 1988). At a typical viewing distance of about 65 cm, a square subtended a visual angle of approximately 1°. The stimuli consisted of a bright green area filling the outline of a bright white square 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, variabilities caused by these keyboard delays add approximately 19 ms to the error variance. Given the large number of cycles in the present study, this was considered acceptable (Segalowitz & Graves, 1990).

Six subjects were simultaneously tested in six sound-attenuated 2.4 × 2.5 × 2-m rooms. There they sat in front of a table on which the keyboard and a computer monitor were positioned. They were monitored by way of a video circuit.

Results

In general, key presses involving an error and the two key presses following that error were discarded from analysis. In each block, the first two cycles were considered as warming-up and also were discarded. To eliminate outliers, we computed individual cut-off values for each condition and session. This eliminated less than 2% of the data. To obtain independence of means and variances, we carried out an arcsine transformation on mean error rates per cell before the data were subjected to analyses of variance (ANOVA)(Winer, Brown, & Michels, 1991). All ANOVAs on response times showed highly significant main effects of session (all ps < .001), which are not separately reported. Sets of three ANOVAs were used for contrasting response groups: Between-subjects analyses were used for compar-
ing the three- and four-key groups and the three- and five-key groups. Within-subject analyses were applied for comparing four- and five-key groups.

The main results concern (a) the timing pattern in unstructured sequences, (b) the group-start/within-group ratios in the unstructured condition, and (c) the comparison of the structured and unstructured within-group intervals. Group-start intervals are response times at the positions of the 750-ms RSIs in the structured condition. The remaining response times are denoted within-group intervals.

First, Figure 2 clearly shows that response times in unstructured sequences reflected the RSI pattern used in the structured 333 and 45 sequences. The ANOVAs on unstructured sequences confirmed that group-start and pooled within-group intervals differed in all three response groups: Pooled three-key groups, $F(1, 9) = 25.8$; four-key group, $F(1, 9) = 32.4$; five-key group, $F(1, 9) = 61.5$; all $p < .001$. These differences increased with practice; $Fs(5, 45) = 15.0, 4.2,$ and $7.5$, respectively, all $p < .001$.

Second, Figure 3 confirms the increasing difference between group-start and within-group intervals with practice in unstructured sequences in that the group-start/within-group ratio increased gradually with practice in 333 and 45: three-key group, $F(5, 45) = 9.2$; four-key group, $F(5, 45) = 13.7$; five-key group, $F(5, 45) = 8.1$; all $p < .001$. In the last unstructured sessions the ratio exceeded 3:1 in the 333 condition and 2:1 in the 45 condition. When pooling four- and five-key ratios, a marginally significant interaction between structure and session was found, $F(5, 90) = 2.02, p = .08$, suggesting that the ratio increased more in 333 than in 45.

Examination of the data of individual subjects showed large individual differences. The group-start/within-group ratios in the last unstructured session of individual subjects ranged from 1.0:1 to 8.6:1 in 333 and from 0.9:1 to 6.5:1 in 45. In Session 12 of the 333 condition, 10 out of 18 subjects had ratios of over 2:1, 6 had ratios exceeding 3:1, and 3 had ratios exceeding 7:1. In Session 12 of 45, 3 subjects exceeded 3:1.

Third, within-group response times were smaller in structured than in unstructured response groups: three-key group, 204 versus 298 ms, $F(1, 9) = 44.5$; four-key group, 222 versus 271 ms, $F(1, 9) = 71.3$; five-key group, 236 versus 292 ms, $F(1, 9) = 95.4$; all $p < .001$. These intervals also decreased more with practice in structured than in unstructured response groups; difference between Sessions 1 and 12 in the three-key group, 361 versus 312 ms, $F(5, 45) = 23.5$; in the four-key group, 363 versus 283 ms, $F(5,$

