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BUFFER LOADING AND CHUNKING IN SEQUENTIAL KEYPRESSING

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W.B. Verwey
18 maart 1994, Rapport TM 1994 B-7
TNO Technische Menskunde[1], Soesterberg

MANAGEMENT UITTREKSEL

Dit rapport beschrijft een experiment naar de effecten van oefening in een taak waarin een serie toetsen met verschillende vingers wordt ingedrukt, elke toets in reactie op een corresponderende stimulus. Een trial bestond altijd uit negen responsen waarvan de volgorde consistent bleef gedurende oefening. Trials volgden elkaar zonder onderbreking. Een stimulus werd meestal gepresenteerd direct na het indrukken van de voorafgaande toets maar op twee of drie posities in de Structured conditie werd een stimulus voorafgegaan door een Respons Stimulus Interval (RSI) welke de sequentie in twee of drie groepen verdeelde. Een eerdere studie met deze taak liet zien dat wanneer de RSIs weggehaald werden in een Unstructured conditie, relatief langzame responses voorkwamen op de posities van de RSIs (Verwey & Dronkert, 1993). Gedetailleerde analyse suggereerde dat het opgelegde ritme de ontwikkeling van geïntegreerde chunks had bewerkstelligd, welke de responsgroepen representeerden, en die een belangrijkere rol speelden in Unstructured dan in Structured. De huidige studie bevatte een Practice en een Transfer fase. In de Practice fase was de hoofdvraag of de prestatie langzamer zou toenemen in Unstructured dan in Structured: De prestatie in Unstructured zou bepaald worden door de verwachte langzame ontwikkeling van chunks terwijl in Structured de mogelijkheid om de sequentie van tevoren in een buffer te laden zich sneller zou ontwikkelen. Daarnaast werd gekeken of responsgroepen in Unstructured vertraagd zouden worden door gelijktijdige voorbereiding van de volgende responsgroep. Daarnaast werd gekeken of responsgroepen in Unstructured vertraagd zouden worden door gelijktijdige voorbereiding van de volgende responsgroep. De data ondersteunde beide hypothesen. In de Transfer fase werd de hypothese onderzocht dat oefening met een responsgroep de prestatie op nieuwe responsgroepen weinig verbeterd, tenzij de uitvoering voorbereid kan worden en de responsgroep tamelijk kort is. Deze hypothese werd ook bevestigd. Het feit dat delen van de geoefende sequenties in voor de rest nieuwe sequenties voorkwamen droeg nauwelijks bij aan de prestatie op de nieuwe sequenties. De data worden verklaard met een model waarin een zich langzaam ontwikkelende, sequentie-specifieke chunk gebruikt wordt om sequentieuitvoering te sturen (het *wat* mechanisme), en een zich snel vormende sequentie-aspecifiek mechanisme dat voorprogrammeren in een buffer en gelijktijdige informatieverwerking op meerdere niveaus mogelijk maakt en dat gebruikt wordt om de abstracte volgorde informatie van de chunk te vertalen in daadwerkelijke beweging (het *hoe* mechanisme).

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SUMMARY

An experiment is reported on the effects of extensive practice in a task in which a succession of keys was pressed with separate fingers, each keypress in response to a corresponding stimulus. A trial always consisted of nine responses, the order of which remained constant over practice. Trials followed each other without interruption. A stimulus was usually presented immediately upon depressing the previous key but at two or three positions in the Structured condition, a stimulus was preceded by a variable Response Stimulus Interval (RSI), which partitioned the sequence into two or three groups of responses. An earlier study with this task had shown that when these RSIs were removed in an Unstructured condition, relatively slow responses were found at the positions of the previously practised RSIs (Verwey & Dronkert, 1993). Detailed analyses suggested that the imposed rhythm had caused the development of integrated chunks, representing the response groups, which were more important in Unstructured than in Structured. The present study involved a Practice and a Transfer phase. In the Practice phase the main question was whether performance would improve more slowly in Unstructured than in Structured: Performance in Unstructured could rely on the alleged slow chunk development while performance in Structured could rely on the probably faster development of advance buffer loading. In addition, delayed execution of response groups in Unstructured by concurrent preparation of forthcoming response groups was tested. The data supported both hypotheses. In the Transfer phase the hypothesis was tested that practice with a response group does only improve execution of a new response group substantially when there are ample opportunities for advance preparation and when the group is relatively short. This hypothesis was also confirmed. The occurrence of parts of practised response groups in otherwise new response groups had only a limited effect on the production rate of these response groups. A two level model of sequence production is proposed involving a slowly developing, sequence-specific chunk which is used to control sequence execution (the *what* mechanism), and a rapidly evolving, sequence-aspecific execution mechanism involving advance programming and concurrent processing which translates abstract order information into actual movements (the *how* mechanism).

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Soesterberg

Het laden van de motor buffer versus het gebruik van motor chunks bij sequentiële toetsdrukseries

W.B. Verwey

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1 INTRODUCTION

Since the early days of research on human motor behaviour it has been known that practice is the predominant factor in shaping performance. Yet, the basic mechanisms underlying practice effects are still largely unknown. One classic but still influential notion is that with practice elements pertaining to a specific task are encapsulated in integrated chunks which, then, can be handled as a single and more simple representation (Miller, 1956). As regards the execution of movement sequences, this could mean that chunks are constructed by combining representations of elementary, sometimes innate, movements or movement patterns (e.g., Adams, 1984; Book, 1908; Bruner, 1973; Fentress, 1984; Keele, 1986; Lashley, 1951; Miller, Galanter & Pribram, 1960; Paillard, 1960). The benefit of movement chunks would lie in the associated reduction of storage and retrieval capacity (see e.g. Gallistel, 1980; Jones, 1981; Newell & Rosenbloom, 1981).

Relatively little is known about the characteristics of movement chunks and their relation to producing movement sequences in various situations. The main purpose of the present paper consists of investigating the notion of movement chunking and pursuing its relation to the production of relatively short movement sequences and motor storage. To that end, the first part of the paper describes a Practice phase which investigates the development of movement chunks in a sequential keypressing task in which the inclusion of a few long intervals at fixed positions is assumed to determine the boundaries between developing chunks (Verwey & Dronkert, 1993). In the second part of the paper, the Transfer phase addresses the specificity of practice as implied in the chunking notion.

Verwey and Dronkert (1993) investigated chunk development in a task involving prolonged repeated production of the same sequence of keypresses. Each trial consisted of nine self-paced key responses to nine stimuli which were carried out in rapid succession with nine fingers and each trial was immediately followed by the next identical trial. In this way there was in fact continuous keypressing during a block of trials. In the *Structured* condition, each trial had three or two Response Stimulus Intervals (RSIs) which partitioned a sequence into three response groups for half the subjects (333 condition) and into two response groups for the remaining subjects (45 condition). On occasion all subjects carried out the *Unstructured* condition which had no RSIs at all, so that a new stimulus immediately followed the depression of the preceding key. The results showed that Unstructured interkey times, clearly and increasingly, reflected the RSIs in Structured. That is, the intervals preceding the first responses in each group in Structured (i.e. the group-start intervals) were longer in Unstructured than the intervals preceding the other responses in each group (i.e. the within-group intervals). This accords with the notion that movement chunks are separated by relatively long intervals (Gee & Grosjean, 1983; Machlis, 1977; Rosenbaum, Kenny & Derr, 1983; Sternberg, Knoll & Turock, 1990). Possibly, in the course of practice consistently loading a motor buffer in advance of response group execution (Henry & Rogers, 1960; Sternberg, Monsell, Knoll & Wright, 1978) leads to the formation of associations between ensuing responses in a response group and, hence, to movement chunks (Brown & Carr, 1989; Fischman & Lim, 1991; MacKay, 1982, 1987). This notion was corroborated by correlational analyses which suggested that subjects who had made more use of the RSIs in the Structured condition for advance preparation of the forthcoming response group (as indicated by higher group-start/within-group ratios) also had higher group-start/within-group ratios in Unstructured.

The present study aimed at replicating and extending the results obtained by Verwey and Dronkert (1993). The reasoning in this paper rests upon the following two notions. (1) *Buffer loading* (Henry & Rogers, 1960; Sternberg et al., 1978): if there is sufficient time available, sequences can be programmed in advance in a short-term motor buffer. In principle, buffer loading is not specific to a certain sequence. Longer sequences require more programming time than shorter sequences (i.e. the complexity effect) and the average within-group intervals increase with sequence length. (2) *Chunking* (Brown & Carr, 1989; MacKay, 1982): movement chunks develop as a result of repeatedly filling the motor buffer with the same elements through the gradual development of inter-element associations. Hence, chunks are specific with regards to the sequences they represent. It is assumed that loading a buffer with a chunk requires less time than when, in the absence of a chunk, the individual sequence elements in the motor buffer need to be selected and loaded one by one. However, once loaded both types of sequences can be executed rapidly. So, the consistent execution of the same sequence induces the formation of a chunk but, when there is ample time for advance preparation the development of a chunk need not affect performance much. Only in the absence of preparation the existence of chunks play a dominant role. This paper addresses the relative role of buffer loading and chunking in Verwey and Dronkert's (1993) continuous keypressing task.

2 PRACTICE PHASE

The buffer loading and chunking notions allow a prediction for Verwey and Dronkert's (1993) keypressing task which has not yet been tested: When performance relies on advance programming, performance will improve rapidly. The point is that general mechanisms such as buffer loading are easily learned (MacKay, 1982; Verwey, in press-1). In the Structured condition, the possibility of preparing a sequence in advance in a motor buffer renders the existence of a movement chunk relatively unimportant for execution. In Unstructured there is no opportunity for advance preparation—due to the absence of RSI—so that performance will rely more on the existence of chunks. Since chunks are assumed to develop very gradually (MacKay, 1982; Verwey, in press-1), group-start and within-group intervals in Unstructured should slowly reach their asymptote. Verwey and Dronkert (1993) observed that at the end of their practice period, intervals in Unstructured were longer than in Structured. Yet, there seems to be no reason for this difference other than limited practice. After extended practice, the durations of the intervals at Unstructured should approach those at Structured.

