Effects of extended practice in a one-finger keypressing task

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This paper addresses skilled operations underlying the initiation and execution of rapid movement sequences in a task consisting of three sequential keypresses made with one finger. It sought to provide evidence for the notion that, as a result of practice, processes required to produce a keypressing sequence become concurrent. The results of the experiment show, first, that unpacking of the third keypress in a three-keypress sequence, which is assumed to occur normally after execution of the second keypress, is shifted in time during practice so as to occur during or before actual depression of the second key. Second, no evidence was found that selection of a stimulus-dependent key occurring later in the sequence could be performed during execution of earlier, stimulus-independent keypresses. Third, the pattern of dual-task interference suggested that attention is required for preparing as well as for executing movement sequences. Dual-task interference hardly reduced with practice which was interpreted as evidence for the notion that reduction of attentional demands of keypressing with practice is used only for increasing the amount of concurrent unpacking. In conclusion, the present experiment suggests that a major reason that movement sequences are executed faster with practice is that the reduction of attentional demands of individual subprocesses is utilized to increase the amount of concurrent processing.

1. Introduction

During recent years there has been a growing interest in operations underlying acquisition of perceptual-motor skills among which the production of rapid movement sequences. Several views acknowledge that the production of a series of rapid movements involves two basic steps. First, abstract representations of the individual movements are retrieved from long-term memory and, after preliminary processing, they are temporarily stored as subprograms in a short-term motor buffer. For movements that do not depend on the stimulus this occurs before stimulus presentation. For stimu-

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lus-dependent movements retrieval and storage is completed upon stimulus presentation. Second, before execution of each individual movement in the sequence the corresponding subprogram is retrieved from the buffer, unpacked into its constituents, and initiated (e.g. Henry, 1986; Sternberg et al., 1978; Rosenbaum et al., 1984; Van Galen et al., 1986). By now there is ample evidence that these steps need not necessarily occur in strict serial order but they may also occur concurrently. Thus, earlier movements of the sequence may be initiated before later ones have been stored in the motor buffer (e.g. Garcia-Colera and Semjen, 1988; Van Donkelaar and Franks, 1991; Rosenbaum et al., 1987). Also, retrieval and unpacking needed for the execution of a movement may overlap with the execution of earlier movements (Van Galen and Teulings, 1983; Van Galen et al., 1986).

To investigate whether or not practice causes the above-mentioned processes to occur concurrently an experiment was conducted in which subjects practiced short keypressing sequences. The issue of concurrent processing was investigated in three ways. First, the observation was verified that practice has a different effect on the time taken by earlier and later movement elements. Second, the paper examined whether selection and retrieval of a stimulus-dependent movement can, after sufficient practice, concur with executing earlier stimulus-independent movements. Third, the effects of a dual task, viz., tone counting, on the time to initiate the movement sequence, interresponse times, and errors were explored in detail. These points will be elaborated in the next paragraphs.

There is reason to believe that practice plays an important role in the development of concurrent processing. It has been known for some time that the difference in the time to initiate a long and a short sequence (i.e. the complexity effect, Henry and Rogers, 1960; Sternberg et al., 1978) decreases with practice (Brown and Carr, 1989; Fischman and Lim, 1991; Hulstijn and Van Galen, 1983). One interpretation of this finding is that it is due to an increasing degree of concurrent processing during sequence execution (Hulstijn and Van Galen, 1983). Recently, this notion has been confirmed by findings that the movement time of the initial segment of a six-segment writing sequence profited less from practice than the movement times of later segments (Portier et al., 1990; Portier and Van Galen, 1992). It was concluded that retrieving and unpacking later segments of the sequence was gradually realized during execution of the initial segment and that more and more movement segments were dealt with at the same time, that is, as one motor chunk (Brown and Carr, 1989; Portier et al., 1990). Portier et al. (1990) and Portier and Van Galen (1992) did not report practice effects on execution times of later segments in the sequence because earlier studies had shown that movement times of final segments are lengthened by the oncoming stop at the end of the sequence. Apparently, some additional processing is required to stop writing. This is unfortunate in the sense that Portier et al.
(1990) could not test the hypothesis that final segments in the sequence were performed faster with practice than earlier segments because final segments are not slowed by concurrent processing and earlier segments are. Also, Portier et al. (1990) did not distinguish between effects of concurrent processing and of motor chunking and assumed that both had contributed to the reduced effect of practice on the first movement in the sequence. This raises the question whether the one can occur without the other. For example, is it possible to develop concurrent processing when there are no possibilities for chunking a number of forthcoming segments? To resolve this issue the present study examined the effect of practice on the second and third keypress in a sequence of three keypresses which were made with one finger. Basically, the times preceding the second and third keypress are thought to reflect retrieval and initiation (i.e. unpacking) of the oncoming keypress. But if unpacking the third keypress shifts in time so that it occurs during execution of the first and/or second keypress then, theoretically, it is expected that the intervals preceding these keypresses decrease less with practice than the time preceding the third keypress. This phenomenon is expected irrespective of whether or not there are stimulus-dependent elements in the sequence because unpacking and response selection are independent processes (Sanders, 1990).

