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EFFECTS OF PRACTICE IN SELECTING AND EXECUTING KEYPRESSING SEQUENCES

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SUMMARY

This paper describes three experiments that aimed at examining the effects of practice in a sequential keypressing task. In Experiment 1 a two-choice sequence production task was practiced extensively. Experiment 2 assessed the effect of this practice on the production of a series of slightly changed sequences. In Experiment 3 a four-choice reaction task was performed which included the practiced pair of sequences as well as a new pair in order to assess the effects of frequency of occurrence of each pair and their mutual similarity in terms of length and spatial lay-out.

The results are taken as evidence for the development of two sequence execution mechanisms. One allows programming to continue while the earlier keypresses in the sequence are already executed, i.e. concurrent programming. The other allows unpacking of individual motor elements from a short-term motor buffer during execution of the preceding keypresses, i.e. concurrent unpacking. Practice with consistent stimulus-sequence mappings made performance less sensitive to the presence of similar sequences than practice with varied mappings which suggests that stimulus-sequence associations develop with consistent stimulus-sequence mapping.

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Effecten van oefening op het selecteren en uitvoeren van een sequentiële toetsdruktaak

W.B. Verwey

SAMENVATTING

Dit rapport beschrijft drie experimenten die tot doel hadden de effecten van oefening op een sequentiële toetsdruktaak vast te stellen. In Experiment 1 werd een twee-keuze taak uitgebreid geoefend. Experiment 2 stelde het effect van deze oefening vast op de uitvoering van enigszins veranderde toetsdruk-sequenties. In Experiment 3 werd een vier-keuze taak uitgevoerd die zowel de twee geoefende als ook twee nieuwe sequenties bevatte. Het doel was hier de effecten vast te stellen van een lage en hoge frequentie van elk der sequentie-paren en van een onderlinge gelijkenis van de paren in termen van lengte en ruimtelijke configuratie.

De resultaten geven evidentie voor de ontwikkeling van twee mechanismen die snelle uitvoering van bewegingssequenties mogelijk maakt. Het ene zorgt ervoor dat programmering van toetsdrukken doorgaat terwijl eerdere toetsdrukken al uitgevoerd worden, het zgn. "concurrent programming". Het andere mechanisme maakt het mogelijk om individuele toetsdrukken uit een motor buffer te laden terwijl de voorafgaande toetsdruk nog uitgevoerd wordt, het zgn. "concurrent unpacking". Oefening met een consistente stimulus-sequentie mapping maakte de selectie van sequenties minder gevoelig voor de aanwezigheid van gelijksoortige sequenties dan oefening met gevarieerde mapping hetgeen lijkt te wijzen op de ontwikkeling van stimulus-sequentie associaties na consistente oefening.

1 INTRODUCTION

It is a commonplace that perceptual-motor performance improves with practice. Thus, fixed action patterns and movement sequences are executed faster and more fluently. But what do people exactly learn when selecting and producing movement sequences? The mechanisms underlying practice effects are not well understood (e.g. Logan, 1988; MacKay, 1982; Rabbitt, 1989). This paper is concerned with potential mechanisms underlying practice in a choice reaction task in which the reaction consists of a sequence of rapid keypresses with one finger. Various mechanisms have been proposed for perceptual-motor performance and three experiments are reported to test their merits. In the first, two groups of subjects carried out sequences of keypresses for about six hours with either a consistent or a varied practice schedule. Predictions from two hypothetical sequence production mechanisms were tested. Experiment 2 brought the subjects from Experiment 1 in conditions with new stimuli and/or sequences so as to assess costs and benefits of earlier practice effects when subjects are faced with a new task. Experiment 3 investigated the effect of consistent and varied practice on the sensitivity of selecting and executing keypressing sequences to the addition of two new sequences.

Research on practicing keypressing sequences has been discussed in terms of two kinds of execution models whose mutual dependencies are as yet unclear, i.e. *concurrent processing* and *associative motor unitization*. Concurrent processing assumes that, with practice, processes involved in sequence production occur more and more concurrently with the actual execution of elements. In fact, two aspects can be distinguished. First, distributed programming assumes that early in practice the whole sequence is programmed before initiating the first movement. Later, execution of earlier elements starts before programming the total sequence has been completed which means that programming is concurrent with execution (Klapp & Wyatt, 1976; Portier et al., 1990; Portier & Van Galen, in press; Rosenbaum et al., 1986). The second aspect is that on-line retrieval and "unpacking" (Sternberg et al., 1978) of motor elements from a short-term motor buffer (Henry & Rogers, 1960) is supposed to shift from the interval between subsequent keypresses to the actual execution of the preceding keypress (Thomassen & Van Galen, 1992; Van Galen, 1991; Verwey, 1991). Both aspects share the assumption that the amount of concurrent processing during execution increases with practice. Yet, these operations are not supposed to fully occur in parallel. Hence, execution is disrupted to some extent so that the intervals between successive elements in the sequence are lengthened.

The second kind of execution model assumes that, with practice, associations develop between internal representations of successive movements (Brown & Carr, 1989; Carr, 1984; Fischman & Lim, 1991; Keele & Summers, 1976). As associations increase in strength, an integrated motor unit develops which can be as easily selected, retrieved and executed as the representation of a simple movement. Once initiated, an associative motor unit runs off automatically because execution of a particular movement elicits the forthcoming movements of the unit. Hence, the associative motor unitization model is concerned with representation as well as with processing while the concurrent processing model is only concerned with processing. The associative motor unitization concept was originally developed in speech production (MacKay, 1982; Wickelgren, 1969) but it has also been used in studies on sequential keypressing (Brown & Carr, 1989), sequential target striking (Fischman & Lim, 1991), and hand writing (Hulstijn & Van Galen, 1988; Teulings et al., 1983).

The issue studied in the first experiment was the extent that practice in key-pressing sequences is suggestive for concurrent processing or associative motor unitization. They allow various predictions which were explored in a two-choice reaction task in which the responses consisted of a sequence of two or four keypresses. Subjects carried out over 3200 trials so as to detect also effects that only emerge after considerable practice.

Concurrent programming predicts that the effect of sequence length—i.e. the complexity effect—reduces or disappears altogether because programming a sequence no longer occurs completely before its initiation (Brown & Carr, 1989; Fischman & Lim, 1991; Henry, 1980; Hulstijn & Van Galen, 1983). The price is that the earlier interkey intervals, i.e. those interkey intervals during which programming still proceeds, will show less effect of practice than later interkey intervals which are not affected by concurrent programming.

Concurrent unpacking of elements from the motor buffer will also lengthen the time required to execute the preceding sequence element. Since the last item in the sequence will not be hindered the interval preceding the last keypress will show a larger practice effect than earlier elements in the sequence. The present study had sequences of either two or four keypresses. Thus, the time between the first and second (i.e. T_{2L}), and between the second and third keypress in the longer sequence (T_{3L}) are expected to profit less from practice and to reach a value that is larger than the final interkey interval in the short (T_{2S}) and long (T_{4L}) sequence.

Concurrent processing is a model describing *when* processes take place but not saying *what* is being programmed or unpacked; hence concurrent processing does not predict an effect of whether the same pair of keypressing sequences is consistently practiced or whether various sequences are practiced in alternation. Finally, previous work has indicated that concurrent processing may develop quite rapidly. For example, evidence for concurrent programming has been found in blocks of only 22 trials (Rosenbaum et al., 1987) and 80 trials (Laszlo & Livesey, 1977).

Associative motor unitization also predicts that the complexity effect reduces with practice because unitization reduces the time for selecting and retrieving a longer sequence more than for a shorter sequence (Brown & Carr, 1989;

Fischman & Lim, 1991). As to sequence execution interkey intervals should decrease more with practice as they occur later in the sequence (Brown & Carr, 1989). This would result from increasing anticipatory priming by the execution of earlier elements (MacKay, 1982). Hence, associative motor unitization predicts that with practice a later interkey interval becomes shorter that its preceding one.

Associative motor unitization is response-specific. Hence it should develop more rapidly when the same keypressing sequences are consistently practiced (CP) than when various sequences are practiced in alternation (VP). Another feature of associative motor unitization is that it develops fairly slowly (Brown & Carr, 1989; MacKay, 1987) which fits with the fact that it originated from research in a highly practiced skill, namely speech. For example, Brown and Carr (1989) reported a gradual development of associative motor unitization in the course of about 300 practice trials. Table I summarizes the predictions of concurrent processing and associative motor unitization.