As regards the capacity of the motor buffer, various authors (Hulstijn & Van Galen, 1983, 1988; Teulings, Mullins & Stelmach, 1986) have suggested that practice has the effect that longer sequences can be programmed in advance. One might argue that this is possible because chunks have developed which load the buffer less than ad hoc generated sequence representations. If so, evidence of the development of chunks would not only occur in Unstructured: Chunk development would also be indicated in Structured by the possibility to produce a long sequence without a need of breaking it up into parts. This would induce within-group intervals of similar duration. Evidence for this possibility has been reported by Verwey (in press-1) who found that, initially, the third response in a four-key sequence was relatively slow, which effect disappeared with practice. Similar effects of practice have been reported by Schneider and Fisk (1983) and Verwey and Dronkert (1993).

More detailed analysis of the Verwey and Dronkert (1993) data showed that the slowing of within-group intervals in Unstructured was more pronounced in 333 than in 45. Why would longer response groups suffer less from the absence of RSI than shorter response groups? One explanation rests upon the notions that the time to initiate a chunk is independent of its size (indicated by the reduction of the complexity effect—Fischman & Lim, 1991; Hulstijn & Van Galen, 1983; Teulings, Mullins & Stelmach, 1986; Verwey, in press-1; Wing, 1978) and that longer response groups allow more "concurrent preparation"[2] of a forthcoming response group than shorter ones (Semjen, 1992; Van Galen, 1991; Verwey, in press-2; Verwey & Dronkert, 1993). Together, these principles could explain the slower intervals at 333 as compared to 45. In Unstructured a response group is less slower as it is longer—in view of more opportunity for concurrent preparation—while the slower intervals do not depend on the size of the forthcoming group—due to chunking. This assertion needs verification.

So, the present study examined the development of chunks and concurrent preparation in an experiment similar to the one by Verwey and Dronkert (1993). Some procedural changes were made in an attempt to reduce individual differences and to strengthen practice effects. First, the subjects had about 50 percent

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[2]Part of the evidence for concurrent preparation comes from findings of slower execution (e.g. Van Galen, 1991). Therefore, the term "concurrent" is considered more appropriate than "parallel" which suggests interference-free processing. The data do not allow distinguishing processes involved in preparation. So, preparation is seen as comprising any process that occurs before execution of a response group and may include response selection, motor programming, and motor adjustment (Sanders, 1990).

more practice than those in the Verwey and Dronkert (1993) study. Second, since intervals of a fixed duration may become part of a sequence representation (Keele & Summers, 1976) response groups were separated by a variable rather than a fixed RSI. It was hoped that this would increase the tendency to separate response groups. Besides, RSIs were assumed to be sufficiently long for advance preparation of the response groups. Third, subjects were explicitly instructed to use the RSIs in Structured so as to prepare the forthcoming responses. It was expected that these procedural changes would lead to more homogeneous performance over subjects than in Verwey and Dronkert (1993).

In Structured, the Practice phase had a 333 condition, involving three three-key groups separated by variable RSIs, and a 36 condition involving a three- and a six-key group. The possibility to load the motor buffer in Structured was expected to be indicated by group-start and within-group intervals, which should rapidly reach their asymptotic value. The development of movement chunks, caused by repeated buffer loading of the same response groups in Structured, would be indicated in Unstructured by relatively slow interval reduction which, following extensive practice, would eventually reach the level of Structured intervals. Chunking would also be indicated by a reduction of the differences among within-group intervals in the six-key group because, after practice, the buffer can contain the entire sequence so that loading is required only once. Finally, the Practice phase sought evidence for concurrent preparation of a next group while executing the previous group in that the difference between Structured and Unstructured was expected to be smaller for the six- than for the three-key groups. This would confirm earlier findings (Verwey & Dronkert, 1993) but it remains to be seen whether the three-key groups in 333 and 36 are indeed unaffected by whether they are embedded in a 333 or in a 36 sequence.

2.1 **Method**

2.1.1 *Tasks*

A block started with the instruction on the screen to position the left little, ring, middle, and index finger on the z, d, f, g keys of an ordinary PC keyboard and the right thumb, index, middle, ring and little finger on the space bar, j, k, l, and / keys, respectively. These assignments were chosen so that each finger could easily press a separate key (Fig. 1). The computer screen displayed white outlines of nine squares in the same spatial arrangement as the assigned keys. The task started when the area enclosed by 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 keypresses was carried out in which each of the nine keys was pressed once. Keys could be released after ensuing ones had been depressed. Immediately upon completion of the nine-key sequence the next trial started which involved the same sequence of nine keypresses.

Q W E R T Y U I O P
A S $\underline{D}_2$ $\underline{F}_3$ $\underline{G}_4$ H $\underline{J}_5$ $\underline{K}_6$ $\underline{L}_7$;
$\underline{Z}_1$ X C V B N M , . $\underline{/}_8$
$\underline{\text{space bar}}_9$

Fig. 1 Layout of the response keys on an ordinary PC keyboard. Underlined keys and the space bar were operated by nine different fingers. Indices denote location numbers which are used in the text to indicate response order.

The RSIs in *Structured* always occurred at the same positions of the sequence and had either a zero or a variable interval. In order to prevent subjects from anticipating the moment of stimulus arrival a non-ageing interval was used as variable interval. Non-ageing intervals are intervals with a larger probability of shorter than of longer durations (see Gottsdanker, Perkins & Aftab, 1986 for an elaborate discussion). The interval was always in the 500-4000 ms range. Half of the subjects performed in the **333** group. They practised with the following time structure: NAI-0-0-NAI-0-0-NAI-0-0 ms (Non-Ageing RSI between R_9 and S_1, 0 ms between R_1 and S_2 and between R_2 and S_3, etc.). The remaining subjects performed in the **36** condition and practised the same keypressing sequence with the RSI sequence NAI-0-0-NAI-0-0-0-0-0 ms. *Unstructured* did not contain intervals between response onset and stimulus presentation that differed from 0 ms so that all subjects had the same task.

The same basic sequence was used for all subjects but each of the nine keys functioned as starting key for two subjects of the 333 and the 36 group. For example, when the stimulus locations are designated 1 through 8 for the fingers from left to right and the right thumb is designated 9 one sequence was |5 9 1|7 4 2|6 8 3 (i.e. |J space Z|L G D|K / F, see Fig. 1). The first vertical line in this sequence indicates the RSI in the 333 and 36 condition and the second line indicates the RSI in the 333 condition. Two other subjects of each group executed 9 1 7|4 2 6|8 3 5, two performed 1 7 4|2 6 8|3 5 9, etc. In this way, all response times had all between-hand and within-hand transitions. This is important since they are known to affect the time between subsequent keypresses (Coover, 1923; Kornblum, 1965; Lahy, 1924).

2.1.2 *Procedure*

On the first day a written instruction was handed out to the subjects which briefly introduced the task and the way the computer had to be controlled. Subjects were instructed to type as fast and accurately as possible in order to maximize their score at the end of each block. They were told that the five highest scoring subjects of each group of 18 subjects would earn a bonus. All individual blocks were also preceded by a written instruction on the computer monitor, again indicating the sequence to be pressed and, in Unstructured, that no RSIs would occur. At the beginning of Day 2 the experimenter explicitly suggested to use the RSIs for preparing the forthcoming keypresses as the data in Verwey and Dronkert (1993) had shown large individual differences in this respect. This turned out to be useful in that some subjects indicated not to have considered the possibility.

Each subject carried out seven sessions on three consecutive mornings or afternoons and one on the fourth day (the remaining Day 4 sessions will be discussed in the Transfer phase). Six subjects performed the task simultaneously on six different computers. Three of them were in the 333 and three in the 36 group. Six other subjects relaxed in an adjacent room. After a session the first six could relax and the second six performed the task. This resulted in a rest and test schedule of about 17 min. for each subject. Given the total of 36 subjects the experiment required the presence of three times twelve subjects at the institute.

All sessions consisted of 4 blocks of trials. The fourth block of Session 1, 3, 5, 7, 9, 11, 13, 16, 18, 20, 22 had the Unstructured condition[3]. The fourth block of the other sessions involved the Structured condition. A block had 30 trials. Blocks were separated by a 20 s break.

During a block of trials the keys were always pressed in a fixed order. Hence, the subjects soon knew which key to press next. This had the effect that in Structured they could press the key before the 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 3500 ms interval. In these three situations keypressing could only continue after pressing the correct key.

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. Given that performance improvement obeys a power law (Newell & Rosenbloom, 1981) the score was determined with a logarithmic function so that late in practice a relatively small improvement still yielded a perceivable score increase. Accuracy affected scoring in that high error rates were 'punished' by reducing the score: each additional percent error equalled 20 ms slower responding. Error rates over six percent elicited the instruction to reduce errors. To prevent cautious and, hence, slow keypressing, error rates of less than three percent evoked the instruction to increase keying speed—unless the average response time was below 150 ms. Below three percent errors, the error rate was artificially increased before calculating the score. So, with three percent errors

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[3]On Day 2 one block was discarded due to time pressure. This caused the "jump" from Session 13 to 16.

the RT-based score was reduced least. Subjects were not informed about this procedure and average response times or error scores were not displayed.

2.1.3 *Apparatus*

The experiment was conducted on six identical IBM AT compatible (386) computers with NEC Multisync VGA 3D colour monitors. Stimulus presentation and response registration were controlled through Micro Experimental Laboratory software (MEL—Schneider, 1988). This software package is specially developed for running PC-based experiments. 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). Although MEL can measure times with 1 ms precision by reprogramming the internal timer, variances caused by keyboard delays add approximately 19 ms to the error variance which, given the large number of trials in the present study, is 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 the experimenter through a closed video circuit.