**FIGURE 2.** Response times in structured and unstructured sequences of the 333 and 45 groups at two levels of practice. Squares indicate key presses that, in the structured condition, were preceded by a 750-ms RSI (i.e., group-start intervals).
45) = 40.6; in the five-key group, 372 versus 294 ms, F(5, 45) = 25.2; all p < .001. The difference between structured and unstructured within-group response times was larger in the three- than in the four- and five-key groups: Pooled across sessions, the differences in the three- and four-key groups were 94 and 49 ms, F(1, 18) = 8.4, p < .01, and were 94 and 56 ms in the three- and five-key groups, F(1, 18) = 8.3, p < .01. For four- and five-key groups, the difference between structured and unstructured within-group response times was comparable, F(1, 9) = 1.3, p > .20. This pattern of results suggests that four- and five-key groups were less hampered by concurrent preparation than three-key groups were, but all were slowed to some extent.

Average error proportions in structured sequences amounted to 4.2% in 333 and 5.5% in 45, F(1, 18) = 4.3, p < .06. A Structure x Session interaction, F(13, 234) = 2.5 p < .01, indicated that errors decreased in 333 (Sessions 1 and 2, 4.7%; Sessions 13 and 14, 3.8%) and not in 45 (5.3% and 5.6%, respectively). In unstructured sequences, the average error percentage amounted to 7.3% in 333 and 7.7% in 45. No significant effects were found in the error analyses of the unstructured sequences.

Various effects of secondary interest were observed. First, in Sessions 1 and 2 a difference was found between group-start and within-group response times in the structured three-key groups. As shown in Figure 2, these differences largely disappeared in later sessions. In the three-key group, the difference between pooled group-start times (T1, T4, and T7) and pooled within-group response times (T2, T3, T5, T6, and T8) amounted to 37 ms over all sessions, F(1, 9) = 51.8, p < .001. This difference decreased with practice from 72 ms in Sessions 1 and 2 to 14 ms in Sessions 13 and 14, F(1, 9) = 5.3, p < .001. In 45, group-start and within-group intervals did not differ. The larger reduction with practice of the initiation interval of three- as compared with four-key groups (initiation of three-key groups was 30 ms slower than initiation of four-key groups in Sessions 1 and 2 and 26 ms faster in Sessions 13 and 14) led to a significant Three- versus Four-Key x Session interaction, F(13, 234) = 3.5, p < .001. Together, these findings offer support for the notion that concurrent preparation occurred in structured 45 sequences but did not, or did so to a lesser degree, in structured 333 sequences.

Second, comparisons of within-group response times suggested that longer groups were executed more slowly than fewer keys groups. In unstructured sequences, the response times within the four-key group were faster than those within the five-key group (271 vs. 292 ms), F(1, 9) = 5.1, p < .05. In structured sequences, within-group times tended to be longer in five- than in three- and four-key groups; 209 versus 177 ms, F(1, 18) = 3.2, p < .10, and 209 versus 195 ms, F(1, 9) = 3.9, p < .08, respectively. An unpredicted indication that preparation can overlap more with the preceding response group when it is longer was the observation that the unstructured four-key group tended to be initiated faster than the unstructured three-key group (384 ms vs. 448 ms, respectively), F(1, 18) = 3.7, p < .08.

Third, comparison of a scatter plots of the ratios obtained in the structured condition with those in the unstructured condition showed that subjects with a large group-start/within-group ratio in the last two unstructured sessions also demonstrated a relatively large ratio in structured blocks of these sessions, whereas subjects with relatively small unstructured ratios had small or intermediate structured ratios. This was corroborated by correlations between the ratios in both conditions (333, r = .42, p < .09; 45, r = .33, p > .15; together, r = .32, p < .06).

A final observation concerned a negative correlation between individual group-start/within-group ratios in the unstructured sequences and individual within-group response times (333, r = -.55, p < .05; 45, r = -.44, p < .07; together, r = -.49, p < .01). Such a relationship was not found between the individual ratios and the individual group-start times (333, r = -.33, p > .15; 45, r = .06, p > .20; together, r = -.23, p > .15). The latter two observations suggest that subjects who had used the timing structure of the structured condition for partitioning more also partitioned the unstructured sequence more and had smaller within-group response times than subjects who had used the timing in structured sequences for partitioning less.