A second issue in this paper addresses the possibility to select and retrieve stimulus-dependent movements in the sequence during execution of earlier stimulus-independent ones. Welford (1967) and, more recently, Pashler (1984, 1990) and McCann and Johnston (1992) have convincingly shown that, when two simple sensorimotor tasks are performed in rapid succession, response selection for one stimulus can only start when response selection for the earlier stimulus has been completed. On the other hand, response selection for one task can occur together with perceptual processing of a slightly later stimulus. In other words, response selection constitutes a major single-channel bottleneck for dual task performance. In the present context, this raises the question whether, as a result of practice, stimulus-dependent selection of a later movement can occur concurrently with execution of an earlier stimulus-independent movement. Garcia-Colera and Semjen (1988) used a sequential tapping task in which only the force of the last element was stimulus-dependent. They found that, when increasing sequence length, choice RT did not drop to the level of simple RT and concluded that subjects tended to postpone responding until the response had been selected, presumably due to a ‘safety strategy’. Yet, Garcia-Colera and Semjen (1988) used only 48 trials for each individual sequence. Since it is generally assumed that demands on response selection (e.g. Logan, 1988, 1990) and movement execution reduce with practice (Brown and Carr, 1989; Hulstijn and Van Galen, 1988; Schmidt, 1975, 1987; Teulings et al., 1986) it may well be that, following extensive practice, response selection and motor execution can occur in
parallel. In that case a sequence including a stimulus-dependent element at a later position should take as much time to initiate as a fixed sequence that is completely known in advance.

In order to investigate this issue only the third keypress in the keypressing sequence was stimulus-dependent while the first and second one remained fixed across conditions and could be prepared in advance of the imperative stimulus. A fixed foreperiod was used in the hope that stimulus presentation would be immediately followed by a first already fully prepared keypress while the third keypress would be selected during executing the first and second one. A fixed sequence in which the third key was also known in advance served as control condition. If selection of the third keypress gradually occurs during execution of the first and second keypress, sequence initiation time in the stimulus-dependent conditions should drop to the level of the fixed sequence. The reason is that initiation time in the stimulus-dependent sequence would involve initiating the sequence as a whole and the onset of the first keypress itself as in the fixed sequence but selecting the third key would no longer occur during sequence initiation.

Note that the usage of a fixed foreperiod does not allow sequence initiation time to be used for evaluating concurrent unpacking due to confounding with the development of proper time estimation. Yet, sequence initiation time may still be indicative for concurrent response selection because time estimation skill is assumed to be similar in fixed and stimulus-dependent sequences.

The hypothesis that stimulus-dependent selection and unpacking occur more concurrently with practice was further investigated by way of a dual task condition. The dual task involved presentation of a tone at one unpredictable moment during production of each keypressing sequence. The subjects’ task was to count, in each dual task block, tones with a specific pitch (i.e. targets) and to ignore tones with a different pitch (no-targets).

The rationale for introducing the dual task was to examine interference during the various phases of sequence production and see whether there would be interactions with practice. Sequence preparation is expected to suffer from dual task interference (Neumann, 1987; Schmidt, 1972). But what happens when a tone is presented during sequence execution? Multiple resource theories of dual task performance (e.g. Wickens, 1984) suggest that no interference occurs between motor processing and tone counting as long as the whole sequence is prepared in advance. In reviewing the literature, Logan (1985) also advanced the view that preparatory processes are sensitive to dual-task interference while execution processes are relatively little sensitive. On the other hand, the reduced effect of practice on the first segment in the task used by Portier et al. (1990) and Portier and Van Galen (1992) suggests that execution as well as unpacking are, and remain, attention demanding and, hence, the dual task may continue to interfere with sequence
execution and even increasingly so if the amount of concurrent processing
increases.