2.1.4 *Subjects*

Subjects were 36 paid students (15 males and 21 females) from Utrecht University. Eighteen subjects were randomly assigned to the 333 and eighteen to the 36 group. They were paid 180 Dutch guilders for participation. Five subjects in each group received a bonus of 50 guilders. Four of the 36 subjects were replaced because of poor performance.

2.2 **Results**

Analyses of variance (ANOVAs) were carried out on mean response times per condition, subject, and location of the keypress in the sequence. Response times—the time between onset of a stimulus and depression of the corresponding key—are designated T_1-T_9. In 333, T_1, T_4, and T_7 are termed *group-start intervals* because these are the first intervals in a group of responses and are associated with RSIs in Structured. The remaining intervals are *within-group intervals*. In a similar vein, T_1 and T_4 in 36 are called group-start intervals and the rest within-group intervals.

Sets of three ANOVAs were used for contrasting response groups in the various conditions: Comparing three-key groups in 333 and 36 required analyses with 333 vs 36 as between-subjects variable. Because there is no reason to expect differences between the three three-key response groups in 333, T_1, T_4, and T_7 were pooled in the analyses. Likewise, T_2, T_5, and T_8 were pooled, as well as T_3, T_6, and T_9. Throughout the remainder of this paper, the three key group in 36 is denoted by 36(3). Besides the between-subjects ANOVA on 333 and 36(3), between-subjects ANOVAs were carried on 333 and the six-key groups in 36 [i.e. 36(6)], and within-subject ANOVAs were used to analyze 36(3) vs. 36(6). Session covered the effect of practice which was significant in all ANOVAs on response times (all $ps<.001$) and is not reported separately. All ANOVAs involved Key-Order as variable to account for effects caused by balancing response locations over fingers. Key-Order effects are not reported either.

Keypresses involving an error and the two keypresses following that error were discarded from analysis. In each block, the first two trials were considered as warming-up and also discarded. To eliminate outliers cut-off values were computed for each condition and session. Excluding RTs exceeding these values eliminated less than two percent of the data. Arcsine transformations were carried out on mean error rates per cell before the data were subjected to ANOVAs in order to obtain independence of means and variances (Winer, Brown & Michels, 1991).

2.2.1 *Structured condition*

Group-start and within-group intervals in Session 1 and in Session 20 and 22 are presented in Fig. 2. This figure shows that the intervals associated with RSIs were longer than the other intervals. In Structured this can be attributed to the time uncertainty associated with these responses. For this reason, group-start and within-group intervals in Structured are not compared.

The ANOVAs on the group-start intervals showed no significant differences between the various group-start intervals [333 vs 36(3): $F(1,18)=0.8$; 333 vs 36(6): $F(1,18)=0.9$; 36(3) vs (36(6): $F(8,9)=0.8$, all $ps>.20$] and, hence, there was no evidence for the complexity effect].

Pooled within-group intervals in 333 did not differ from those in 36(3) [$F(1,18)=0.5$, $p>.20$]. The difference between pooled within-group intervals in the three- and six-key groups was marginally significant in the 333 vs 36(6) ANOVA [333: 139 ms, 36(6): 169 ms, $F(1,18)=3.2$, $p=.08$] and highly significant in the 36(3) vs 36(6) ANOVA [36(3): 130 ms, $F(1,9)=45.9$, $p<.001$]. With practice, within-group intervals in 36(3) decreased more rapidly and asymptoted earlier than those in 36(6). So, the difference increased from 29 ms in favour of 36(3) in Session 1 to 57 ms in Session 7 and then reduced again to 23 ms in Session 22 [$F(21,189)=3.6$, $p<.001$].

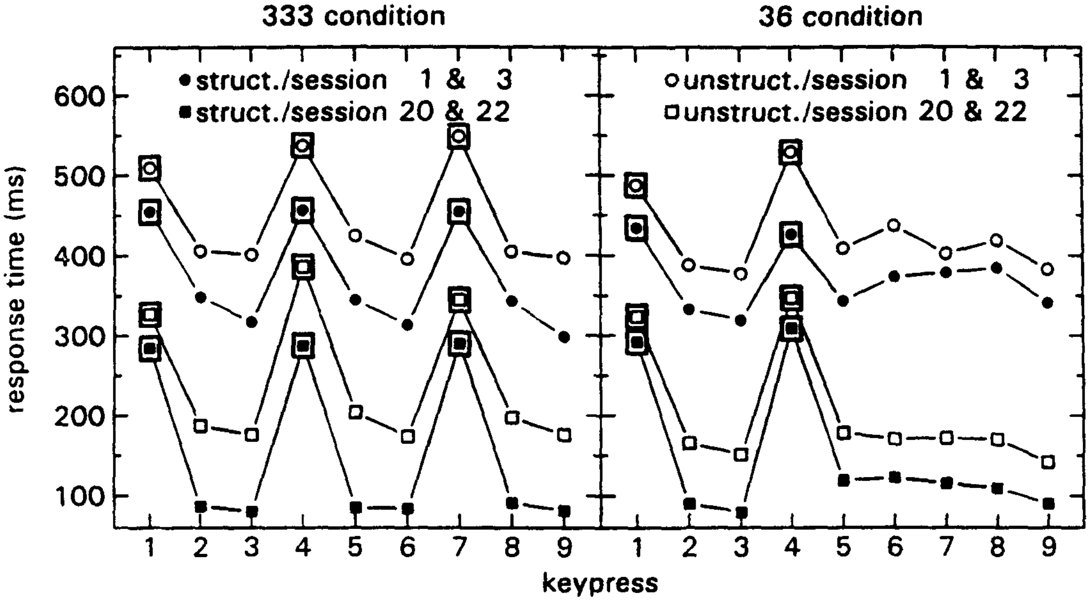

Fig. 2 Interkey intervals early and late in practice as function of 333 vs 36 and Structure. Squares indicate the positions of RSIs in Structured.

Detailed analysis of the second and third response in each three-key group in a 333 vs 36(3) ANOVA, showed that T_3 was generally smaller than T_2 [142 vs 127 ms, $F(1,18)=11.0$, $p<.01$]. This difference reduced with practice in 333 and not in 36(3) [$F(21,378)=2.0$, $p<.01$; see Fig. 2]. An ANOVA on the various within-group intervals in 36(6) showed a Response x Session interaction [$F(80,720)=1.9$, $p<.001$]. It was caused in part by a relatively long T_6-T_8 as compared to T_5 in the earlier sessions [Session 1-4: $F(1,9)=32.0$, $p<.001$] which effect disappeared with practice [Session 19-22 $F(1,9)=0.9$, $p>.20$]. In addition, a Response main effect also indicated a persistent difference between responses [$F(4,36)=3.5$, $p<.01$] which was caused by the relatively small T_9 as compared to T_5-T_8 (see Fig. 2) [planned comparison on all sessions: $F(1,9)=15.7$; Session 19-22: $F(1,9)=9.7$, $ps<.01$].

Group-start/within-group ratios grew with practice in all conditions [333 vs 36(3): $F(21,378)=44.3$; 36(6) vs 36(6): $F(21,42)=6.2$, $ps<.001$] and grew larger with practice in 333 and 36(3) than in 36(6) [$F(21,378)=2.0$; $F(21,42)=2.4$, $ps<.01$]. The average ratios in Session 21 and 22 amounted to 4.0 (333), 4.2 [36(3)], and 3.3 [36(6)].

Table I shows average error percentages per day in the three- and the six-key response groups. The ANOVA on 333 and 36(3) confirmed that error rate increased for the second response and not for the first and third [$F(42,756)=5.9$, $p<.001$]. A similar effect of practice was found in 36(6) response groups where the error increase with practice was stronger for later responses with the exception of the last response [$F(100,900)=2.2$, $p<.001$]. Both interactions were superseded by significant Response and Session main effects.

Table I Error percentages for the responses in the Structured three- and the six-key response groups as a function of day.

		response in three-key group			response in six-key group					
		1	2	3	1	2	3	4	5	6
	1	4.3	3.9	4.1	3.6	3.2	5.3	5.1	5.3	4.4
Day	2	4.9	6.2	3.2	3.7	3.8	6.3	7.4	10.1	4.7
	3[1]	5.0	6.4	3.0	3.3	4.6	6.0	7.1	9.8	3.8
mean		4.7	5.5	3.4	3.5	3.9	5.9	6.5	8.4	4.3

Note: [1] Day 3 includes Session 22 from Day 4 as well.

2.2.2 *Unstructured condition*

Group-start intervals were longer than the pooled within-group intervals. In the 333 vs 36(3) ANOVA [$F(1,17)=61.8$, $p<.001$] this difference increased from 118 ms in Session 1 to 160 ms in Session 22 [$F(10,170)=2.1$, $p<.05$]. These findings also emerged in an ANOVA on 333 vs 36(6) [$F(1,17)=96.4$, $p<.001$; 107 ms in Session 1, 170 ms in Session 22, $F(10,170)=3.7$, $p<.001$].

Comparison of the group-start intervals in 333 and 36(3) and in 333 and 36(6) showed no difference [333 vs. 36(3): $F(1,17)=2.8$; 333 vs 36(6): $F(1,17)=0.3$, $ps>.10$]. Only when comparing group-start intervals in 36(3) and 36(6) a significant difference was found indicating a complexity effect [$F(1,9)=15.9$, $p<.01$]. This difference changed with practice [$F(10,90)=2.8$, $p<.01$]: In Session 1 the difference amounted to 3 ms (T_1: 553 ms, T_4: 556 ms), in Session 3 and 5 it increased up to 80 and 89 ms (Session 3 T_1: 422 ms, T_4: 502 ms, Session 5 T_1: 402 ms, T_4: 492 ms), and then it gradually reduced again down to 22 ms in Session 22 (T_1: 310 ms, T_4: 332 ms). Both the increase in Session 1, 3, and 5, and the subsequent reduction of the difference in later sessions were significant [$F(2,18)=5.1$, $p<.05$ and $F(8,72)=2.6$, $p<.05$, resp.].