Table I Predictions of concurrent programming, concurrent unpacking and associative motor unitization. "→ ←" indicates a reduction of the complexity effect with practice. "<" indicates that the first T mentioned will decrease faster, reaching an asymptote at a smaller value than the second one, ">" indicates that the first T mentioned will decrease slower than the second one and will reach an asymptote at a higher value, and "=" that no difference is expected.

comparison	concurrent programming	concurrent unpacking	associative motor unitization
T_{1S} vs. T_{1L}	→ ←	=	→ ←
T_{2S} vs. T_{2L}	<	<	=
T_{2S} vs. T_{4L}	=	=	>
T_{2L} vs. T_{4L}	>	>	>
T_{2S} vs. T_{3L}	</=	<	>
T_{2L} vs. T_{3L}	=/>	=	>
T_{3L} vs. T_{4L}	=/>	>	>
rate of development	fast	fast	slow
practice consistency	no effect	no effect	strong effect

1.1 Method

1.1.1 *Task*

Each trial started with a written request to press the home key, i.e. the "5" key in the center of the keypad (see Fig. 1). This action removed the request from the screen and the outline of a square appeared in the center of the screen. The square served as a warning stimulus and remained visible for a randomly varying duration. There was a base duration of 500 ms but the ultimate length was determined by adding 10 ms in successive iterations until a random variable (probability of success=.99) failed. It guaranteed that subjects could not infer when the stimulus would appear on basis of the duration that had already elapsed (Gottsdanker et al., 1986). The foreperiod always terminated at 5000 ms. Following the foreperiod the square was erased and the stimulus was presented in the center of the screen. The stimulus was either a "D" or a "6" and was chosen at random.

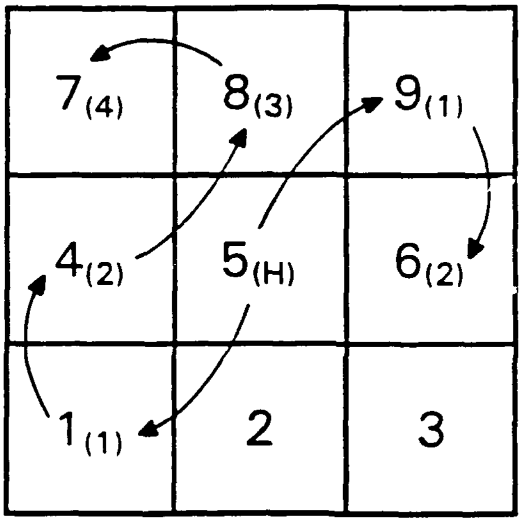

Fig. 1 Lay-out of the numerical keypad on the AT keyboard. As an example key positions in one pair of sequences is indicated by subscripts.

One response consisted of two successive key-presses (short sequence) which was given in response to "D", the other of four successive key-presses (long sequence) and was given in response to "6". Responses were given on the numerical key pad of a normal AT computer keyboard (Fig. 1). The following four pairs of sequences were used as response: [9 6] and [1 4 8 7], [7 8] and [3 2 4 1], [3 2] and [7 8 6 9], and [1 4] and [9 6 2 3]. Subjects in the consistent practice (CP) condition always practiced the same pair whereas subjects in the varied practice (VP) condition had a different pair in each block.

The sequences are characterized by the fact that the first and third transition —corresponding to T_{1L} and T_{1S} (i.e. between home key and R_1 in long and short sequences) and to T_{3L} (between R_2 and R_3)—required a diagonal movement of 2.7 cm. The second transition in short and long sequences—corresponding to T_{2L} and T_{2S} (between R_1 and R_2 in long and short sequences)—and the fourth transition in a long sequence—corresponding to T_{4L} (between R_3 and R_4)— always required a horizontal or vertical movement of 2.0 cm.

1.1.2 *Design*

Sequence length was varied within subjects and consistency was varied between subjects. Subjects in the Consistent Practice group (CP) practiced the same pair of sequences and stimulus-sequence mappings throughout Experiment 1. In contrast, subjects in the Varied Practice group (VP) practiced sequences and stimulus-sequence mappings that changed at each block with the same stimuli and the same mapping of stimuli and sequence length. Finally, practice involved 22 sessions, six at the first day and eight at both the second and the third day.

1.1.3 *Procedure*

Experiment 1 took place on three consecutive mornings. At their first arrival subjects received a written instruction describing the task. The instructions stated that all responses had to be carried out as rapidly and accurately as possibly with the right index finger. Before each block the assignment of stimuli to keys for each of the sequences was displayed on the screen. Subjects were urged to pay close attention to the assignment before starting the first trial since no further indication of the mappings would be given.

A sequence was considered wrong when an incorrect key was pressed, when the order was incorrect, or when an additional key had been pressed within 500 ms after the last key of the sequence had been released. In addition, when the time between stimulus onset and pressing the first key exceeded 1000 ms or the time between pressing one key and the next exceeded 400 ms, the sequence was also considered wrong. In case of an error a message indicated that the sequence was wrong or had been too slow.

Each group of eight subjects worked for about 15 min. during a session and rested about the same period of time while the other group was tested. Each session contained two blocks, each consisting of 74 trials (4 initial dummy, 70 experimental trials). There was a forced break between two blocks in a session of 25 s.

Following a block, performance feedback was displayed in terms of the mean time between stimulus onset and the moment of pressing the final key of a sequence and in terms of the error proportion. When the mean time between stimulus onset and pressing the last key exceeded 2000 ms a warning message stated that the subject was too slow. When the errors exceeded 8 percent the subject was informed that she or he had committed too many errors. Before the start of the experiment subjects were informed that a bonus would be given to the four subjects with the smallest number of warning messages. On each day all subjects worked for about two hours and rested about one and a half hours in between sessions.

1.1.4 *Apparatus*

The experiment was conducted on IBM AT compatible computers with NEC multisync monitors. Stimulus presentation and response collection were controlled through Micro Experimental Laboratory software (MEL—Schneider, 1988). Stimuli were presented at the center of a display screen. At a typical viewing distance of about 65 cm the warning signal—a square—subtended a visual angle of approximately 1°. The imperative stimuli subtended an angle of approximately 0.5°. The stimuli were presented in bright white on a black background and were viewed under normal room illumination.
Eight subjects were simultaneously tested in eight sound-attenuated 2.4 x 2.5 x 2 m rooms. There they sat in front of a table on which a keyboard and a computer monitor were positioned. They were monitored by way of a video circuit.

1.1.5 *Subjects*

Sixteen right-handed students (11 females and 5 males) of Utrecht University participated as subjects. They all received Dfl. 180 for their participation. The four subjects with the fewest errors while still responding sufficiently fast received a bonus of Dfl. 45.

1.2 **Results**

Mean sequence initiation times (T_1) for correct response sequences were computed separately for short and long sequences and for each session. They were subjected to a three-way analysis of variance (ANOVA) with practice consistency as between-subject factor, and session and sequence length as within-subject factors. In order to achieve homogeneity of the error variance, an arcsine transformation was performed on the mean error rate per cell before the same analysis was used as on the T_1 data.

Table II presents mean T_1 for long and short sequences during consistent practice (CP) and varied practice (VP). On the first day there was a marked decline of T_1 during the first 6 sessions, followed by a fairly constant T_1 during the remaining sessions. The effect of session was significant [$F(21,294)=32.9$, $p<.001$]. This effect of practice on T_1 was accompanied by a similar effect on accuracy. Mean error percentage per session was below 6 percent except for the first session in which 9.5 percent of the sequences was wrong [$F(21,294)=5.6$, $p<.001$]. Separate ANOVAs for each day showed that the effect of session on T_1 was only significant on day 1 [$F(5,70)=46.9$, $p<.001$] and not on days 2 and 3 [resp. $F(7,98)=0.6$ and $F(7,98)=1.2$, both $p>.25$]. Mean T_1 on day 2 and 3 was resp. 624 and 612 ms indicating that asymptotic performance was almost reached. Averaged over all sessions T_1 was about 15 ms shorter for VP than for CP. This difference was about 20 ms on day 3. These differences were not significant [all sessions: $F(1,14)=0.7$; day 3: $F(1,14)=0.5$, both $p>.25$] nor was there a significant effect of practice consistency on percentage of errors [$F(1,14)=0.9$, $p>.25$].