One could imagine that when practice reduces the demands of sequence
production the ‘free’ capacity is fully utilized to increase concurrent pro-
cesses related to sequence production. In that case the effect of the dual task
on sequence production should not decrease with practice. It may also be
that, due to timing constraints of the sequence of movements, some capacity
becomes available for the second task so that interference decreases. This
would be consistent with the general notion that dual task interference
diminishes with practice (e.g. Brown and Carr, 1989; Carr, 1984).

In summary, this paper addresses the question to what extent selecting
and unpacking an individual keypress in a movement sequence may occur
concurrently with the execution of other keypresses and how this develops
with practice. Concurrent unpacking is indicated by less effect of practice on
the second than on the third keypress. Selection of the third keypress during
execution of the earlier keypresses is reflected in equal sequence initiation
times for fixed and stimulus-dependent sequences. Examining the pattern of
dual task interference during practice shows whether reduced demands of
movement selection and execution allow increasing concurrency of processes
involved in sequence production or whether capacity becomes available to
other tasks.

2. Method

2.1. Tasks

A trial started with the presentation of an outline of a square in the center
of a computer screen. The square functioned as a warning stimulus and
remained visible for 500 ms. After the outline had been erased, one stimulus
letter, from a set of four uppercase letters (W, X, S, F), appeared at the
location corresponding to the center of the square. These letters were
selected because they are very unlike each other (compared to for example E
and F or D and O). That is, the letters share no common features available
early in visual processing that could allow response preparation in parallel to
the perception process in the case of an appropriate mapping between
stimuli and responses (cf. Miller, 1982; Ziessler et al., 1990). The stimulus
required a sequence of three keypresses (R₁, R₂, and R₃) and remained on
until the last key of the response sequence had been pressed. The response
sequence consisted of keypresses on the numerical keypad of a normal
AT-like keyboard with the right index finger. The first and second keystroke
were always the ‘3’ and ‘5’ keys (Fig. 1). The third key was contingent upon
the letter presented. Presentation of W required pressing the ‘2’ key. Like-
wise, presentation of X, S, or F required pressing the '4', '6', or '8' key. Subjects were instructed to let their right index finger rest gently on the first key of the sequence (i.e., the '3') before display of the warning stimulus.

The stimulus-dependent sequence condition consisted of sessions with four subsequent blocks of 64 trials (4 initial dummy, 60 experimental trials). At each trial the stimulus was randomly chosen from the set of four possible stimuli. In contrast, the sessions in the fixed sequence condition consisted of four separate blocks of 64 trials with only one of the four stimuli in each block. Prior to each fixed block subjects were told which stimulus to expect.

Another variation was single vs. dual task. Dual conditions consisted of trials during each of which a single tone was presented. This tone could be presented at either one of five positions during sequence production or not at all. The moments at which a tone could occur are depicted in Fig. 2. At each dual task trial, each tone position (1 to 5) and trials without a tone had the same a-priori probability of one-sixth. Onset of Tones 1 and 3 coincided with onset of the visual warning and the imperative stimulus whereas the onset of tones at Position 4 and 5 immediately followed upon detection of key depression.

There were high (2000 Hz) and low pitched tones (200 Hz). Whether low or high pitched tones were targets in a particular dual block was randomly
determined before each block in order to limit practice effects on tone counting. Prior to each dual block, subjects were told which tone was the target. It was the subjects’ task to count the targets in one block while ignoring no-targets. At the end of that block the subjects had to enter the number of targets they had counted. Subsequently, the correct number was presented. At each trial the a-priori probability on a target tone was 0.5 so that the actual number of targets in a 64 trial block was about normally distributed with an average of 32.

2.2. Subjects

Twelve right-handed students (7 females and 5 males) of Utrecht University served as subjects. They all received Dfl. 180 for participation. In addition, the four subjects that had the least sequence errors, responded fastest and did best on tone counting received a bonus of Dfl. 45.