Pooled within-group intervals in the response groups of 333 and 36 did not differ significantly [333 vs 36(3): $F(1,17)=0.8$; 333 vs 36(6): $F(1,17)=0.4$, $ps>.20$]. Only in when comparing 36(3) and 36(6) there was a trend toward a difference [$F(1,9)=3.9$, $p=.08$]. Session did not affect the within-group intervals differently in the three- and six-key groups ($ps>.20$). Analyses on the individual responses showed no difference between the second and third key in 333 and 36(3) [333: 23 ms $F(1,8)=4.1$, $p=.08$; 36(3): 14 ms $F(1,9)=1.1$, $p>.20$]. A planned comparison to test whether the last response in 36(6) (T_9) was faster than earlier ones (T_5, T_6, T_7, and T_8) showed that T_9 was 23 ms smaller [$F(1,9)=6.9$, $p<.05$] which effect was maintained during practice (Session 1 and 3: 33 ms; Session 20 and 22: 31 ms). On the other hand, post-hoc Tukey testing showed that the initially slow R_6 (in Session 1, 3, 5 and 7: $ps<.01$) became faster with practice so that all differences between R_5-R_8 had disappeared in later sessions (16, 18, 20, and 22: $ps>.20$).

The group-initiation/within-group ratios showed an increase with practice. They all started at about one in Session 1 and increased to 2.3 (333), 2.4 [36(3)], and 2.2 [36(6)] in Session 22 [333 vs 36(3)-key: $F(10,180)=7.9$; 333 vs 36(6)-key: $F(10,180)=10.4$; 36(3)-key vs 36(6)-key: $F(10,90)=5.8$, all $ps<.001$]. The increase with practice appeared not different for the various response groups [333 vs. 36(3)-key: $F(1,18)=0.9$; 333 vs. 36(6)-key: $F(1,18)=0.6$; 36(3) vs. 36(6): $F(1,9)=2.8$, $ps>.10$].

The 333 vs 36(3) ANOVA on errors in three-key groups showed a main effect of Session [$F(10,80)=6.3$, $p<.001$] indicating an increase in Session 1 to 4 (3.2, 4.6, 5.4, 6.7%, resp.) after which error percentage remained stable around 6.2 percent. The 36(3) vs 36(6) ANOVA showed a 36(3) vs 36(6) main effect [$F(5,45)=2.4$, $p<.05$] which was mainly caused by the large error rate of R_8 of about 7.4 percent in later sessions while the error rates of other responses were in the 3.9-5.4 percent range in the later sessions.

2.2.3 *Structured vs Unstructured*

Group-start intervals were generally longer in Unstructured than in Structured [333 vs 36(3): $F(1,17)=19.2$; 36(6): $F(1,9)=12.4$, $ps<.001$]. The earlier findings of a complexity effect in Unstructured 36 and no complexity effect in Structured 36 were confirmed [$F(1,9)=24.7$, $p<.001$]. The rate of decrease with Session differed for Structured and Unstructured in 333 and 36: Structured group-start intervals dropped much faster with practice than those in Unstructured but later the disadvantage for Unstructured reduced again because the reduction levelled off soon in Structured and not in Unstructured (Fig. 3) [333 vs 36(3): $F(10,170)=8.6$, $p<.001$; 36(6): $F(10,90)=16.6$, $p<.001$]. The initially increasing and subsequent decreasing difference between Structured and Unstructured was tested by separate ANOVAs on Session 1 and 3, and on Session 3 to 22. In the three-key groups of 333 and 36(3) group-start intervals were 22 ms smaller in Structured than in Unstructured in Session 1 and 118 ms smaller in Session 3 [$F(1,18)=33.1$, $p<.001$]. Then the difference decreased again to 59 ms and 38 ms in Session 20 and 22 [$F(9,153)=6.4$, $p<.001$]. In 36(6), group-start intervals in Structured were 19 ms smaller in Session 1 and 187 ms smaller in Session 3 [$F(1,9)=24.6$, $p<.001$]. This advantage for Structured decreased again to 47 and 30 ms in Session 20 and 22 [$F(9,81)=18.3$, $p<.001$].

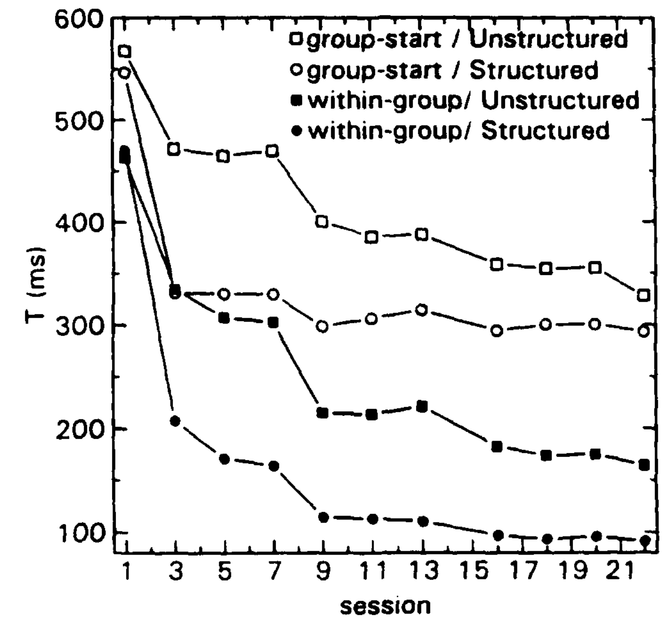

Fig. 3 Group-start and within-group intervals, pooled over 333 and 36, as a function of Structure and Practice.

Pooled within-group intervals in Structured were generally slower in Unstructured than in Structured [333 vs 36(3): $F(1,18)=136.4$; 36(6): $F(1,9)=43.3$, $ps<.001$]. As shown in Fig. 3, they dropped sharply after Session 1 and were later approached again by those in Unstructured [333 and 36(3): $F(10,170)=28.2$; 36(6): $F(10,90)=43.9$, $ps<.001$]. In 333 and 36(3) the difference increased from 1 ms in Session 1 to 131 ms in Session 3 [$F(1,18)=126.3$, $p<.001$] and then reduced again to 91 ms in Session 20 and 82 ms in Session 22 [$F(9,162)=12.2$, $p<.001$]. In 36(6) the difference increased from 27 ms in Session 1 to 119 ms in Session 3 [$F(1,9)=43.8$, $p<.001$] and reduced again to 58 ms and 53 ms in Session 20 and 22 [$F(9,81)=22.3$, $p<.001$]. The difference between Structured and Unstructured was greater for three- than for six-key within-group intervals [in 333 and 36(3): 104 ms, in 36(6): 72 ms; 333 vs 36(6): $F(1,18)=8.0$, $p<.01$; 36(3) vs 36(6): $F(1,9)=7.8$, $p<.05$].

Differences in error rates in the Structured and Unstructured conditions were evaluated with several ANOVAs. These showed a Structure main effect on three-key groups in 333 and 36 showing that more errors were made in Unstructured than in Structured [Structured: 4.3%, Unstructured: 5.3%, $F(1,8)=112.3$, $p<.001$].

2.2.4 *Individual differences*

In the last Unstructured session (22), individual ratios ranged between 0.8 and 8.0 in 333 (mean was 2.3), between 0.5 and 7.4 in 36(3) (mean 2.4), and between 1.1 and 4.9 in 36(6) (mean 2.2). In Session 22 of Structured the ratios ranged from 1.9 to 8.9 (3.9) in 333, from 1.5 to 11.5 (4.3) in 36(3), and from 1.6 to 9.2 (3.3) in 36(6). Individual group-start/within-group ratios in Unstructured and Structured clearly correlated in 333 ($r=.63$, $p<.01$), especially in Session 1 to 8 ($r=.70$, $p<.001$) and less in Session 16 to 22 ($r=.50$, $p<.05$). Computation of the correlations for each session showed the highest correlation at Session 7 ($r=.77$, $p<.001$). In 36, however, ratios in Structured and Unstructured did not correlate significantly [36(3): $r=.20$; 36(6): $r=.18$, $p>.20$]. Still, the highest correlations were found at Session 7 [36(3): $r=.42$, $p=.08$; 36(6): $r=.66$, $p<.05$]. Individual ratios in 36(3) and 36(6) correlated quite clearly (Unstructured: $r=.80$; Structured: $r=0.84$, $ps<.001$).

The correlation between ratio and within-group intervals in Unstructured was highest early in practice [Session 1-8: 333: $r=-.72$; 36(3): $r=-.75$; 36(6): $r=-.70$, $ps<.001$] and reduced with practice [Session 16-22: 333: $r=-.50$, $r<.05$; 36(3): $r=-.38$, $p=.12$; 36(6): $r=-.32$, $p=.20$]. In contrast, the correlation between ratio and group-start intervals was not significant early in practice [Session 1-8: rs between .10 and .34, $ps>.16$] but increased with practice [Session 16-22: 333: $r=.66$; 36(3): $r=.66$; 36(6): $r=.57$, $ps<.01$]. So, subjects who had a strong tendency to group responses early in practice in Unstructured also had relatively small within-group intervals in those early Unstructured sessions. Later in practice, subjects with high ratios had relatively long group-start intervals while within-group intervals appeared to remain relatively small. The correlations between average ratios in Session 1-7 and in Session 16-22 over subjects (333: $r=.57$; 36 3-key: $r=.65$, 6-key: $r=.60$, $ps<.01$) suggest that grouping was a relatively stable individual characteristic. Finally, correlations between all pooled intervals and ratios in Unstructured showed only quite small correlations [333 and 36(3): $r=.-13$; 36(6): $r=-.34$, $ps>.17$] which decreased with practice [Session 16-22, 333 and 36(3): $r=.01$, 36(6): $r=-.13$, $ps>.20$] suggesting that grouping (i.e. high ratios) was not necessary to reach skilled performance levels (i.e. short intervals).