Table II T_1 (in ms) in the short and long sequences as function of practice consistency and session and the respective complexity effects.

		consistent practice (CP)			**varied practice (VP)**		
		seq. length		compl.	seq. length		compl.
day	session	short	long	effect	short	long	effect
1	1	817	840	23	846	926	80
	2	730	751	21	728	770	42
	3	675	697	22	672	709	37
	4	666	693	27	666	671	5
	5	667	681	14	633	659	26
	6	656	656	0	647	666	19
mean T_1	1-6	702	720	18	699	733	34
2	7	629	632	3	618	652	34
	8	622	624	2	612	637	25
	9	617	618	1	608	636	28
	10	634	638	4	609	626	17
	11	627	640	13	600	623	23
	12	624	636	12	603	620	17
	13	633	640	7	598	610	12
	14	636	652	16	614	626	12
mean T_1	7-14	628	635	7	608	629	21
3	15	618	627	9	610	636	26
	16	602	622	20	593	610	17
	17	603	623	20	588	618	30
	18	600	639	39	598	612	14
	19	609	634	25	591	609	18
	20	610	642	32	604	624	20
	21	608	642	34	594	606	12
	22	603	634	31	590	604	14
mean T_1	15-22	607	633	26	596	615	19

The data showed a complexity effect in that T_1 preceding short sequences was smaller than T_1 preceding long sequences (Table II). Averaged over all practice sessions and practice consistency the complexity effect amounted to about 20 ms [$F(1,14)=6.8$, $p<.05$]. Also, more errors occurred in long than in short sequences

[5.3% vs. 3.2%, $F(1,14)=19.3$, $p<.001$]. Consistent with the general expectation the complexity effect decreased from 52 ms in the first session of day 1 to 15 ms in the last two sessions of day 1. On day 2 and 3 the complexity effect was 14 resp. 23 ms. In a separate analysis for day 1 sessions the decline of the complexity effect, as indicated by a session x sequence length interaction, was significant [$F(5,70)=2.4$, $p<.05$] but, presumably due to its further constancy, the decline of the complexity effect did not reach significance in the analysis on all practice sessions [$F(21,294)=1.0$, $p>.25$].

The complexity effect was slightly but insignificantly smaller under consistent practice (17 ms) than under varied practice [24 ms, $F(1,14)=0.2$, $p>.25$]. Also, Table II shows an increase of the complexity effect on day 3 in CP but this did not lead to a significant sequence length x session x practice consistency interaction [$F(21,294)=1.1$, $p>.25$].

Interkey intervals, i.e. the time between pressing the first and second key (T_{2S} and T_{2L}), between the second and third key (T_{3L}), and between the third and fourth key (T_{4L}) were first submitted to separate ANOVAs. All showed a significant effect of session [T_{2L}/T_{2S}: $F(21, 294)=10.1$; T_{3L}: $F(21,294)=12.7$; T_{4L}: $F(21,294)=22.2$, each $p<.001$].

Practice consistency appeared not to have had any effect neither as a main effect in any of the analyses on interkey intervals (each $p>.25$) nor in interaction with any of the independent variables in these analyses (each $p>.17$).

Examination of the interkey intervals revealed daily "warming-up" effects for the first few sessions (Fig. 2). Therefore, Newman-Keuls comparisons of mean Ts per day were carried out to find out whether the decreases tended to level off. The differences between the first day on the one hand (T_{2L}/T_{2S}: 187 ms, T_{3L}: 199 ms, T_{4L}: 177 ms), and the second (T_2: 177 ms, T_{3L}: 186 ms, T_{4L}: 162 ms) and third day (T_{2L}/T_{2S}: 174 ms, T_{3L}: 182 ms, T_{4L}: 156 ms) on the other hand were significant for all interkey intervals ($p<.05$) but the differences between day 2 and 3 were not significant for any interkey interval suggesting that, by and large and apart from "warming-up" effects, asymptotic performance had been almost reached for the interkey intervals, as well.

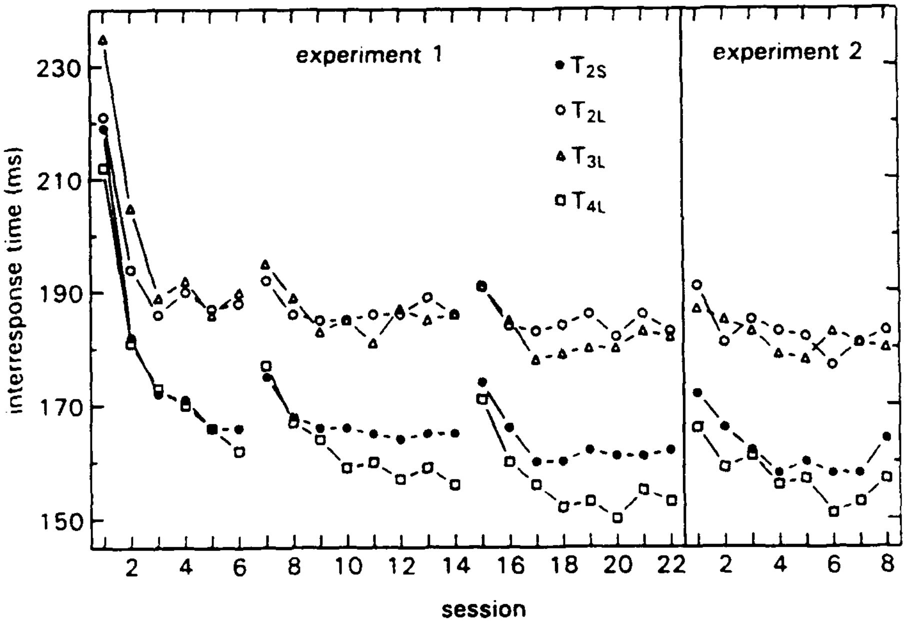

Fig. 2 Interkey intervals in the short and long sequence as a function of session on day 1-3 and in regular blocks of Experiment 2 (to be reported in Experiment 2).

Multivariate planned comparisons were carried out to test the predictions of concurrent processing and associative motor unitization as summarized in Table I. In total four sets of planned comparisons were performed; each set involving six pair-wise comparisons of two interkey intervals. The first two sets involved comparisons of mean initiation and interkey intervals on day 1 and on day 1-3 (Table III) while the third and fourth set concerned the effects of practice on day 1 alone and on day 1-3 (Table IV). Fig. 2 suggested that T_{4L} decreased faster and more than T_{2S} but the effect was contaminated by the daily "warming-up". Though interesting by itself this effect was excluded in the analyses of Table III and IV by including only the last four sessions at each day in the analyses. The main effects of sequence length and their interactions with sessions as discussed earlier are also shown in Table III and IV in order to obtain a similar format as the predictions in Table I.

Table III Comparison of the predictions and results on main effects. Presented are F-ratios and levels of significance[a] of long and short sequence initiation times and mean interkey intervals at day 1 and day 1-3[b].

comparison	PREDICTED conc. proc.	 asso. unit.	OBSERVED DAY 1 main effect	 DAY 1-3 main effect
T_{1S} vs. T_{1L}	</=	</=	< 11.2**	< 6.8*
T_{2S} vs. T_{2L}	<	=	< 23.2***	< 28.3***
T_{2S} vs. T_{4L}	=	>	1.9	> 7.1*
T_{2L} vs. T_{4L}	>	>	> 20.0***	> 56.1***
T_{2S} vs. T_{3L}	</=	>	< 44.5***	< 26.8***
T_{2L} vs. T_{3L}	=/>	>	2.5	0.2
T_{3L} vs. T_{4L}	=/>	>	> 49.9***	> 80.8***

[a] degrees of freedom for F-ratios of comparisons involving interkey intervals are (1,14), for degrees of freedom of the T_I comparisons see text; * indicates: $p < .05$, **: $p < .01$, and ***: $p < .001$.

[b] only the last four sessions at each day have been included in the interkey interval comparisons.

Exclusion of "warming up" in the rate of decrease analyses as shown in Table IV yielded contrasts between interkey intervals and the first vs. last three sessions at day 1 and between interkey intervals and the first vs. last six sessions at day 1-3 after the first sessions at each day had been excluded (i.e. session 3-6, 11-12 was contrasted with session 13, 14, 19-22). The first observation column in Table IV presents differences in the rate of initiation and interkey interval decreases at day 1 and shows that the predictions of concurrent processing agree with the data except for T_{3L}. Examination of Fig. 2 shows that T_{3L} was relatively slow in session 1-2 but not in later sessions. This was not directly expected from a concurrent processing point-of-view but subjects may have paused after completing the two first keypresses to program the remaining two (Beggs & Howarth, 1972; Brown & Carr, 1989; Pew, 1966). To test whether this post-hoc explanation can account for the observed deviation the means of T_{3L} in session 1 and 2 were artificially reduced to the level of T_{2L} on the assumption that the longer T_{3L} was not due to a larger interkey distance but only to breaking up the sequence in two parts. This assumption seems reasonable, given the finding that, with practice, interkey intervals became much shorter than T_{3L} as observed in session 1 and 2 (see e.g. T_{2S} and T_{4L} and also T_{3L} on day 2 and 3) and, thus, this effect could not have been caused by mere movement constraints. Planned comparison of these corrected T_{3L} data showed that T_{3L} no longer decreased faster in session 1-6 than T_{2L}. Instead planned comparison of T_{3L} and T_{4L} in interaction with session 1-3 vs. 4-6 showed that T_{4L} decreased faster than T_{3L} (Table IV).

When practice consistency was added as contrast to the multivariate planned comparisons no significant effects were found (each $p > .12$)

Table IV Comparison of the concurrent processing and associative motor unitization predictions presented in Table I and the results with respect to effects of practice. Also presented are F-ratios and levels of significance[a]. "corrected" indicates comparisons on corrected T_{3L} in session 1 and 2 (see text).