2.3. Procedure

The twelve subjects visited the Institute on four consecutive afternoons. On the first day, a written instruction was handed out which briefly introduced the tasks and the way the computer had to be controlled. Then, subjects received a training procedure in which they were further instructed and had about fifteen minutes training in order to master the mapping of the stimuli to the third key. In the training procedure one of the stimuli was randomly chosen and displayed and subjects were asked to press the appropriate key. After pressing a key, feedback was given and all stimulus–response mappings were displayed until the subject indicated that the next stimulus could be presented. For each correct response a counter corresponding to that key was decreased by one. All counters started at 15. When making an error, the counter was incremented by two. Only when all four counters were below zero, the training procedure was ended. This procedure ensured that subjects had a reasonable knowledge about the mapping of the stimulus on the third key during the experimental trials. During the training procedure low and high pitched tones were presented on several occasions so that the subjects knew what to consider as low and high pitch.

After the training procedure subjects performed a session of four blocks with a single stimulus-dependent sequence. This session was considered practice and was not included in the analyses. After this practice session the subjects performed in four experimental sessions in which single vs. dual condition and stimulus-dependent vs. fixed condition were factorially combined. Hence, two of these sessions included fixed and two included stimulus-dependent sequences and one of each pair included a single condition and the other a dual condition. The order of presentation of these
experimental conditions was balanced over sessions and subjects according to a Latin square.

On day two, three and four, subjects started with three practice sessions each with four single stimulus-dependent sequence blocks which were not analyzed followed by, again, the four experimental conditions balanced over subjects and sessions. So, subjects practiced the stimulus-dependent condition much more than the fixed condition and more the single task than the dual task.

During the experiment, a sequence of keypresses was considered wrong when an incorrect key was pressed or the order was incorrect. In addition, when pressing the first key took more than 2000 ms or pressing the second and third key took more than 1500 ms each the sequence was considered wrong. In case of an error, subjects were informed about what kind of error they made after the third key had been depressed. Inter-trial times lasted about 1200 ms, the first 1000 of which were reserved for presentation of an error message in case this was required.

Following a block of 64 trials performance feedback was displayed in terms of the mean time between stimulus onset and the moment of pressing the third key and in terms of the percentage error trials. When the mean time between stimulus onset and pressing the third key exceeded 1000 ms an additional message stated that the subject had been too slow. When more than four error trials (i.e. 7%) occurred at a particular trial block subjects were informed that they had made too many errors. After completing a block of trials subjects indicated the number of targets. Subsequently, the correct number of targets was displayed. When subjects deviated more than 10% they were warned and urged to pay more attention to tone counting. At the average dual block with 32 targets this implied a warning for deviations of more than 3 targets. The total number of warnings on sequence production and tone counting on day two to four was used to determine which subjects received a bonus (see Subjects section).

One group of six subjects worked for about 15 min in one session and rested for the same period of time while the other group was tested. Each session included four blocks each lasting about three to four min. At the end of each block subjects got performance feedback, entered the number of targets (when appropriate) and rested for 23 s. Then the next block of trials started with a short reminder about which stimuli could be expected, whether tones were to be counted and, if so, whether that was the low or high pitched tone.

2.4. Design and analysis

Mean duration of the intervals between the imperative signal and the onset of the first keypress (referred to as $T_1$), the time between onset of the
first and second keypress (T₂), and the time between onset of the second and third keypress (T₃) were the times measured. These measures were analyzed with a 2 × 4 × 2 × 6 within-subjects Analysis of Variance (ANOVA) (fixed vs. stimulus-dependent sequence × day × single vs. dual task × tone position). Separate 2 × 4 × 6 × 2 (fixed vs. stimulus-dependent sequence × day × tone position × tone type) analyses were carried out on the data obtained in the dual conditions for differentiating between effects of tone type (i.e., targets vs. no-targets) on sequence production. This was done to test for the possibility that arousal caused some of the effects.

In order to achieve homogeneity of the error variance, an arcsine transformation was performed on the mean error rate per cell. These transformed data were entered into the same ANOVAs as the time data. Two further error analyses were performed to distinguish between response selection errors and execution errors. Response selection errors involved those error trials in which the third keypress was a key that would have been correct with one of the other stimuli. For example, depression of a '4', '6', or '8' as third key in response to a 'W' instead of the '2' key was considered a response selection error. All other errors were considered execution errors. These analyses were carried out to find whether there were differential effects of practice and the dual task on preparation and execution phases of sequence production.