2.3 Discussion

The Practice phase was concerned with the effects of extensive practice on a nine key pressing sequence, which cycled continuously so that the end of a sequence was immediately followed by the beginning of the next sequence. The main results were (1) Unstructured interkey times increasingly reflected the positions of the RSIs in Structured. (2) Unstructured group-start and within-group intervals diminished more slowly with practice than their Structured counterparts, but after extensive practice the difference between Unstructured and Structured became smaller again. These two findings are consistent with the suggestion that buffer loading was predominant in Structured whereas chunking dominated performance in Unstructured. (3) Early in practice, there were differences among within-group intervals both at the Structured and Unstructured six-key groups which disappeared later in practice. This indicates the importance of chunking with longer response groups: Chunking not only affected the production of six-key groups in Unstructured, but also in Structured. (4) Within-group intervals were longer in Unstructured than in Structured and this difference was larger for three- than for six-key groups. No difference was found in this respect between three-key groups in 333 and 36. This is in line with the notion of concurrent preparation of the forthcoming response group.

Indications for buffer loading in Structured—i.e. response groups were programmed in advance of the first stimulus and subsequently executed as a whole—follow from the observation that, at least after some practice, within-group intervals of the same response group had similar values. Also, within-group intervals in three- and six-key groups reflected the sequence length effect which can be considered evidence that the entire response groups were produced from a nonshrinking buffer (Sternberg et al., 1978). In line with the notion that general processes such as buffer loading improve rapidly with practice (MacKay, 1982), Structured performance reached its lower limit rapidly. Finally, the relatively fast last response in most response groups and the development of a fixed error distribution over the response groups in Structured indicate buffered sequence production in Structured.

The results confirm the indication for chunking in Verwey and Dronkert (1993): There were longer group-start than within-group intervals in Unstructured which difference became more pronounced with practice as also indicated by the increasing group-start/within-group ratio. The prediction of the chunking notion advanced in the Introduction was affirmed in that Unstructured group-start and within-group intervals diminished relatively slowly with practice but, eventually, approached the level of Structured intervals. The second prediction, derived from the notion that chunking results in less motor buffer load, was also confirmed in that Structured and Unstructured six-key groups initially had some long within-group intervals which disappeared with practice. This might suggest that longer chunks developed more slowly than shorter ones. This notion is corroborated by the observation in Unstructured that group-start intervals in 36(6) diminished more slowly than in 36(3), but, ultimately, this difference reduced again. The observation of a fixed error distribution pattern over response groups and the relatively fast last response in most response groups in Unstructured provide further support for integrated execution of response groups. Note that these effects corroborate the notion advanced by Verwey (in press-1) that retrieving a single keypress from the motor buffer concurs with execution of the preceding one. Because all keypresses in the sequence except the last one are slowed by concurrent retrieval the last keypress in a sequence is usually quite fast (e.g., Brown & Carr, 1989; Sternberg et al., 1978). This type of concurrent processing should be distinguished from concurrent preparation of forthcoming chunks as discussed above.

Verwey and Dronkert's (1993) finding was replicated that within-group intervals were longer in Unstructured than in Structured and that this difference was smaller for longer than for shorter response groups. Slowing of the three-key group in Unstructured was about the same for 333 and 36. Hence, longer response groups appear to be slowed less than shorter ones and slowing seems independent of the size of the forthcoming group. This corroborates the two principles in the Introduction: The amount of concurrent preparation for a forthcoming response group is independent of its size and concurrent preparation slows longer response groups less than shorter groups. However, the persistence of the relatively long group-start intervals in Unstructured shows that concurrent preparation can not entirely replace advance preparation.

The range of group-start/within-group ratios in the various conditions appeared not very different from those reported by Verwey and Dronkert (1993) and the mean ratios per condition were even slightly smaller. This indicates that the procedural changes in practice in this study—more practice, variable RSIs, instructions to prepare during RSIs in Structured—did not change the way the sequence in Unstructured was carried out. In conjunction with the relative independence between performance and ratios in Unstructured indicated by the correlations, this suggests that, even with extended practice, one is free whether chunks are being carried out as a group—i.e. with a relatively long group-start interval and utilizing the motor buffer—or not. For individual subjects this tendency to perform a chunk as a group in Unstructured appeared fairly constant over practice and over three- and six-key groups. For now, it is unclear whether the extent that chunks need to be carried out as groups or not, is strategically determined and can be changed at will. Alternatively, it might be consolidated with practice because, for example, concurrence of certain processes develops only with practice.

The relative independence between performance and ratios in Unstructured has in fact been discussed before (Greeno & Simon, 1974; Semjen, 1992) and may indicate a dissociation between an abstract sequence control mechanism and a mechanism translating abstract codes into individual keypresses (Adams, 1984; Allport, 1980; MacKay, 1982, 1987). The present data provide evidence for independent control and execution mechanisms in that the last keypress was faster in Structured as well as in Unstructured. Such additivity is only expected with independent mechanisms (Sternberg, 1969). This possibility will be pursued in the next section of this paper.

In short, the results in the Practice phase support the notion that, with consistent practice, movement chunks develop when sequence production involves the consistent partitioning of the same sequence. The existence of chunks is important under time pressure when it is difficult to prepare sequences in advance and, with long sequences, when advance preparation is possible. In the case of rapid production of short sequences in combination with ample preparation time, the operation of chunks is less important in view of the possibility of loading the motor buffer in advance. Without opportunities for advance preparation, preparation for chunks concurs to some extent with execution of earlier movements—which then slow down. In the presence of chunks, the amount of slowing appears to depend on the size of the ongoing response group and not upon the size of the prepared response group. Finally, the existence of a chunk describing a response group does not enforce integrated sequence execution. One-by-one execution remains optional.

3 TRANSFER PHASE

In the Transfer phase, the effect of the chunks developed in the Practice phase was studied on performing a different keypressing sequence. The Transfer phase tested the contention that chunks are *specific* with regard to the constituents of the sequence (Sternberg et al., 1990). So, when even one sequence element is changed, performance of the entire chunk should be considerably affected. This accords with various models of skill acquisition outside the domain of movement sequences (Estes, 1986; Logan, 1988, 1992; Welford, 1968). Evidence for sequence production has been mainly derived from error analyses (Drummond, 1981; Fentress, 1983; Fromkin, 1981; Gallistel, 1980; Zimmer & Körndle, 1988) but interval durations should be affected as well.

The notion of sequence-specific practice effects is quite at odds with some experimental results on sequence production. When comparing performance in practised and in new sequences, transfer of earlier practice to new sequences has been shown to be nearly perfect (Chamberlin & Magill, 1992b; Verwey, 1990a, 1990b, 1992). Also, practising either one or four sequence pairs did not show any effect on performance (Verwey, in press-1). These findings suggest that practice has foremost *aspecific* effects, which is more consistent with notions that memory representations of motor skills have a generally abstract form (a general motor program or schema) that can be easily adapted to different situations (Chamberlin & Magill, 1992a; Schmidt, 1975, 1982). This would argue against the notion that practising movement sequences yields sequence-specific effects, as also assumed by chunking.

The Transfer phase tested an explanation for the apparent contrast between the theoretically expected specific and experimentally obtained aspecific effects of practice. This explanation emerges from the notions discussed earlier: When there is ample time to prepare sequence production, performance relies on advance buffer loading which is relatively insensitive to prior practice (MacKay, 1982). Sequence-specific effects in the form of chunk development only emerge as the sequence exceeds the buffer capacity, and in the absence of opportunities for advance preparation.

The Transfer phase examined this suggestion in two conditions which differed with regard to the opportunity for advance preparation. The first condition was the *Unstructured* condition which had also been used in the Practice phase. Due to the absence of any RSI in this condition, performance was assumed to be more dependent upon the existence of movement chunks. Unlike the Unstructured condition, the *Discrete* condition gave ample possibilities for advance preparation in that response groups were shown immediately before their execution.

Each of these two conditions contained four Sequence Types. The first type involved the *Practised* response groups from the Practice phase. The second type involved *New* response groups. Comparisons of these two sequence types in Unstructured and Discrete would show the extent transfer of training depends on familiarity with the keypressing order, on the possibility for advance preparation, and on the number of keypresses in a response group. In addition, two other response groups were produced. These response groups contained parts of the practised response groups embedded in new keying orders and were called the **ABB** and **AAB** response groups. In 333 these response groups involved keys that used to follow each other in the Practice phase as well. However, in ABB the first response used to be the last of one response group (denoted by A) and the second and third in ABB (denoted by BB) used to be the first and second of the next response group in Practice. The AAB response group started with the second and third responses of an earlier practised response group (AA) which were followed by the first of the group that used to follow in Practice (B). This set up allowed testing the notion that associations develop between responses within a group and not between responses separated by relatively long intervals. According to chunking one would expect that the second of a pair from one chunk benefits from the presence of the first (MacKay, 1982) but such benefits are not expected with responses from different chunks.

Since buffer loading is supposed to dominate in Discrete where timing allows advance preparation, the differences between Practised, New, ABB, and AAB, were assumed to be limited for three-key groups in Discrete. For six-key groups, however, buffer limitations should induce some relatively long within-group intervals in New, ABB, and AAB. In ABB and AAB these long within-group intervals might occur at the first response of a familiar part when these parts are also loaded and executed as a whole. By contrast, Unstructured is supposed to rely mainly on chunking which implies that the effect of prior practice is expected to be much stronger: Response groups in Practised were expected to be initiated and executed faster than in New, ABB, and AAB. As these latter three response groups would rely mostly on one-by-one execution no differences were expected between three- and six-key groups.