	PREDICTED		OBSERVED		
			DAY 1		DAY 1-3[b]
comparison	conc. proc.	asso. unit.	uncorrected interaction with session	corrected interaction with session	interaction with session
T_{1S} vs. T_{1L}	$\rightarrow\leftarrow$/=	$\rightarrow\leftarrow$	$\rightarrow\leftarrow$ 2.4*		1.0
T_{2S} vs. T_{2L}	<	=	< 12.1***		1.2
T_{2S} vs. T_{4L}	=	>	0.3		> 4.7*
T_{2L} vs. T_{4L}	>	>	> 23.6***		> 10.8**
T_{2S} vs. T_{3L}	</=	>	0.9	< 9.4**	0.9
T_{2L} vs. T_{3L}	=/>	>	< 6.2*	0.8	2.3
T_{3L} vs. T_{4L}	=/>	>	0.6	> 34.5***	> 11.5**

[a] degrees of freedom for F-ratios of comparisons involving interkey intervals are (1,14), for degrees of freedom of the T_1 comparisons see text; * indicates: $p<.05$, **: $p<.01$, and ***: $p<.001$.

[b] only the last four sessions at each day have been included in the interkey interval comparisons.

1.3 Discussion

The main results of Experiment 1 are (a) a reduction of the complexity effect and of the interkey intervals during the first day of practice, (b) a relatively slow T_{2L} and T_{3L} in comparison with T_{2S} and T_{4L} (c) a gradual developing reduction of T_{4L} in comparison with T_{2S}, and (d) no difference between the CP and VP conditions. There are two additional effects worth mentioning namely (a) a relatively long T_{3L} during the first two sessions at day 1 and (b) a pronounced "warming up" effect for all interkey intervals at each new day.

This pattern of results is more consistent with concurrent processing than with motor unitization: There was no difference between the CP and VP conditions, the effects on interkey intervals developed rapidly, and T_{2L} and T_{3L} were much longer than T_{2S} and T_{4L}. The fact that T_{4L} became gradually less than T_{2S} is at the credit side of motor unitization. Yet, since no other indications for motor unitization were observed it seems reasonable to attribute the effect to the notion that concurrent processing might maintain less residual effects on a longer than on a shorter sequence. Note that this effect is at variance with the claim that elements in a sequence have to be located in a non-shrinking motor buffer (Sternberg et al., 1978). Then T_{4L} would have been longer than T_{2S} instead of shorter.

The relative contributions of concurrent programming and unpacking are not easily distinguished in this study. On the one hand the pronounced reduction of the complexity effect is indicative for concurrent programming. On the other hand, the short final interkey intervals—irrespective of sequence length—seem most consistent with unpacking. Hence, both seem to have played a significant role.

The additional effects can be considered post-hoc. The relatively long T_{3L} during session 1 and 2 is not predicted by any model. It might have been due to breaking up the sequence in two parts. Evidence for this possibility has been reported earlier (Beggs & Howarth, 1972; Brown & Carr, 1989; Pew, 1966). There may be several reasons that a pause occurred following the second keypress: it was halfway the long sequence, it was at the moment that the short sequence would have ended so that subjects may initially have been tempted to only prepare a short sequence, and it was the only diagonal movement between horizontal and vertical movements. Any way, this effect disappeared after a few sessions and is no serious threat for concurrent processing.

The "warming up" effects for all interkey intervals at each new day are unexpected but harder to explain by motor unitization than by concurrent processing. Associative motor unitization asserts that sequence execution relies on relatively passive traces which should not require substantial practice to be reactivated after a night's rest. Since only interkey intervals showed the effect and not sequence initiation times, it suggests that different processes underlie the reduction of the complexity effect (possibly concurrent programming) and the effects on the interkey intervals (possibly concurrent unpacking) (cf. Sanders, 1990). Then the "warming-up" effect can be attributed to the need for practice to reinstate concurrent unpacking after a night's rest.

2 EXPERIMENT 2

Experiment 1 dealt with the effects of practice on the production of keypressing sequences. Experiment 2 basically addressed the role of practice on response selection but also tried to find confirming evidence for concurrent processing. In Experiment 1 performance in CP was not better than in VP. This suggests that consistent practice was not beneficial to performance in comparison with varied practice. This, basically, is in contrast with associative models of response selection that assume that after consistent practice the response is triggered automatically through associative links (Cheng, 1985; Logan, 1988; Proctor et al., 1991 see also Kornblum et al., 1990). According to this type of models CP should have yielded a smaller T_1 than VP. One possible reason that Experiment 1 failed to show an effect of practice consistency may have been that it involved conditions of low decisional demands which allow selection and execution processes to be activated in advance (Anzola et al., 1976; Callan et al., 1974; Spijkers & Walter, 1985) thereby compensating for the easier access to responses after consistent practice. The importance of advance activation of the response set is illustrated by the fact that several investigators (Buckolz & Rodgers, 1980; Goodrich et al., 1990; Mowbray, 1964) found evidence that the advantage of simple RT over choice reaction time is due to an increased amount of advance activation of a response set. When the advance processes are interfered with, this advantage disappears. On the other hand, there is the possibility that automatic effects also developed in VP because this condition included an higher order consistency (Fisk et al., 1988; Kramer et al., 1990) in that a "6" always indicated a long sequence and a "D" always indicated a short sequence, or because four independent stimulus-to-response associations had developed.

Whether or not associations at the response selection level had developed in Experiment 1 was tested in a condition with the same stimuli and keypressing sequences as practiced in Experiment 1 but with reversed stimulus-sequence mapping. If strong stimulus-to-sequence associations had developed in CP as well as in VP mapping reversal was expected to yield equal performance deterioration in either of both conditions (Kramer et al., 1990; Pashler & Baylis, 1991; Shiffrin & Dumais, 1981). When performance in CP and VP were similar in Experiment 1 because of low decisional demands while stimulus-to-sequence associations had only developed in CP then the reversal effect was expected to affect CP but not VP.

Other conditions were selected with the rationale in mind that an abstract response code becomes associated to the stimulus used in practice. Potential codes are emergent response features such as the length of the sequence and the spatial lay-out of the sequence pair (Proctor & Reeve, 1986). For example, when the sequence length is used in selecting the correct response sequence initiation time will increase when the short sequence is lengthened so that sequence length is no longer an emergent feature. Furthermore, initiation time would increase even more when the stimulus-to-sequence length is reversed. Yet, when preparation is able to compensate for such effects initiation and interkey intervals of new sequences are not expected to be longer than in the practiced sequences.

Concerning sequence execution, Experiment 1 favored concurrent processing as the mechanism responsible for the practice effects. Experiment 2 was designed to further explore predictions of concurrent processing and associative motor unitization. Since concurrent processing is not sequence specific it predicts that the pattern of interkey intervals presented in Table I for concurrent processing occurs to an equal degree in new as well as in practiced sequences and irrespective of practice consistency. The possibility that the amount of practice used in Experiment 1 was not sufficient for associative motor unitization is pursued in Experiment 2 by providing additional practice. Hence, Experiment 2 tested whether later interkey intervals were smaller than earlier ones and whether this would lead to a difference between interkey intervals of practiced and new sequences that would increase with position.

A final issue concerns the relation between response selection and sequence execution. That is, following practice in Experiment 1 presentation of a stimulus may trigger a sequence either through an intermediate sequence code (Sanders, 1990) or the separate elements in the sequence may be activated directly. In the first situation, mapping reversal will only increase the time to initiate the sequence but not the interkey intervals. Alternatively, direct triggering of the individual sequence elements will be indicated by an increase of interkey intervals, as well.

2.1 Method

2.1.1 *Stimuli and keypressing sequences*

The nine sequence type conditions of Experiment 2 are shown in Table V (also see Fig. 1). One condition (PRA) involved the same task as practiced in Experiment 1 serving as baseline and allowing subjects to continue normal practice. The PRA condition preceded any block with the new sequence conditions. The other eight conditions involved a two-choice response task in which the stimulus, the sequence, their mapping, or a combination of these three elements changed relative to Experiment 1. The first of the other eight sequence type conditions included a reversed S-R mapping (RMA) condition, two conditions involved new stimuli (SSC, RSC), four conditions involved different sequences (LOO, RLE, SLA, CLA) and in one condition new sequences were given in response to new stimuli (SLE). The order of these conditions was balanced across subjects.

2.1.2 *Procedure*

Experiment 2 took place on the day immediately following day 3 of Experiment 1. In each session, the first block consisted of a continuation of earlier practice: alternating sequences for VP subjects and identical sequences for CP subjects. The second block of each session involved the sequence type conditions described before.

2.1.3 *Subjects and apparatus*

All subjects who participated in Experiment 1 also participated in Experiment 2. The same set of apparatus was used as in Experiment 1.