The difference between the actual number of targets and the number indicated by the subjects was divided by the total number of targets and an arcsine transformation was performed before analysis with a 2 × 4 (fixed vs. stimulus-dependent sequence × day) within-subject ANOVA.

2.5. 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). The visual stimuli were presented in the center of the display screen. At a typical viewing distance of approximately 65 cm the warning square subtended a visual angle of approximately 1°. Stimulus letters subtended a visual angle of approximately 0.5°. Tones were presented on the computer speaker and were clearly audible. Their intensity was about 53 dB(A) against an ambient noise background level resulting from the computer of about 45 dB(A). The keyboard had delays of about 10 ms for the

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1 Actually, a random tone position was determined in single and dual trials – irrespective of actual tone presentation. In order to simplify the analysis tone position was included as factor even though of course, tone position was not expected to have an effect in the single conditions where no tone was presented.
response keys used. Average amount of timing inaccuracies reported by MEL were 3 ms per trial.

Subjects were simultaneously tested in seven dimly-lit sound-attenuated 2.4 × 2.5 × 2 m rooms in front of a table on which their keyboard was positioned. They were allowed to sit as preferred as long as their right index-finger rested on the first key before the start of a trial.

3. Results

3.1. General effects

Effects on T₂ and T₃

As shown in Fig. 3 T₃ was significantly greater in the stimulus-dependent conditions than in the fixed conditions (25 ms F(1, 11) = 19.0, p < 0.01) while T₂ did not differ (3 ms F(1, 11) = 2.3, p > 0.15). At subsequent days of testing T₃ reduced (F(3, 33) = 6.72, p < 0.01) while T₂ did not (F(3, 33) = 0.42). Pooled over conditions T₃ diminished with 23, 2, and 7 ms and T₂ did not vary more than 4 ms over days. The effects of fixed vs. stimulus-depen-

![Graph showing time intervals](image)

**Fig. 3.** The time between the stimulus and the first keypress (T₁) and interresponse times between the first and second keypress (T₂) and between the second and third keypress (T₃) as a function of fixed vs. stimulus-dependent condition on Day 1 and 4.
dent response sequence and day of testing did not interact on \( T_2 \) or \( T_3 \) (\( T_2^* \): \( F(3, 33) = 1.7, p > 0.17; T_3^* \): \( F(3, 33) = 1.0, p > 0.30 \)).

**Effects on \( T_3 \) and errors**

In the stimulus-dependent conditions \( T_3 \) was significantly greater than in the fixed conditions (57 ms \( F(1, 11) = 34.4, p < 0.001 \)) and \( T_3 \) clearly reduced with day of testing (\( F(3, 33) = 83.6, p < 0.001 \)). Pooled over conditions \( T_3 \) diminished with 92, 41, and 6 ms between successive days. No interaction was found between fixed vs. stimulus-dependent response sequence and day of testing (\( F(3, 33) = 1.6, p > 0.20 \)).

Less errors were made in stimulus-dependent (2.8%) as compared to fixed conditions (3.7%, \( F(1, 11) = 13.0, p < 0.01 \)). Further analyses showed that about half of the errors in stimulus-dependent conditions was due to response selection errors (1.3%) and half was due to execution errors (1.5%). Virtually all errors in the fixed condition were execution errors (3.6%). There were no significant interactions with day of testing.

### 3.2. Dual task data

**Task interference**

Simultaneous tone counting in the dual condition lengthened all response intervals as indicated by main effects of single vs. dual task: \( T_1 \) by 46 ms (\( F(1, 11) = 24.4, p < 0.001 \), \( T_2 \) by 11 ms (\( F(1, 11) = 13.5, p < 0.01 \)) and \( T_3 \) by 13 ms (\( F(1, 11) = 28.6, p < 0.001 \)). The percentage of keypressing errors decreased from 3.5% to 3.0% (\( F(1, 11) = 16.0, p < 0.01 \)).