3.1 Method

3.1.1 *Tasks*

The Transfer phase used subjects who had also served in the Practice phase. They carried out two Timing conditions: the Discrete and the Unstructured condition. In *Discrete*, each trial consisted of two (in 36) or three (in 333) groups of sequential key presses. Before carrying out a response group, the computer informed subjects about the responses in a response group by sequentially filling either three or six squares with a white content and presenting a number at the centre of each square indicating its location within the response group. The rationale behind this procedure was that new response groups should be produced with ample opportunity for advance preparation. Onset asynchronies between squares amounted to 400 ms. After the last one had been presented the display remained unchanged for 2500 ms showing all filled squares with their location number. Then all squares were cleared and after a non-ageing interval in the range of 500 and 4000 ms, the first square in the response group turned green indicating the stimulus corresponding to the first key press in the response group. Immediately after pressing the corresponding key the square was cleared and the next one in the response group turned green. This was repeated until all three or six keys had been pressed. So, there was only temporal uncertainty at the start of the response group but no uncertainty with regards to the keys in the group and their order. When an error was made or when an additional key was pressed within 500 ms after pressing the last key of the response group an error message was presented. Next, the ensuing response group was shown and subjects were asked to repeat it. The order of the keys within the two or three response groups in a trial of nine key presses remained the same in one block of trials. The response groups in the Discrete condition were identical and in the same order as in the *Unstructured* condition. But in Unstructured each stimulus followed the preceding response immediately (no RSI), making the timing of Unstructured identical to the timing in the Unstructured condition of the Practice phase. This manipulation allowed comparing performance with and without the possibility for advance preparation.

Each of these Timing conditions involved the same set of four Sequence Types: one as practised in the Practice phase, one new, and two in which parts of the practised sequence occurred. These sequences appear in Table II. This table shows that in the New condition, each response followed another response than the one practised in the Practice phase with the exception of the last two responses[4]. The two sequence types containing parts from the practised sequences, AAB and ABB, are characterized by the fact that all three-key response groups in 333 involved keys that had also followed each other during practice. Either the first and second (in AAB) or the second and third (in ABB) had originally followed each other in a single response group in the Practice phase whereas the remaining third (AAB) or first (ABB) key had also preceded or followed the other pair but had belonged to another response group. As in the Practice phase, the sequences cycled across the 18 subjects in a group so that there were pairs of subjects in 333 and in 36 who had the same sequences.

[4]This was actually unintended but was nonetheless interesting to analyze.

Table II Overview of the sequences performed in the Transfer phase for the 333 and 36 subjects. The numbers indicate the positions of the keys as pressed in the Practice phase and in the Practised Sequence Type of the Transfer phase. Vertical lines in Discrete represent the start of separate response groups.

	333			36	
	Discrete				
Practised	1 2 3	4 5 6	7 8 9	1 2 3	4 5 6 7 8 9
New	7 6 5	1 9 8	4 2 3	7 6 5	1 9 8 4 2 3
AAB	2 3 4	8 9 1	5 6 7	2 3 4	8 9 1 5 6 7
ABB	3 4 5	9 1 2	6 7 8	3 4 5	9 1 2 6 7 8
	Unstructured				
Practised	1 2 3 4 5 6 7 8 9			1 2 3 4 5 6 7 8 9	
New	7 6 5 1 9 8 4 2 3			7 6 5 1 9 8 4 2 3	
AAB	2 3 4 8 9 1 5 6 7			2 3 4 8 9 1 5 6 7	
ABB	3 4 5 9 1 2 6 7 8			3 4 5 9 1 2 6 7 8	

A session in the Transfer phase contained either the Discrete or the Unstructured condition. Half of the subjects performed a Discrete session as first and third session and an Unstructured session as second and fourth session. For the remaining subjects this was reversed. The four sequence types were performed in the four blocks of a single session. The order of sequence type blocks was balanced over subjects.

3.1.2 *Procedure*

After three days of practice in the Practice phase, subjects performed five sessions at Day 4. The first session has been reported as Session 22 of the Practice phase. Then, prior to the four transfer sessions, subjects received a brief introduction describing the transfer tasks. Half of the subjects started with a 17 minutes session containing the Unstructured Transfer condition. After completing this session the subjects rested and the other half of the subjects started with a 30 min. Discrete session. Then the first subjects did the 30 min Discrete session followed by the second group who did their 17 min Unstructured Transfer session. Then, each subject repeated these two sessions in the same order. In the Transfer phase the same equipment was used as in the Practice phase.

3.2 **Results**

Data analyses were similar to those described in the Practice phase. An overview of the data is presented in Figs 4 and 5.

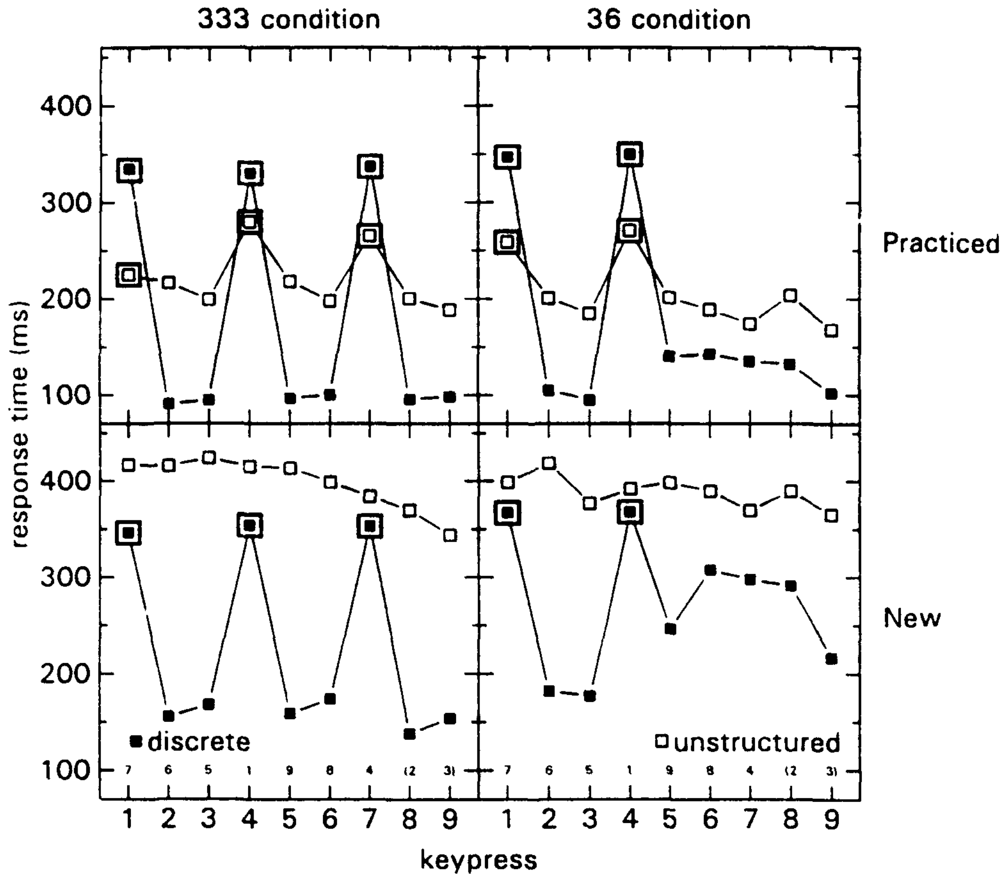

Fig. 4 Response time as a function of 333 vs 36, Timing, and Response in the Practised and New Sequence Types. The numbers at the bottom of the New frames indicate the number of that response in the Practised sequences. Brackets indicate previously practised pairs and the large squares show the start of response groups in Discrete and, with regard to Practised, of the RSIs in the Practice phase.

In general, these figures show that Discrete three-key groups in all conditions were performed quite fast, with limited differences between Practised, and New, ABB, and AAB. In contrast, six-key groups in New, ABB, and AAB showed one or more relatively long within-group intervals which tended to coincided with the first of familiar response pairs and triplets. In Unstructured, performance was generally much better in Practised than in New, ABB, and AAB. The occurrence of practised pairs and triplets appeared to have had a minor performance effect.

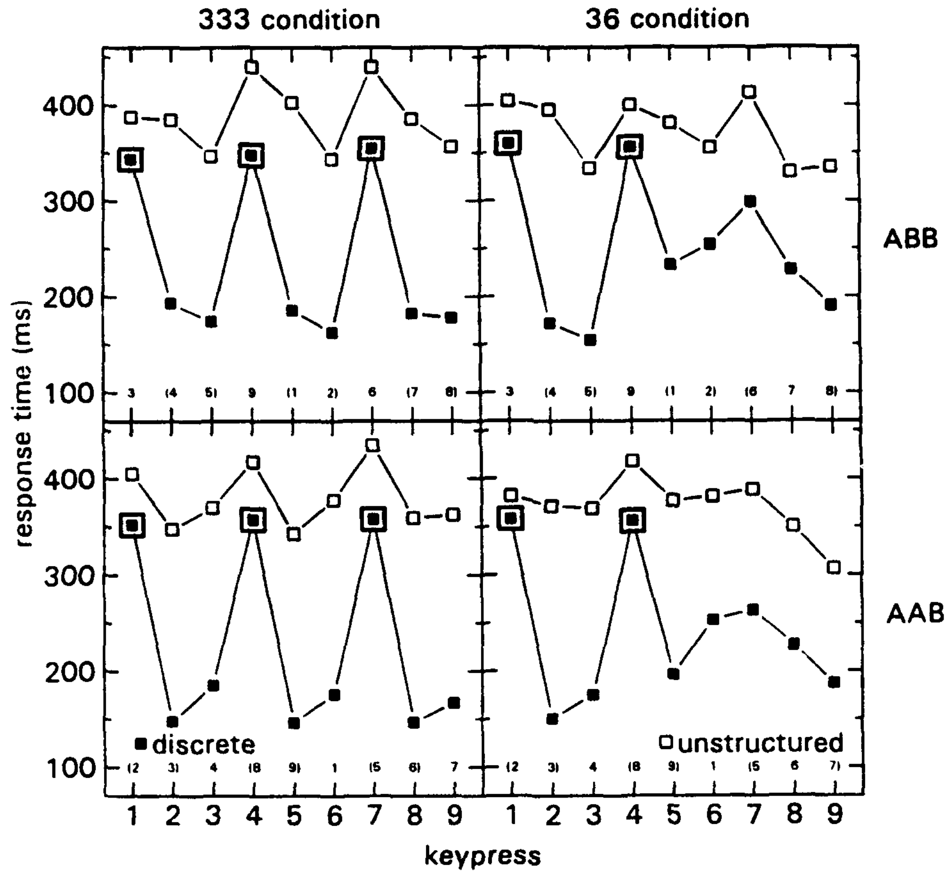

Fig. 5 Response time as a function of 333 vs 36, Timing, and Response in ABB and AAB. See Fig. 4 for the meaning of bracketed numbers and large squares.