**Discussion**

As pointed out earlier, this study bears on two issues: sequence reproduction by way of natural rhythm versus motor chunking and concurrent processing in unstructured sequence production. The data endorse motor chunking and
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consistent processing and reject the natural rhythm hypothesis.

Consistent with the natural rhythm hypothesis, the RSI pattern in the structured 333 condition determined the response times in the unstructured 333 condition. This replicates Summers's (1975) data. However, the natural rhythm hypothesis can be rejected for several reasons. First, it is unable to predict the response times obtained in the unstructured 45 condition. In fact, the interval durations in 45 did not match a binary tree representation for either response group as would be expected by the rhythm hypothesis. Second, the group-start and within-group response times did not adhere to 2:1 ratios but exceeded 3:1 in 333 and 2:1 in 45. For some subjects the ratio even developed up to 8:1 in 333 and up to 6:1 in 45. A third problem for the rhythm hypothesis is that it predicts either a 1:1 or a 2:1 ratio. Detailed examination of the present results showed that the ratios of individual subjects increased only very gradually and not in a step-like manner as suggested by the rhythm hypothesis. If intermediate ratios result from averaging 1:1 and 2:1 cycles, it is hard to see why the ratios of 1:1 and 2:1 cycles would change so gradually for individual subjects. On the basis of these considerations, the natural rhythm hypothesis was rejected for the present task.

The data are more consistent with the view that motor chunks developed and that unstructured response groups were prepared during execution of the preceding response group. First, unstructured response times mimicked the RSI patterns in the structured 333 and 45 conditions. Second, as mentioned above, the average ratio of group-start and within-group intervals exceeded 2:1 in the 333 and 45 conditions. The difference between group-start and within-group response times increased gradually with practice, affirming the view that subjects increasingly selected and programmed the key presses as a group before initiating the first element of that group. This is no direct proof that chunks developed, but chunking is a plausible explanation for this apparent shift in preparation load. Future work might address the existence of motor chunks in a transfer paradigm by showing that changed response groups, for which no chunks exist, are executed more slowly than practiced response groups (see Verwey, in press). The finding that grouping also occurred in the 45 condition suggests that key-pressing chunks can contain more than the two or three elements that would usually make up a group (Gordon & Meyer, 1987; Rosenbaum, Kenny, & Derr, 1983).

It is important to note that subjects showed highly consistent individual response patterns in structured and unstructured sequences; some reacted strongly to the timing structure (large ratios) although others did not react at all (ratio 1:1). On the one hand, the finding that individual ratios in structured and unstructured conditions were correlated suggests that it was indeed the tendency to execute key presses in groups in the structured condition that induced the development of motor chunks, which, in turn, increased the ratios in the unstructured condition. On the other hand, the finding that not all subjects used the timing structure for partitioning indicates that future studies should use more explicit ways to force subjects to break up the movement sequence into groups. One may, for example, explicitly instruct subjects to execute key presses as groups, or one may increase the temporal separation between response groups by practicing them in complete isolation.

The second issue, related to motor chunking, concerns whether preparing a response group in the unstructured condition overlaps with execution of the previous group. The data support this notion because unstructured within-group response times were longer than structured within-group times—that is, the data reflect interference between execution and preparation. One could expect that preparation of a forthcoming response group in unstructured sequences might eventually concur entirely with the execution of the preceding response group. In that case, group-start times would reduce to the level of within-group response times. This did not occur, and concurrent preparation remained a second-order effect. Possibly, not all processes involved in preparation can concur with execution. For example, after the appropriate chunk has been selected during execution of the preceding group, loading the motor buffer might have to wait until the earlier group has been entirely executed (for other processes that might concur, see Sanders, 1990; Spijkers, 1990). That, in the present study, slowing of unstructured response groups did not disappear with practice whereas it did when only response selection occurred while key presses were executed (Verwey, 1995) is in line with the notion that processes other than response selection concur with execution of the response groups.