Table V Summary of the stimuli and keys used in Experiment 2. Regular trials were performed in the first block of each session whereas one of the other sequence type conditions was performed in the second block of each session. CP subjects produced only sequences shown in one of the four columns while VP subjects cycled through the columns so that, eventually, they had produced two of the sequence pairs in each column.

condition		stimuli	keypressing sequences			
PRActiced		6	1487	3241	7869	9623
trials	(PRA)	D	96	78	32	14
Reversed S-R		6	96	78	32	14
MApping	(RMA)	D	1487	3241	7869	9623
Same Stim.		5	1487	3241	7869	9623
Category	(SSC)	K	96	78	32	14
Reversed		8	96	78	32	14
Stim. Cat.	(RSC)	L	1487	3241	7869	9623
LOng Only		6	1487	3241	7869	9623
	(LOO)	D	9623	7869	3241	1487
Reversed		6	14	32	78	96
LEngth	(RLE)	D	9623	7869	3241	1487
Same spat.		6	7869	9623	1487	3241
LAy-out	(SLA)	D	32	14	96	78
Changed spat.		6	7863	9621	1489	3247
LAy-out	(CLA)	D	14	78	32	96
Same		*	9621	7863	3247	1489
LEngth	(SLE)	$	36	98	12	74

2.2 Results

A general overview of the data is given in Table VI and, with respect to the interkey intervals in regular trials (PRA), in Fig. 2. Sequence initiation time and interkey intervals were analyzed in a three-way ANOVA with practice consistency as between-subject variable, and sequence type and length as within-subject variables. Interkey intervals were compared using multivariate planned comparisons.

Table VI Initiation and interkey intervals in the short and long sequences as function of practice consistency, sequence type and whether the sequence was practiced or new.

	consistent practice						**varied practice**					
	T_{1S}	T_{1L}	T_{2S}	T_{2L}	T_{3L}	T_{4L}	T_{1S}	T_{1L}	T_{2S}	T_{2L}	T_{3L}	T_{4L}
							practiced sequences					
PRA	629	629	158	181	180	155	592	624	167	186	184	160
RMA	746	798	155	177	177	149	614	645	186	176	182	154
SSC	644	678	157	179	180	151	590	612	162	184	178	160
RSC	653	661	158	183	177	150	602	596	157	179	174	156
LOO(pr.)	-	694	-	182	177	156	-	644	-	185	177	163
RLE(VP)							646	707	161	176	183	155
							new sequences					
RLE(CP)	694	707	164	172	182	172						
LOO(new)	-	664	-	171	178	165	-	665	-	181	178	155
SLA	695	722	164	179	204	166	591	722	166	180	175	159
CLA	673	680	162	175	217	165	606	680	166	182	185	171
SLE	663	677	167	171	196	166	635	677	165	180	200	165
							mean times as function of new vs. practiced sequences[a]					
new seq.	681	697	164	174	195	167	611	693	166	181	185	163
pract.seq.	668	692	157	180	178	152	609	637	167	181	180	158
diff.	13	5	7	-6	17	15	2	56	-1	0	5	5

[a] RMA has not been included in the mean T_1s.

In order to test the prediction of associative response selection that practice deteriorates performance when stimulus-to-sequence mapping is reversed, performance in the practiced mapping condition (PRA) and the reversed mapping condition (RMA) was compared. A main effect of sequence type indicated that performance had deteriorated [$F(1,14)=22.3$, $p<.001$] and the effect was stronger in CP [$F(1,14)=11.4$, $p<.01$]. For CP subjects the difference between RMA and PRA amounted to 131 ms [$F(1,14)=32.8$, $p<.001$]. Since mapping reversal occurred for VP subjects in both RMA and RLE while PRA and SLA contained practiced mappings, a separate analysis was carried out for the VP data on PRA and SLA vs. RMA and SLE. This showed that in VP mapping reversal increased T_1 by 32 ms which was marginally significant [$F(1,14)=3.5$, $p<.09$] if tested nondirectionally, or $p<.05$ if tested as a directional prediction of the theory (Keppel, 1982, pp. 113-114). Error rates were not different in CP and VP [$F(1,14)=1.5$, $p>.20$]. Further tests showed that only T_1 increased as a result of mapping reversal and not the interkey intervals.

A main effect of sequence type showed that T_1 differed among the sequence type conditions [$F(8,112)=3.84$, $p<.001$]. An interaction between practice consistency and sequence type [$F(8,112)=2.26$, $p<.05$] indicated that these effects differed as a function of practice consistency during practice. However, exclusion of RMA from the ANOVA made the sequence type main effect and the practice consistency x sequence type interaction in T_1 become insignificant [resp. $F(7,98)=2.04$, $p<.06$ and $F(7,98)=1.1$, $p>.35$] suggesting that these effects were mainly caused by RMA. The effect of sequence type was also significant in the error analysis as shown by a main effect of sequence type [$F(8,112)=2.6$, $p<.05$]. Examination of the data showed that most errors were made in RMA (5.6%), RLE (5.3%), and LOO (4.8%). All others were below 4%. Planned comparison of errors in PRA and RMA showed that more errors were made in RMA trials [RMA: 5.6%, PRA: 2.6%, $F(1,14)=5.6$, $p<.05$].

The effects of additional practice with practiced and new sequences on the complexity effect were also analyzed. The data showed that the complexity effect occurred throughout Experiment 2 (Table VI). Pooled over all conditions T_1 was 17 ms smaller for short than for the long sequences [$F(1,14)=6.00$, $p<.05$]. The sequence type x sequence length interaction was not significant [$F(8,112)=1.5$, $p>.18$] suggesting that the complexity effect was similar for all sequence types. An analysis on arcsine transformed error proportions confirmed the complexity effect. More errors were made with long sequences (4.2%) than with short sequences [3.1%, $F(1,14)=4.8$, $p<.05$]. Hence, the complexity effect did not disappear in Experiment 2 and was similar for practiced and new sequence types.

Predictions of concurrent processing and associative motor unitization as shown in Table I were tested by comparing pairs of mean interkey intervals over all sequence type conditions. The results are presented in Table VII and are consistent with the findings in Experiment 1. Again, none of the comparisons in Table VII were different as a function of practice consistency (all ps$>.11$).

Table VII Comparison of the predictions presented in Table I and the results obtained in Experiment 2 combined for all sequence types. Interactions with new vs. practiced sequences are indicated as well.

	PREDICTED		OBSERVED	
comparison first vs. second	conc. proc.	asso. unit.	results^{a} (main effects)	interaction with new vs. practiced seq.
T_{2S} vs. T_{2L}	<	=	$< 21.5^{***}$	0.3
T_{2S} vs. T_{4L}	=	>	$> 6.7^{*}$	1.8
T_{2L} vs. T_{4L}	>	>	$> 40.3^{***}$	5.8^{*}
T_{2S} vs. T_{3L}	</=	>	$< 31.7^{***}$	3.2
T_{2L} vs. T_{3L}	=/>	>	2.5	3.1
T_{3L} vs. T_{4L}	=/>	>	$> 103.0^{***}$	0.6

[a] degrees of freedom for F-ratios of comparisons involving interkey intervals are (1,14), for degrees of freedom of the T_1 comparisons see text; * indicates: $p<.05$, **: $p<.01$, and ***: $p<.001$.

Also, the prediction of associative motor unitization was tested that differences between interkey intervals in new and practiced sequences increase with position. The data in Table VI show that T_{4L} was 15 ms smaller in practiced sequences than in new sequences [$F(1,14)=21.1$, $p<.001$]. The 17 ms smaller T_{3L} in practiced sequences of CP was not significant [$F(1,14)=4.0$, $p<.07$] and could be attributed to one condition only (CLA) without which no effect remained [$F(1,14)=2.5$, $p>.10$]. The effect on T_{4L} is confirmed by the finding that T_{2L} decreased by 4 ms and T_{4L} increased by 10 ms in the new sequences (Table VII). This was not different for CP and VP [$F(1,14)=0.8$, $p>.25$] even though the effect was stronger in CP. Hence, T_{4L} was found to be smaller in practiced than in new sequences. In the VP condition, T_2, T_{3L} and T_{4L} were not significantly different in practiced and new sequences (all $ps>.22$).

Finally, additional analyses were carried out to test some unexpected results. First, in Experiment 1 there were indications that with little practice T_{3L} was relatively long. Table VI shows that this was also the case for CLA and SLA sequences in the CP condition of Experiment 2. This was confirmed by an interaction between practice consistency and sequence condition [$F(8,112)=2.2$, $p<.05$]. Newman-Keuls comparisons showed that the interaction was mainly caused by T_{3L} in the CLA condition of CP since this T_{3L} differed significantly from T_{3L} in most other sequence types (all $p<.01$, except CLA which did not differ from SLA, $p>.10$).