3.2.1 *Discrete condition*

Fig. 6 gives an overview of the group-start and pooled within-group intervals in the various conditions. Discrete group-start intervals of the three-key groups [333 and 36(3)] showed a slight advantage for Practised over the three transfer groups [333 and 36(3): $F(3,54)=3.7$, $p<.05$; Practised: 340 ms, New: 359 ms, ABB: 354 ms, AAB: 357, all planned comparisons $ps<.05$]. Comparisons of three- and six-key groups showed no complexity effects.

Advantages of Practised were observed of pooled within-key intervals in three- and six-key groups [333 and 36(3): $F(3,54)=39.3$, 36(6): $F(3,27)=38.4$, $ps<.001$; all pairwise planned comparisons of Practised and New, ABB, and AAB: $ps<.001$]. Besides, pooled within-group intervals were longer in six- than in three-key groups [$F(1,9)=110.8$, $p<.001$]. This difference was smaller in Practised than in New, ABB, and AAB [general: $F(3,27)=15.7$, $p<.001$; planned comparisons $ps<.01$]. Also, the difference between pooled within-group intervals in three- and six-key groups was smaller in AAB than in New [$F(1,9)=18.9$, $p<.01$].

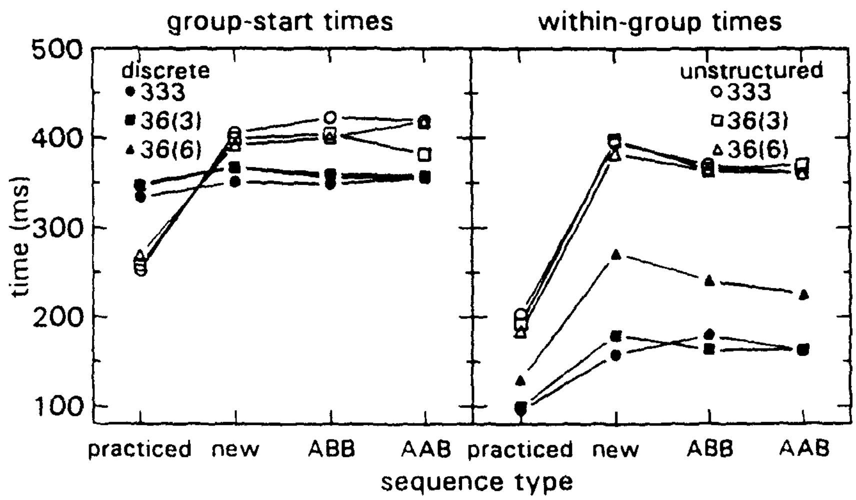

Fig. 6 Group-start and within-group times as a function of Timing, Response Group, and Sequence Type.

Detailed analyses of separate within-group intervals showed minor effects of prior practice (Figs 4 and 5): In the three-key groups of 333 and 36(3), the second response was slower than the third in ABB (179 ms and 163 ms, $p<.01$) and faster in AAB (149 ms and 176 ms, $p<.001$). In New 333, the practised response pair (R_8 and R_9) was faster than the new pairs (i.e. R_2, R_3, R_5, and R_6) [18 ms, $F(1,9)=14.9$, $p<.01$]. In ABB 36(6), T_7 was greater than T_5, T_6, T_8, and T_9 [$F(1,9)=18.6$, $p<.001$] suggesting that R_7-R_9 had formed a single response group. In AAB, both T_6 and T_7 were longer than T_5, T_8, and T_9 [$F(1,9)=29.4$; $F(1,9)=22.6$, $ps<.001$] also suggesting grouping of R_7-R_9. Finally, in Practised and New 36(6), T_9 was smaller than the pooled T_5-T_8 [$F(1,9)=19.6$, $F(1,9)=26.9$, $ps<.001$]. In Practised this suggested concurrent retrieval of individual key presses from the motor buffer, in New it suggested grouping of R_8 and R_9.

Error percentages associated with group-start responses in the three- and six-key response groups did not exceed 4 percent. Pooled within-group error rates were generally below 5 percent. Relatively high error scores were found in New within-group responses [averaged over three- and six-key groups: New: 5.7%, Practised, ABB, AAB: 3.7%; 333 and 36(3): $F(3,54)=7.4$, $p<.001$; 36(6): $F(3,27)=5.0$, $p<.01$].

3.2.2 *Unstructured condition*

Sequence Type main effects in the 333 vs 36(3) and in the 36(6) ANOVA [$F(3,54)=61.4$; $F(3,27)=19.9$, $ps<.001$] were caused by shorter group-start times in Practised than in the other three Sequence Type conditions as can be seen in

Fig. 6 [all three pairwise planned comparisons: $ps < .001$]. The complexity effect in Practised did not reach significance ($p > .20$).

Likewise, pooled within-group intervals were smaller in Practised than in New, ABB, and AAB [333 vs 36(3): $F(3,54) = 102.9$; 36(6): $F(3,27) = 103.4$, $ps < .001$, all planned comparisons: $ps < .001$]. Besides, in 333 and 36(3), ABB and AAB had smaller within-group intervals than New [$F(1,18) = 5.0$, $F(1,18) = 6.4$, both $ps < .05$]. Pooled within-group intervals in the three- and six-key groups did not differ [$F(1,9) = 1.8$, $p > .20$].

Examination of separate within-group responses showed a Sequence Type × Response interaction [$F(3,54) = 8.0$, $p < .001$] for three-key response groups. It was caused by a faster third response in Practised [19 ms, $F(1,18) = 13.5$, $p < .001$] and ABB [52 ms, $F(1,18) = 76.6$, $p < .001$] which effect was greatest in ABB [$F(1,18) = 22.2$, $p < .001$]. In New, T_8 and T_9 were shorter than T_2, T_3, T_5, and T_6 [$F(1,9) = 10.5$, $p < .01$]. In the six-key groups, R_7 was slower than R_8 and R_9 in ABB and AAB [$F(1,9) = 21.8$, [$F(1,9) = 17.6$, $ps < .01$].

Comparisons of group-start and within-group intervals showed that group-start intervals were greater than pooled within-group intervals in Practised, ABB, and AAB [$F(1,18) = 17.8$; $F(1,18) = 9.7$; $F(1,18) = 6.8$, $ps < .01$] but not in New [$F(1,18) = 0.3$, $p > .20$]. In the various six-key response groups, group-start intervals were longer than pooled within-group intervals in Practised, ABB and AAB [$F(1,9) = 29.6$, $p < .001$; $F(1,9) = 9.9$, $p < .05$; $F(1,9) = 8.5$, $p < .05$, resp.] and, again, not in New [$F(1,9) = .2$, $p > .20$]. In six-key groups of ABB and AAB T_4 and T_7 were not different [$ps > .20$].

Sequence Type main effects in 333 vs 36(3) and in 36(6) on transformed error proportions [$F(3,54) = 6.8$; $F(1,9) = 14.9$, $ps < .001$] were caused by the occurrence of less errors in Practised than in New, ABB, and AAB. Error percentages amounted to 3.6, 6.5, 7.7, and 5.8 in three-key groups and 2.3, 7.4, 5.6, and 6.8 in six-key groups. This was confirmed by planned comparisons between Sequence Types (all $ps < .05$).

3.2.3 *Timing: Discrete vs Unstructured*

As shown in Fig. 6, Practised group-start intervals were smaller in Unstructured than in Discrete whereas this was the other way around for New, ABB, and AAB [333 vs 36(3): $F(3,54) = 36.9$; 36(6): $F(3,27) = 14.7$, $ps < .001$]. Six pairwise analyses, all involving Practised and either New, ABB, or AAB, confirmed this ($ps < .001$).

As reported above, both in Discrete and in Unstructured within-group intervals were smaller in Practised than in New, ABB, and AAB. These differences were greater in Unstructured than in Discrete [333 vs 36(3): $F(3,54) = 38.0$; 36(6): $F(3,27) = 9.1$, $p < .001$]. Pairwise analyses of Practised and each of the other Sequence Types confirmed this [five $ps < .001$, Practised vs New six-key group:

$p<.05$]. Besides, within-group intervals of the six-key group decreased less when going from Unstructured to Discrete than those in the three-key groups [$F(1,9) = 175.0$, $p<.001$]. This effect was significant in separate analyses on Practised, New, and ABB ($ps<.01$) but not in AAB ($p=.10$; see Figs 4 and 5).

More errors had been made in Unstructured than in Discrete [333 vs 36(3): 5.0 vs 3.3%, $F(1,18)=42.8$, $p<.001$; 36(6): 6.1 vs 3.6 %, $F(1,2)=23.5$, $p<.05$]. These effects were primarily caused by the relatively low error proportions associated with Discrete group-start responses (2.2%) as compared to Unstructured group-start errors (4.8%) and within-group errors (Discrete: 4.8%, Unstructured: 4.9%) [333 vs 36(3): $F(3,54)=4.1$, $p<.01$; 36(6): $F(1,2)=25.3$, $p<.05$].