**Effects of tone position**

In the dual conditions \( T_3 \) also depended on the moment of tone presentation as indicated by a single vs. dual task \( \times \) tone position interaction (\( F(5, 55) = 12.5, p < 0.001 \)) in that \( T_3 \) was smaller when a tone occurred at an earlier position than at a later position. Analyses on the effect of tone type revealed that this was primarily due to targets: a main effect of tone type on \( T_3 \) (\( F(1, 11) = 49.6, p < 0.001 \)) could be mainly explained by an interaction between tone type and tone position (\( F(5, 55) = 16.9, p < 0.001 \)) (see Fig. 4). A stimulus-dependent vs. fixed \( \times \) tone type \( \times \) tone position interaction (\( F(5, 55) = 2.7, p < 0.05 \)) together with the data in Fig. 4 suggested that the difference of \( T_3 \) between early targets and early no-targets was greater in fixed than in stimulus-dependent sequences. Subsequent Newman-Keuls confirmed this: the position of no-targets did not significantly affect \( T_3 \) in fixed sequences whereas in stimulus-dependent sequences \( T_3 \) was significantly \( (p < 0.05) \) smaller when a no-target was presented at Position 1 than at Position 3 (6 ms) and Position 4 to 6 (15 ms).
Error rates were relatively high if a tone was presented at Position 1 (7.3% of all trials with a tone at Position 1) and 2 (2.9%) as compared to Position 3 to 6 (1.8-2.1%) \((F(5, 55) = 16.3, p < 0.001)\) (fig. 4). This effect was mainly due to targets at the early positions: 8.9% of all trials with a target at Position 1 was an error trial whereas no-targets at Position 1 yielded 4.3% errors \((F(5, 55) = 10.2, p < 0.001)\). There was no difference for fixed and stimulus-dependent conditions \((F(5, 55) = 0.6, p > 0.25)\).

Separate analyses on selection and execution errors showed that the decrease with tone position was present in response selection and execution errors \((F(5, 55) = 3.4, p < 0.01; F(5, 55) = 15.6, p < 0.001, \text{ resp.})\). Response selection error rate decreased from 2.5% of the trials with a tone at Position 1 to below 1.6% of the trials with tones at later positions. There was no difference between effects of targets and no-targets. The effect on execution errors was stronger for targets than for no-targets \((F(5, 55) = 9.44, p < 0.001)\) and stronger in fixed vs. in stimulus-dependent sequences \((F(5, 55) = 2.9, p < 0.05)\). Targets at Position 1 caused 7.4% execution errors and no-targets 3.3%. Tones at later positions caused execution error rates below 2%. 
Likewise, tones at Position 1 in fixed sequences caused error rates of 7.6% and in stimulus-dependent sequences of 3.1%. These number clearly decreased at later positions to below 2.5% in fixed and below 1.3% in stimulus-dependent sequences.

**Practice effects**

There was a minor practice effect on tone counting performance. The difference between the correct number of targets and the numbers mentioned by the subjects amounted to 5.9%, 2.0%, 1.5%, 1.5% on Day 1 to 4 ($F(3, 33) = 8.32, p < 0.001$). There was no general decrease of the interference effect on any of the time variables as shown by the absence of significant single vs. dual × practice interactions (all $ps > 0.17$). Yet, in each of the analyses on $T_1$, $T_2$, and $T_3$ there was a single vs. dual task × tone position × practice interaction indicating minor effects of practice. With respect to $T_1$, this interaction indicated that the $T_1$ decrement caused by tones at Position 1 and 2 became slightly smaller with practice. This was indicated by the finding that when a tone was presented at Position 1 at Day 1 $T_1$ did not increase as compared to the single task condition whereas it did at later days ($F(15, 165) = 2.6, p < 0.01$). In addition, comparison of the effects of tones at Position 1 and tones at Position 4 to 6 showed that this relative decline of $T_1$ had been caused by a relatively large $T_1$ decrease at Day 1 (55 ms) which lessened at later days (resp. 38, 43, and 36 ms). On the other hand, the difference between single task $T_1$ and $T_1$ with tones at Position 4 to 6 remained relatively stable with practice (Day 1: 55 ms, Day 2: 67 ms, Day 3: 68 ms, Day 4: 51 ms). Together, this shows that the decreasing effect of tones at Position 1 on $T_1$ declined with practice. There was no effect of whether the tone was a target or a no-target ($F(15, 165) = 0.6$).

By contrast, the single vs. dual task × tone position × practice interaction implied for $T_2$ that the effect of early tones decreased with practice ($F(15, 165) = 2.2, p < 0.01$); at Day 1 $T_2$ was a monotonically decreasing function of tone position and $T_2$ was 9 ms longer when the tone was presented at Position 1 than when it was presented at Position 5 or not at all (Position 6). At Day 2, 3, and 4 this difference reduced to 3, 2, and 2 ms. Again, this was not different for targets and no-targets ($F(15, 165) = 0.9$).