Second, Experiment 1 showed that T_1 was about 10 ms longer in CP than in VP. In Experiment 2 the advantage of VP on T_1 became larger (66 ms) and significant [$F(1,14)=5.0$, $p<.05$]. At this point this effect can only be explained by a subjects-group difference. This notion will be further pursued in Experiment 3.

2.3 **Discussion**

The most interesting effects in this experiment were (a) that mapping reversal yielded an increase of sequence initiation time, especially after consistent practice, while (b) there was virtually no difference in the time to initiate the new and practiced sequences when new or practiced stimuli were presented. (c) The final interkey interval in each of the sequences was shorter than earlier interkey intervals. This occurred in new as well as in practiced sequences and irrespective of practice consistency. Finally, (d) interkey intervals were virtually equal in all conditions, only in SLA and CLA of CP T_{3L} was somewhat longer.

In the introduction the possibility was raised that automatic effects had developed with practice in the selection of sequences but that this was obscured in Experiment 1 by anticipatory response activation. The data support the view that sequence selection had automatized because T_1 increased when mapping was reversed whereas interkey intervals did not increase. For CP this confirms earlier findings (Kramer et al., 1990; Pashler & Baylis, 1991; Shiffrin & Dumais, 1981) but it is interesting to see that, though less powerful, it had also developed in VP. It suggests that automaticity may also develop when only higher order response properties remain consistent during practice (Fisk et al., 1988). Possibly, in VP sequence length had been used to select sequences whereas in CP direct associations had developed. Yet, the effect in VP was not very strong. Future research should investigate whether this effect was caused by the development of some emergent ad-hoc response category node (Proctor & Reeve, 1986 also see Pashler and Baylis, 1991) here involving sequence length and spatial lay-out or that it had been caused by the development of four independent stimulus-to-response associations.

When ignoring the effect of mapping reversal no significant differences were observed between sequence initiation times nor was there any significant interaction with sequence consistency. This seems to suggest that properties like sequence length and spatial lay-out were not used in sequence selection but it may also corroborate the view that anticipatory activation of the response set may be able to compensate for sequence-specific effects of practice on initiation and interkey intervals of new sequences and that specific properties of the sequences can be used for selection any way. Experiment 3 will address this possibility.

The pattern of interkey intervals support concurrent unpacking for new and practiced sequences. Again, T_{4L} was found to be less than T_{2S}. Yet, despite the additional practice in this experiment T_{2L} and T_{3L} still did not differ as expected by associative motor unitization. Investigation of the prediction that the difference between interkey intervals in new and practiced sequences increases with position was confirmed in that T_{4L} was smaller in practiced than in new sequences whereas T_{2S}, T_{2L} and T_{3L} did not differ much. The T_{4L} effect is obviously a sequence-specific effect. Again, with the lack of other evidence for associative motor unitization the T_{4L} advantage as compared to T_{2S} may be explained in terms of the better possibility for concurrent unpacking in longer sequences, especially when practiced sequences are involved.

Finally, the absence of any effect of mapping reversal on interkey intervals affirms the view expressed in Experiment 1 that a response is first selected as a whole (i.e. as an abstract code) and only then executed (i.e. separate steps, Sanders, 1990).

3 EXPERIMENT 3

In order to address the effect of advance processing on the production of keypressing sequences, Experiment 3 involved a four-choice RT task in which the pair of sequences practiced in Experiment 1 and 2 was extended with a new pair of sequences. By manipulating the frequency of each of these pairs it was possible to test whether concurrent programming and unpacking depend on advance activation of responses. If they do, the complexity effect should increase and the pattern of interkey intervals should be different for low-frequency sequences than for high-frequency sequences.

The condition with reversed stimulus-to-sequence mappings in Experiment 2 suggested that selection of the correct sequence involved automaticity in CP and less in VP. Since no advantage was observed for CP over VP in Experiment 1 and 2 (except for the differential effect of mapping reversal) it was assumed that these automatic effects could be compensated for by activating the response set. If so, an advantage for CP over VP should emerge in situations with limited advance response activation because access to information on infrequent sequences would be easier in CP than in VP.

Notions of cross-talk and confusability (Navon, 1985; Navon & Miller, 1987) predict that performance is hampered when both pairs possess similar properties in terms of length and spatial lay-out. Yet, direct stimulus-response associations, which may have developed in CP, may make response selection less vulnerable to cross-talk because there these properties are not used for response selection whereas they may be used in VP (cf. Experiment 2). Therefore, the experiment tested the hypothesis that performance in VP would deteriorate more than in CP when sequences with the same length and spatial lay-out (though rotated) are added as compared to when sequences with different length and lay-out are included.

3.1 **Method**

3.1.1 *Tasks and design*

The experiment contained the seven conditions presented in Table VIII. There were four four-choice conditions which involved two factorially combined within-subject manipulations, sequence similarity and sequence frequency. In addition, there were three two-choice conditions. One of these, PRA2, contained regular practice trials (equal to PRA in Experiment 2) and another, RMA2, contained trials with reversed S-R mappings (RMA in Experiment 2). In addition, all subjects performed a one-key control (OKC) condition in which only the first key of the practiced key-pressing sequences was pressed. This condition was added to check for the group differences found in Experiment 1 and 2. The order of these conditions was balanced over the subjects of each group according to a latin square. All sessions consisted of two 74 trial blocks.

Table VIII Overview of the stimuli and keys used in Experiment 3. Consistent with Experiment 2 CP subjects produced key-pressing sequences shown in one column whereas VP subjects cycled through the columns.

condition	stimuli	keypressing sequences				probability
PRActiced	6	1487	3241	7869	9623	.5
trials (PRA2)	D	96	78	32	14	.5
Reversed S-R	6	96	78	32	14	.5
MApping(RMA2)	D	1487	3241	7869	9623	.5
One Key	6	1	3	7	9	.5
Control (OKC)	D	9	7	3	1	.5
Infreq. Practiced	6	1487	3241	7869	9623	.1
Freq. Different	D	96	78	32	14	.1
(IPFD)	$	789	147	963	321	.4
	*	321	963	147	789	.4
Freq. Practiced	6	1487	3241	7869	9623	.4
Infreq. Different	D	96	78	32	14	.4
(FPID)	@	789	147	963	321	.1
	+	321	963	147	789	.1
Infreq. Practiced	6	1487	3241	7869	9623	.1
Freq. Similar	D	96	78	32	14	.1
(IPFS)	&	78	14	96	32	.4
	#	3241	9623	1487	7869	.4
Freq. Practiced	6	1487	3241	7869	9623	.4
Infreq. Similar	D	96	78	32	14	.4
(FPIS)	>	78	14	96	32	.1
	?	3241	9623	1487	7869	.1

3.1.2 *Procedure*

Subjects started Experiment 3 with two practice sessions containing the regular trials that had been practiced in Experiment 1 and 2. Session three to nine involved the seven sequence type conditions described before. Subjects were explicitly reminded that in order to get the best performance they should concentrate on the frequent sequence pair without, of course, forgetting about the infrequent pair.

3.1.3 *Subjects and apparatus*

Fourteen out of the sixteen subjects who participated in Experiment 1 and 2, also took part in Experiment 3. This group included seven CP and seven VP subjects. Not all subjects could return on the same day: four returned 13 days after the last day in Experiment 1, seven returned 15 days later, one 22 days later and two 26 days later. They received Dfl. 45 for participation. The four subjects that had the least errors and still responded fast received a bonus of Dfl. 15. The same apparatus was used as in Experiment 1 and 2.

3.2 Results

Mean sequence initiation times (T_{1S} and T_{1L}) and interkey intervals (T_{2S}, T_{2L}, T_{3L}, T_{4L}) in correct trials were computed separately for short and long sequences per block and were submitted to a general three-way analysis of variance (ANOVA) with practice consistency as between-subject factor, and sequence length and sequence type (PAR2, RMA2 and the four-choice condition sequences, practiced and new, except those with length 3 in IPFD and FPID) as within-subject factors.