3.3 **Discussion**

The results provide the following main results. (1) The Discrete condition had smaller average within-group intervals for Practised than for New, ABB, and AAB in the three- and six-key groups. This difference was larger for the six- than for the three-key groups. Chunking appears to have contributed to sequence production in Practised and more to six- than to three-key groups. Inspection of the individual within-group intervals showed that the relatively long within-group intervals in the Discrete six-key groups of New, ABB, and AAB were due to some relatively long within-group intervals. These tended to coincide with the first of familiar pairs and triplets. (2) In Unstructured, Practised also had smaller within-group intervals than New, ABB, and AAB and *this difference* was considerably larger in Unstructured than in Discrete. In addition, group-start intervals in Practised were also less than in New, ABB, and AAB. No effects were found of group-size. The differences with Discrete indicate that chunking had a more profound effect in the Practised condition of Unstructured than of Discrete. Again, the long average within-group intervals in the six-key groups of New, ABB, and AAB were caused by some relatively long within-group intervals which also coincided with the first of practised pairs or triplets. (3) The effects of familiar parts in New, ABB, and AAB appeared only when responses had not been separated by RSIs in the Practice phase indicating that chunk boundaries were determined by these RSIs.

These data are in good agreement with the notion that effects of practice with movement sequences are particularly important if there is no opportunity for preparation (in Unstructured) or, when preparation is possible, if the sequences are long (in Discrete). This strongly suggests that consistent practice with keypressing sequences yields associations between constituents of practised response groups (MacKay, 1982). In contrast to earlier studies (Chamberlin & Magill, 1992a; Verwey, 1990, 1992), practised short sequences in the present study were produced more proficiently than new sequences even though there was opportunity for advance preparation but, as expected, the difference between practised and new sequences increased with sequence length. As predicted, new six-key groups were broken up in parts just as in early practice.

An indication for aspecific practice effects emerges from the advantage of the new response groups in Transfer over response groups in Session 1 in Practice (Figs 2 and 4). This suggests that besides chunking, a sequence-aspecific skill had developed with practice. This skill is probably related to the possibility to rapidly press keys (see below).

The effects of familiar pairs and triplets were limited to somewhat faster responses which had the effect that pooled within-group intervals were smaller in ABB and AAB than group-start intervals. This was not found in New. Also, the Discrete ABB and AAB sequences had less errors than New sequences. Yet, the minor size of these effects lends support to Sternberg et al.'s (1990) contention that the occurrence of parts of an existing chunk does not substantially contribute to performance when embedded in otherwise new sequences. The three-key ABB and AAB conditions show only benefits of familiar key orders with keys that used to belong to a single response group in Practice. This underlines that elements within a sequences can be primed by execution of earlier ones (MacKay, 1982) but show that this occurs only within, and not between, chunks.

The data from the Transfer phase also confirm results from the Practice phase: (1) Unstructured within-group responses in Practised were slower than their Discrete counterparts and again this effect was stronger for three- than for six-key groups supporting concurrent preparation in Unstructured. (2) The last response in the Practised six-key group in Discrete and the third response in the Unstructured three-key groups were relatively fast suggesting concurrent retrieval of individual keypresses from the motor buffer (Verwey, in press-1).

In summary, the data in the Transfer phase show that the effect of practice was more pronounced in Unstructured than in Discrete and that in Discrete the new three-key groups were performed faster than the new six-key groups. The occurrence of familiar parts in otherwise new sequences gave only a very limited advantage. These findings support the notion that chunks have their greatest effect in situations of time pressure or, provided advance preparation opportunity, when long sequences have to be produced. The present data appear to resolve the apparent contradiction between studies showing primarily specific effects of practice (e.g., Fischman & Lim, 1991; Logan, 1988) and those showing predominantly aspecific effects of practice (Chamberlin & Magill, 1992b; Verwey, 1990b, in press-1) by distinguishing the development of a sequence-specific representation or chunk and aspecific practice effects in terms of skills to produce single responses in rapid succession.

4 GENERAL DISCUSSION

The present study shows when the buffer loading and chunking concepts can be applied and illustrates their mutual relation: Motor buffer models (e.g., Henry & Rogers, 1960; Sternberg et al., 1978) can predict performance of relatively short movement sequences that can well be prepared in advance. The possibility to prepare in advance renders performance relatively insensitive to prior practice. Practice in this situation has aspecific and specific effects. Aspecific effects include skills to produce single elements in rapid succession including concurrent preparation of forthcoming sequences and concurrent retrieval of individual keypresses from the motor buffer (Semjen, 1992; Verwey, 1993, in press-1, in press-2). Specific effects involve the formation of chunks that represent what should be done. These chunks play a dominant role under time pressure and with long sequences.

Chunking models (MacKay, 1982, 1987; Wickelgren, 1969) are appropriate for predicting performance of highly practised groups of sequential movements embedded in longer behavioral patterns. This situation usually occurs in tasks such as speech, handwriting, and the rapid control of various types of systems including vehicle control. These tasks are characterized by time pressure which provides less opportunity for loading a buffer in advance. Then, the existence of chunks describing forthcoming movements plays a dominant role in performance. The limited relation between performance and group-start/within-group ratios in the Practice phase, suggest that the existence of chunks does not automatically lead to the use of advance preparation of response groups; chunking appears to support one-by-one execution as well. In fact, this was also shown by Greeno and Simon (1974) who proposed that execution methods differ with regard to number of operations and short-term memory demands. The possibility to use concurrent preparation and, in case the sequence is carried out as a three or two response groups, concurrent retrieval, may have affected the mode of execution. Since the sequences used involved different fingers from both hands suggests that chunking occurs at an effector independent level of processing and that chunking is not so much "motoric" but more abstract. The notion of effector-aspecific representations of movements corroborates similar notions derived from the observation that a person can write with various limbs while retaining ones distinctive handwriting style (Katz, 1951; Merton, 1972, also see Cohen, Ivry & Keele, 1990).

Together, these findings suggest a *two level model of sequence production* in which two independent mechanisms develop with practice: a sequence-specific *what* and a sequence-aspecific *how* mechanism. The *what* mechanism is concerned with a relatively slow development of a chunk, that is, a memory representation which is used for controlling the order of movements in a specific movement sequence (Adams, 1984; Allport, 1980; MacKay, 1982, 1987). It is interesting to determine how existing movement patterns are partitioned into different chunks and whether there are limitations to the size of chunks.

Possibly, partitioning in early practice—based on the initial application of a set of rules (Jones, 1981; Restle, 1970), on temporal separation (Verwey & Dronkert, 1993; this study), or on expectations (Bartz, 1979)—determines chunk development in late practice. This sequence-specific mechanism may also be related to implicit serial learning which is observed when some statistical structure is concealed in otherwise random keypressing sequences (Cohen, Ivry & Keele, 1990; Stadler, 1989, 1992; Willingham, Nissen & Bullemer, 1989). The *how* mechanism involves tuning of processes responsible for translating abstract information into actual movements. As such it is aspecific with respect to the movements produced. It develops rapidly and involves the development of concurrent processing: Both selection and retrieval of a chunk (i.e. concurrent preparation) and retrieval of the individual keypresses from the motor buffer (i.e. concurrent retrieval) can concur with execution of earlier chunks or keypresses in the sequence (Verwey, 1993, in press-1, in press-2). The possibility to prepare a sequence in advance can be also be considered as part of the how mechanism. It seems reasonable to assume that this mechanism is well developed in adults and that, therefore, it is little affected by practice (MacKay, 1982).

There are various indications for a dissociation between a what and a how mechanism. In one study two- and four-key keypressing sequences were practised in response to two stimuli (Verwey, 1992). After reversing the stimulus-response mapping sequence initiation time increased considerably and clearly exceeded initiation time of entirely new sequences. In contrast, within-sequence intervals were equal to those in the practised sequences, including the fast last keypress indicative for concurrent keypress retrieval. The increase in initiation time suggests that the chunk representing the movement sequence was activated automatically by stimulus presentation. This had also been suggested by findings with single responses (Kramer, Strayer & Buckley, 1990; Pashler & Baylis, 1991; Shiffrin & Dumais, 1981) but the use of movement sequences allowed to make a differentiation between selection and execution. Furthermore, Verwey (in press-1) and Brown and Carr (1989) found different learning rates for initiation and interkey intervals and Verwey (in press-1) differentiated between concurrent programming and concurrent element retrieval in that concurrent programming would reduce the complexity effect and concurrent retrieval would slow nonfinal keypresses.

The two level model of sequence production accords with the general framework presented by MacKay (1982) who distinguished various levels of processing in the production of movement sequences and who emphasized that practice has different effects at these different levels. It is also compatible with the notion that "individual movements that comprise the skill are first perfected to the point where they can be made more rapidly and accurately with little variation. Then they become welded together into 'chunks'" (Gallistel, 1980, p.367): only after individual movements can be performed rapidly, chunking becomes useful. Interesting questions for future research concern the merits of the two level model of sequence production in related tasks. The model suggests that the what and how mechanism can be investigated separately by manipulating either sequence characteristics or movement characteristics. Insight in the properties of both mechanisms seems an essential contribution to the question how people learn skills required for everyday tasks.

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

An experiment is reported on the effects of extensive practice in a task in which a succession of nine keys was pressed with separate fingers, each keypress in response to a corresponding stimulus. Trials followed each other without interruption. A stimulus was usually presented immediately upon depressing the previous key but at two or three positions in the Structured condition, a stimulus was preceded by a variable Response Stimulus Interval (RSI). This partitioned the sequence into two or three groups of responses. In the Practice phase performance improved more slowly in Unstructured than in Structured: Performance in Unstructured relied on the alleged slow chunk development while performance in Structured relied on the probably faster development of advance buffer loading. In addition, response groups in Unstructured were executed more slowly than in Structured suggesting concurrent preparation. The Transfer phase showed little effect of earlier practice on new response groups unless there is ample opportunity for advance preparation and the group is relatively short. A two level model of sequence production is proposed involving a slowly developing, sequence-specific chunk which is used to control sequence execution, and a rapidly evolving, sequence-aspecific execution mechanism involving advance programming and concurrent processing which translates abstract order information into actual movements.

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