For $T_3$, the single vs. dual task × tone position × practice interaction indicated that $T_3$ also monotonically decreased as function of tone position and that this effect reduced with practice: at Day 1 $T_3$ was 16 ms longer when the tone was presented at Position 1 than when it was presented at Position 5 or 6. At Day 2, 3, and 4 these differences amounted to 5, 9, 6 ms ($F(15, 165) = 1.8, p < 0.05$). Once again, no difference was found for targets and no-targets ($F(15, 165) = 1.4, p > 0.13$). However, now a fixed vs. stimulus-dependent × single vs. dual task × tone position interaction ($F(5, 55) = 3.9, p < 0.01$) indicated that the decreasing $T_3$ with tone position was only
available in stimulus-dependent sequences (Fig. 4): the difference between $T_3$ with a tone at Position 1 and 4–6 amounted to 17 ms in stimulus-dependent and 0 ms in fixed. Yet, the corresponding four-way interaction between single vs. dual task, stimulus-dependent vs. fixed, tone position, and practice did not reach significance ($F(15, 165) = 1.2, p > 0.25$).

The relatively high error rate caused by early tone presentation decreased with practice ($F(15, 165) = 1.7, p < 0.06$) which was due to a reduction of execution errors only ($F(15, 165) = 2.3, p < 0.01$): at Day 1 execution error rate resulting from tones at Position 1 was 8.6% of all of these kinds of trials which reduced to 2.8, 5.2 and 4.8% at subsequent days. Response selection errors did not reduce over days and remained between 1% and 1.9% when pooled over tone position ($F(15, 165) = 1.4, p > 0.15$).

In summary, there was a clear increase of $T_1$, $T_2$ and $T_3$ in the dual conditions which lasted over practice. If a tone was presented at the earlier positions $T_1$ decreased to the single task level while $T_2$ in fixed and stimulus-dependent sequences, $T_3$ in stimulus-dependent sequences, and execution error rate increased. For $T_1$, the decreasing effect of early tones was mainly due to targets. Response selection and, especially, execution error rates were higher when tones were presented at the earlier positions. Execution error rate was lower for no-targets and in stimulus-dependent sequences. With practice $T_2$ and $T_3$ increased less and $T_1$ increased more due to early tones while the execution error rate decreased. These effects were similar for targets and no-targets and whether a stimulus-dependent or fixed sequence had been involved. Performance on the dual task improved somewhat over practice.

4. Discussion

The aims of the present study were to examine (1) whether, as a result of practice, unpacking of an individual movement in a sequence would gradually occur during execution of the earlier movement, (2) whether selection of a stimulus-dependent movement would occur during execution of earlier movements that were not dependent upon the stimulus, and (3) whether dual task interference would occur during execution as well as during preparation phases of sequence production and whether this would change with practice.

The main findings relating to these questions can be summarized as follows: (1) With practice the time between the second and the third keypress ($T_3$) reduced while the time between the first and second keypress ($T_2$) did not. (2) The time for initiating the keypressing sequence ($T_1$) was smaller in the fixed condition than in the stimulus-dependent condition and, despite a considerable general decrease of $T_1$, this did not change with practice. (3) All
time measures increased under dual conditions and there was hardly an
effect of practice on task interference.

The data provide evidence for the notion that with practice processes,
normally occurring after execution of the preceding movement, may be
advanced and occur during execution of the earlier movement (here before
and during actual depression of that key) because \( T_3 \) reduced with practice
and \( T_2 \) did not. As expected this was independent of whether the sequence
was fixed or stimulus-dependent. This extends Portier et al.'s (1990) sugges-
tion that unpacking can occur during execution of the initial element in a
motor sequence task because concurrent unpacking appears to be pertinent
to later elements of a motor tasks as well and when unpacking includes only
one element. Future research should investigate whether concurrent unpack-
ing holds for all elements in a sequence so that intermovement intervals
preceding non-final movements decrease less with practice than those pre-
ceding the final movement in a sequence.