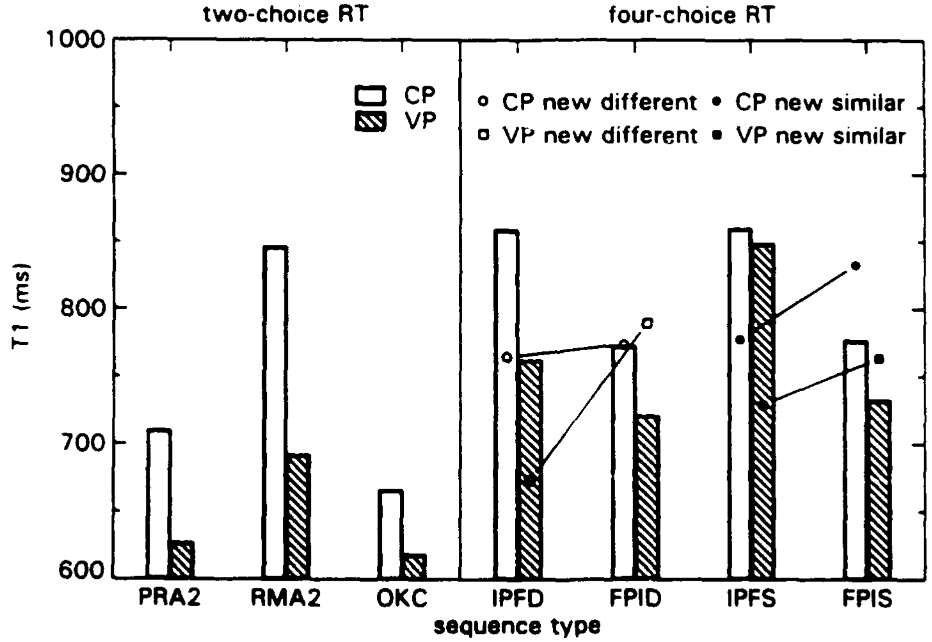

Fig. 3 T_1 obtained for the practiced sequence pairs as a function of practice consistency and sequence type (see Table VIII). T_1 to the added sequence pairs is depicted as well.

In Fig. 3, T_1 is presented as function of practice consistency and sequence type. The overall ANOVA on T_1 showed main effects of sequence type [$F(7,84)=10.8$, $p<.001$] and sequence length [$F(1,12)=25.2$, $p<.001$], and an interaction between sequence type and sequence length [$F(7.84)=3.1$, $p<.01$] indicating that the complexity effect differed among conditions (see Table IX). Planned comparisons in the conditions with similar sequences (FPIS, IPFS) showed that the complexity effect increased from 18 ms when the sequences were frequent to 62 ms when the sequences were infrequent [$F(1,12)=22.6$, $p<.01$]. This was not affected by practice consistency [$F(1,12)=0.3$, $p>.25$], nor did the complexity effect increase differently when practiced and new sequences were compared [$F(1,12)=0.2$, $p>.25$].

Table IX Initiation and interkey intervals in the short and long sequences as function of practice consistency and sequence type. "freq" at one of the bottom rows indicates the mean of FPID, FPIS, and IPFS; "infreq" indicates the mean of IPFD, IPFS, and FPIS.

	consistent practice						**varied practice**					
	T_{1S}	T_{1L}	T_{2S}	T_{2L}	T_{3L}	T_{4L}	T_{1S}	T_{1L}	T_{2S}	T_{2L}	T_{3L}	T_{4L}
							TWO-CHOICE					
PRA2	696	723	155	180	176	149	608	645	172	177	181	155
RMA2	838	854	152	180	170	148	680	703	158	181	171	156
OKC	649	682					619	617				
							FOUR-CHOICE					
							practiced sequences					
IPFD	822	895	153	181	177	147	775	749	157	176	170	154
FPID	755	790	152	182	173	149	716	725	155	179	171	159
IPFS	818	901	155	186	174	151	813	884	156	169	177	157
FPIS	765	788	154	183	176	151	730	734	162	182	175	157
							new sequences					
IPFD	764		182		165		673		173		163	
FPID	774		177		160		789		175		164	
IPFS	774	780	170	176	201	159	714	744	161	172	168	147
FPIS	792	872	172	170	200	159	729	798	161	176	177	158
							frequent vs. infrequent sequences					
freq.	765	786	159	180	183	153	720	734	159	178	171	154
infreq.	811	889	160	179	183	152	772	810	158	174	175	156
diff.	40	103	1	-1	0	-1	52	76	-1	-4	4	2

As in Experiment 2 predictions of concurrent processing and associative motor unitization as presented in Table I were tested by comparing interkey intervals. The interkey intervals in Table IX suggests that the interkey intervals were not affected by frequency of sequence occurrence. Table X shows the comparisons of the interkey intervals in the format of Table I. The table shows that the data are in accordance with the predictions of concurrent processing. It also shows that the predictions applied to infrequent sequences as well as to frequent sequences as indicated by the absence of interactions between frequent vs. infrequent sequences and interkey intervals.

Table X Comparison of the predictions presented in Table I and the results obtained in Experiment 3 in the four-choice sequence conditions (3-element sequences have been excluded). Interactions with frequent (FPID, FPIS, and IPFS) vs. infrequent sequences (in IPFD, IPFS, and FPIS) are indicated as well.

	PREDICTED		FOUND	
comparison first vs. second	conc. proc.	asso. unit.	results[a] (main effects)	interaction with new vs. practiced seq.
T_{2S} vs. T_{2L}	<	=	< 44.8^{***}	0.7
T_{2S} vs. T_{4L}	=	>	2.4	0.1
T_{2L} vs. T_{4L}	>	>	> 62.5^{***}	1.2
T_{2S} vs. T_{3L}	</=	>	< 34.4^{***}	0.5
T_{2L} vs. T_{3L}	=/>	>	0.2	2.9
T_{3L} vs. T_{4L}	=/>	>	> 52.2^{***}	0.3

[a] degrees of freedom for all F-ratios are (1,12), * indicates: $p<.05$, **: $p<.01$, and ***: $p<.001$.

T_1 of infrequent practiced sequences (in IPFS and IPFD) was slower than that of the normal practiced sequences (PRA2) as indicated by a planned comparison of IPFD and IPFS vs. PRA2 [$F(1,12)=76.7$, $p<.001$]. The T_1 increase was not different for CP and VP as indicated by the absence of a significant interaction between IPFD and IPFS vs. PRA2 and practice consistency [$F(1,12)=0.6$, $p>.25$]. This at odds with the expectation.

There were indications for a larger amount of interference due to cross-talk in VP than in CP. First, when in CP infrequent practiced sequences were combined with similar frequent sequences (IPFS) T_1 was equal as when combined with different sequences (IPFD): both amounted to 859 ms. So, similarity of the new frequent sequences to the practiced infrequent sequences did not affect the time to initiate infrequent sequences after consistent practice. However, in VP T_1 to infrequent practiced sequences was 86 ms larger when combined with similar sequences (IPFS) as compared to different sequences (IPFD). This yielded a significant practice consistency x IPFD vs. IPFS interaction [$F(1,12)=6.9$, $p<.05$]. Yet, as shown in Table IX this effect was for the greater part, but not completely, due to the relatively fast sequence initiation time in the long sequences.

A second indication for relatively much interference in VP was found when comparing T_1 to new different infrequent sequences (in FPID) in CP and VP. The comparison showed that in VP the new sequence pair was initiated 116 ms faster when it was the frequent pair (in IPFD) than when it was the infrequent pair (in FPID). For CP this difference was only 9 ms. This yielded an interaction between practice consistency and frequency of the different sequence pair [$F(1,12)=7.8$, $p<.05$]. A comparable effect was not found in the conditions with similar sequences but this can be ascribed to the fact that the similar "new" sequences in IPFS were indeed new to CP subjects but had in fact already been practiced in Experiment 1 and 2 by VP subjects.

In order to check whether the effect of practice in Experiment 1 and 2 was retained over the time between Experiment 2 and 3, the effect of mapping reversal was evaluated again in RMA2. The results obtained in RMA2 showed that the reversal effect in T_1 amounted 101 ms which was significant in a planned comparison [$F(1,12)=11.7$, $p<.01$]. As in Experiment 2 the difference was larger for CP (136 ms) than for VP (65 ms) but the interaction was not significant [$F(1,12)=1.5$, $p>.20$] in this case.

As can be seen in Fig. 3, T_1 was generally longer in CP than in VP. For example, in the practice conditions (PRA2) the advantage of VP was 83 ms [$F(1,12)=5.1$, $p<.05$] confirming the view of group differences between CP and VP. Further confirmation was derived from the OKC condition: T_1 was 47 ms faster in VP than in CP [$F(1,12)=1.3$, $p>.20$].

An unexpected but interesting observation was an interaction in OKC between practice consistency and sequence length [$F(1,12)=4.6$, $p<.06$] indicating that in CP T_1 to the first key of the otherwise long sequence was longer than T_1 to the first key of the otherwise short sequence whereas this was not the case in VP. In CP the difference amounted to 33 ms, in VP it was only 3 ms.

3.3 **Discussion**

The main findings in Experiment 3 were as follows: (a) the complexity effect clearly increased for low-frequent sequences, irrespective of practice, (b) the pattern of interkey intervals was independent of sequence frequency and novelty, (c) low-frequent sequences were initiated slower than high-frequent sequences but this did not differ for CP and VP, (d) low-frequent sequences were initiated slower in the similar than in the different condition of VP while such a difference was not found in CP. An additional observation was that, in pressing single keys (length one) in CP, the time to initiate the first keypress of an otherwise long sequence took more time than the first of an otherwise short sequence. This distinction was not found in VP.