Recent findings by Verwey (1995) showed that the larger demands associated with selecting an incompatible response, as compared with a compatible response, no longer affected a series of earlier, stimulus-independent responses when this series contained four rather than two responses. It was concluded that the effect of concurrent preparation on ongoing sequence execution reduces as the ongoing sequence becomes longer. In a similar vein, one may expect that, in the present study, preparation of a response group slows the preceding response group less as this earlier group gets longer and, therefore, it provides more possibilities for concurrent preparation. The present data provide support for this notion. First, unstructured three-key within-group intervals were slowed more, as compared with structured sequences, than those in unstructured four- and five-key groups. Second, unstructured three-key groups were initiated more slowly than the four-key group was, whereas, with respect to the complexity effect (Sternberg et al., 1978), one would rather expect the reverse effect. Third, group-start/within-group ratios tended to increase more with practice in 333 than in 45: Shifting preparation to the execution phase of the preceding response group may have been easier for the longer four- and five-key groups of 45 than for the three-key groups of 333. Fourth, group-start intervals in the early sessions of the
structured condition were relatively slow in 333 but not in 45: In early practice, the 750-ms RSIs in the structured 333 sequences may not have been long enough for full preparation, causing initiation of the 333 groups to be postponed. Probably there was more time or opportunity for concurrent preparation in the structured 45 than in the structured 333 condition. The resulting higher time pressure in the earlier 333 sessions may explain why error rate reduced with practice in 333 sequences.

Notice that the data do not endorse easier concurrent preparation for longer ongoing response execution when comparing the four- and five-key groups of the 45 condition. In that case, the five-key group should have been executed faster than the four-key group rather than slower. Perhaps the longer time available during execution of the five-key group was not useful and concurrent preparation is a problem only with short response groups (e.g., those with up to three elements).

Summing up, the present study favors the notion that practice in a sequential movement task invokes motor chunks when a timing structure is imposed during prolonged practice. The view that mechanisms underlying rhythmic performance also determine performance in speeded continuous performance is rejected because group-start/within-group ratios exceeded 2:1 and the unstructured 45 condition showed a timing pattern similar to the one that had been practiced in structured 45 sequences. These results may be attributable to either the high execution rate or the spatial demands of the present task, or both. The notion of concurrent processing, which is closely associated with motor chunking, can account for the detailed pattern of the results: When a response group was longer, preparation could concur more easily with execution of the preceding response group, but in unstructured sequences this decreased the execution rate. It is hard to see how the rhythm hypothesis can account for these findings. Future research should establish the robustness of motor chunks in other situations, whether these chunks are entirely specific to their contents, and which preparatory processes can occur during execution with and without interference.

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NOTES

1. This is why the term preparation is preferred here over the more specific term programming.

2. This is probably what happened in Summers's (1975) 551 condition, where two long RSIs were followed by one short RSI. In terms of the chunking hypothesis, this timing structure did not impose a fixed partitioning pattern so that, because of inter- and intraindividual differences, no single, robust grouping structure evolved.

3. One block was discarded because of time pressure during the experiment. This caused the jumps in the unstructured condition from Sessions 5 to 8 (see e.g., Figure 3).

4. As noted by one of the reviewers, the data in Figure 2 suggested smaller ratios than those presented in Figure 3. Indeed, dividing the group-start and within-group intervals of Session 12 yielded the ratios 2.2:1 (333) and 1.9:1 (45). This difference was entirely accounted for by the fact that estimation of ratios from Figure 2 involved averaging intervals across subjects before calculating ratios, rather than averaging across ratios of individual subjects. The difference between both procedures can be explained by the fact that averaging intervals across subjects puts emphasis on slower subjects who, apparently, had smaller ratios. Computation of average ratios on the basis of individual ratios is the only appropriate procedure because the rhythm hypothesis predicts ratios for individual subjects. But even when considering the alternative data, the average ratio in Session 12 of the 333 condition exceeded 2:1, implying that a number of subjects had ratios over 2:1.

5. Note that the seemingly fast structured group-start intervals in Figure 2 were due to the fact that they followed the 750-ms RSI, which allowed subjects to prepare in advance of stimulus presentation and to estimate the moment of stimulus arrival.

REFERENCES


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