The increment of the complexity effect with low-frequency sequences and the unchanged pattern of interkey intervals clearly confirm the results in Experiment 1 and 2 that a response-aspecific mechanism underlies proficient sequence production and that the complexity effect and the pattern of interkey intervals are caused by separate mechanisms, the first affected by sequence frequency and the second insensitive to sequence frequency. These findings are suggestive for the existence of concurrent programming and concurrent unpacking as separable processes underlying skilled keypressing.

The notion that the effect of consistent practice as opposed to varied practice would emerge when the practiced sequences were infrequent was not confirmed. The time to initiate the low-frequency sequences was found to increase about equally in CP and VP. Hence, consistent practice did not yield easier access to inactivated sequence information than varied practice. May be consistent practice does not give easier access to sequence information than varied practice when practice is extensive. Alternatively, the period of 13 to 26 days between Experiment 2 and 3 was long enough to reduce effects of practice as also indicated by the lack of a significant difference between CP and VP in the mapping reversal condition. Also, the present decisional demands may not have been able to make a distinction between effects of consistent and varied mapping.

On the other hand, the notion that performance in CP would be less vulnerable to cross-talk in CP than in VP was confirmed. When consistently practiced sequences were to be produced infrequently the sequence initiation time was equal irrespective of whether the frequent sequences were similar in terms of length and spatial lay-out or not. In contrast, after varied practice T_1 increased more when the frequent sequences were similar with respect to length and spatial lay-out than when they were different. In addition, in CP different sequences were initiated about as fast irrespective of frequency while in VP different infrequent sequences were initiated slower than different frequent sequences. Finally, a trend was found that initiation time of practiced sequences increased more in VP than in CP when infrequent sequences were added. Together, these effects favor the notion that after consistent practice selection of the sequence was facilitated by direct stimulus-sequences associations while after varied practice sequence selection was based on emergent features of the sequences (Proctor & Reeve, 1986).

Unexpectedly and post-hoc some confirming evidence for this notion was supplied by the one-key-control (OKC) condition. In CP, pressing only the first key of each of the sequences was slower when this involved the first key of the long sequence than when this involved the first key to the short sequence. Such an effect was not found in VP.

4 GENERAL DISCUSSION

The objective of the three experiments in this report was to evaluate models of practice effects on selecting and executing keypressing sequences. With regard to the execution of keypressing sequences two models were distinguished. The concurrent processing model assumes that with practice the programming of the whole sequence no longer occurs before execution of the first element of the sequence but that it overlaps with execution of the first few elements. This was called concurrent programming. In addition, concurrent processing asserts that unpacking of individual motor elements from a short-term motor buffer may shift from the interval between successive keypresses to a moment that execution of the preceding keypress has not yet been completed. This was termed concurrent unpacking. The alternative model of sequence execution, associative motor unitization, assumes that practice forms associative links between representations of succeeding movements so that the whole sequence is represented as one closely interlinked representation which can be more easily retrieved and which, once initiated, makes the sequence run off more or less automatically.

In general, there was clear evidence for concurrent processing in that the time taken to execute the last keypress in the sequence became clearly shorter with practice than the times used to execute earlier, i.e. non-final keypresses. As predicted by concurrent processing, this effect was found to develop with limited practice (Experiment 1), transferred easily to new keypressing sequences (Experiment 2 and 3), occurred irrespective of whether the same set of two sequences was practiced consistently or whether four pairs of sequences were practiced in alternation (Experiment 1, 2, and 3), and occurred irrespective of factors delaying initiation time like mapping reversal (Experiment 2 and 3) and low frequency of occurrence (Experiment 3). Hence, the present data strongly suggest that with practice execution of a keypressing sequence may start before programming of the whole sequence has been finished and that unpacking of motor elements from a motor buffer concurs with execution of the preceding motor element. Since early in practice the long sequence seemed to have been programmed in two parts which disappeared after two sessions it may well be that practice allows longer sequences to be programmed at one time (cf. Pew, 1966).

Basically, the present series of experiments could not distinguish very well between concurrent programming and unpacking but the data suggest that both play a role with practice. Concurrent programming was indicated by a reduction of the complexity effect while the time preceding one or more of the earlier keypresses would reduce less with practice than one or more later keypresses because of concurrent programming. The reduction of the complexity effect was a clear indication for concurrent programming but, with the exception of the advantage of final over non-final interkey intervals, earlier intervals were not found to be longer than later ones. Evidence for concurrent unpacking was derived from the shorter last keypresses in each sequence as compared to the earlier ones. A strong indication that the complexity effect and the pattern of interresponse intervals had been caused by different processes was that these effects were sensitive to different manipulations. The complexity effect increased for low-frequency sequences whereas the pattern of interkey intervals obtained with practice only recurred after two or three sessions at a new day. Maybe concurrent programming does not increase interkey intervals whereas concurrent unpacking does.

Associative motor unitization also predicts that the complexity effect reduces with practice. Yet, only two effects on interkey intervals were correctly predicted by associative motor unitization in that the last interkey interval in the long sequence was shorter than in the short sequence (Experiment 1 and 2) and that it was shorter in practiced than in new sequences (Experiment 2). Yet, the predicted higher rate of decrease of the third interkey interval as compared to the second one was not found (Experiment 1, 2, 3) nor was the third interkey interval consistently larger in new sequences than in practiced sequences (Experiment 2). Finally, strong evidence against motor unitization on sequence execution emerges from the absence of an effect of practice consistency on interresponse times. Then the question arises whether the advantage of T_{4L} over T_{2S} can also be explained in terms of concurrent processing. One plausible explanation is that the execution of the first keypress in the short sequence was too short to allow full preprogramming of the second keypress while preprogramming was no problem during the long sequences. This notion that the T_{4L} advantage was a concurrent unpacking phenomenon is consistent with the finding that it was also sensitive to "warming up" as were the other interkey intervals.

The present experiments also supply interesting data on the effects of practice on selecting action sequences. Thus, Experiment 2 aimed at investigating the development of automatic effects in sequence selection. Reversal of the mapping between stimuli and keypressing sequences led to an increase in the time to initiate the sequences suggesting that, indeed, responses are triggered by stimulus presentation and, hence, inhibition is required when mapping is reversed. This effect was pronounced after practice with consistent sequence practice but it also occurred with varied sequences (Experiment 2 and 3). Probably, some automaticity also developed after varied practice. Whether this was caused by the presence of a higher-order mapping consistency (stimulus-to-sequence length) or whether separate associations had developed requires further research.
Subsequently, Experiment 3 tested the notion that with only a few response alternatives as in Experiment 1 and 2 preactivation of the response set can compensate for the lack of automatic effects in selection of the sequences. The hypothesis that when practiced sequences occur only infrequently they would be less disrupted after CP than after VP could not be confirmed. Yet, sequence selection was less sensitive to the presence of sequences with similar length and spatial lay-out after consistent practice than after varied practice. This demonstrates the development of direct associations between stimulus and sequence representations during consistent practice which may replace response selection on the basis of emergent features. Unexpected support for this notion was also provided by the observation that pressing only the first key of the consistently practiced sequences took longer if it involved the long sequence than when it involved the short sequence which effect was absent after varied practice.

Finally, interkey intervals were not increased by mapping reversal which corroborates the general notion that response selection and execution include separate processes (e.g. Sanders, 1990).

In conclusion, there is substantial evidence that (a) concurrent programming as well as concurrent unpacking develop with practice in a sequential keypressing situation. (b) When sequences are practiced with a consistent stimulus-sequence mapping sequence selection is less vulnerable for cross-talk. This may be due to the development of direct associations between their representations. (c) Three effects were independently affected by three different manipulations, i.e., sequence initiation time was increased by mapping reversal, the complexity effect by relative signal frequency, and the pattern of interkey intervals by "warming up". This indicates that they are caused by different processes. Possibly, they are caused by, respectively, response selection, motor programming, and unpacking (Sanders, 1990).

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

This paper describes three experiments that aimed at examining the effects of practice in a sequential keypressing task. In Experiment 1 a two-choice sequence production task was practiced extensively. Experiment 2 assessed the effect of this practice on the production of a series of slightly changed sequences. In Experiment 3 a four-choice reaction task was performed which included the practiced pair of sequences as well as a new pair in order to assess the effects of frequency of occurrence of each pair and their mutual similarity in terms of length and spatial lay-out.

The results are taken as evidence for the development of two sequence execution mechanisms. One allows programming to continue while the earlier keypresses in the sequence are already executed, i.e. concurrent programming. The other allows unpacking of individual motor elements from a short-term motor buffer during execution of the preceding keypresses, i.e. concurrent unpacking. Practice with consistent stimulus-sequence mappings made performance less sensitive to the presence of similar sequences than practice with varied mappings which suggests that stimulus-sequence associations develop with consistent stimulus-sequence mapping.

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