The absence of a significant effect of practice on the difference between
\( T_1 \) in stimulus-dependent and fixed sequences suggests that there is no
increasing tendency to select the third keypress during execution of the
earlier, fixed keypresses. The reason for this may be that selection and
execution can not be carried out concurrently, for instance because of
feedback processing (Portier and Van Galen, 1992). This would suggest that
not only response selection but also motor execution stages contribute to the
single channel bottleneck (cf. McCann and Johnston, 1992). Alternatively,
the time to execute the first and second keypress was too short to allow
concurrent selection and programming of the third keypress (Garcia-Collera
and Semjen, 1988). The first explanation suggests that response selection can
never occur during execution of a keypressing sequence whereas the second
explanation implies that in longer sequences it can.

The data from the dual conditions show that dual task interference
occurred at preparation as well as at sequence execution. Even when no tone
had been presented (Tone Position 6) keypressing slowed down and about
equally for stimulus-dependent and fixed sequences. In the light of the
present research questions this finding suggests that not only preparation but
also execution of an already programmed sequence is and remains attention
demanding.

There was only little effect of practice on dual task interference. The dual
task effect diminished on neither \( T_1 \), \( T_2 \), or \( T_3 \). Performance of the dual task
did improve slightly and the fairly large proportion of execution errors in the
case of a tone at Position 1 and 2 reduced. The stable dual task effect on \( T_1 \),
\( T_2 \), and \( T_3 \) suggests that a reduction in demands of sequence production was
almost entirely used to increase concurrent processing and, hence, to reduce
sequence production time. Virtually no additional capacity came available for
the dual task. The fact that the effect of practice on dual task interference
was so limited is unexpected because it contrasts with the general notion that interference diminishes substantially with practice (e.g. Brown and Carr, 1989; Carr, 1984). It could be that earlier studies showed more substantial effects of practice on dual task interference because subjects learned to expect dual task stimuli and could prepare actions (Broadbent, 1982; Pashler, 1990). This was not possible in the present study.

In addition to the original research questions some interesting additional results were obtained. First, tones at Position 1 and 2 caused T1 to decrease considerably. This was accompanied by a sizable increase in errors. An initial idea was that this shift in speed–accuracy trade-off was caused by an increased level of arousal. In order to prevent an arousal effect low intensity tones had already been utilized (e.g. Sanders, 1990). Examination of the results showed that arousal can not explain the effect because targets reduced T1 and increased error rate more than no-targets. Also, T1 reduced equally for stimulus-dependent and fixed sequences which is not expected with increased levels of arousal (Keuss et al., 1990). Finally, from the arousal point of view one cannot explain why the effect of early presented tones increased with practice on T1 while, at the same time, it decreased on T2 and T3. What then may have caused the shift in speed–accuracy trade-off, the longer T2 and T3 for early tones, and the increment of T1, T2, and T3 for later tones? Target counting obviously involves cognitive operations probably also including vocal processes. Results of an informal pilot study in which a masking tone followed completion of the keypressing sequence suggested that with early tones counting is carried out immediately which interferes with the processes required for sequence planning (Navon and Gopher, 1979; Noble et al., 1981; Posner and Klein, 1973) whereas with later tones counting is postponed until after sequence execution and interference is due only to maintaining the target counter (e.g. Logan, 1980; Pritchard and Warm, 1983; Reisberg, 1983; Shulman and Greenberg, 1971). This hypothesis still requires verification but it explains the persistence of dual-task interference in the sudden absence of a tone and suggests that task interference caused by the need for simultaneous processing can be reduced when one has the possibility to postpone processes needed for one task.

Second, there was a minor effect of practice that early in practice T2 and T3 slowed down when a tone was presented at Position 1. Later this effect diminished but at the cost of a larger T1. This finding could suggest that early in practice the second and third keypress were programmed during T1. This might have been disrupted when the tone required attention, with the consequence that subjects regressed to a step-by-step organization of the sequence – i.e. programming a next movement upon completion of the preceding one – which is characteristic for unskilled performance (Pew, 1974). Practice might have had the effect that programming the later movements during T1 was no longer disrupted. Hence, T2 and T3 decreased, T1
increased and the number of errors decreased. So, one effect of practice may be that keypressing sequences are programmed and executed in a more unitized way which can be regarded as motor chunking.

Third, the finding that in the stimulus-dependent condition T3 slowed most when a tone was presented before the imperative stimulus had occurred is interesting in that it provides evidence for the notion that in the absence of the imperative signal a stimulus-dependent keypress can be still programmed at some abstract level (Ziessler et al., 1990).

In conclusion, the data show that concurrent unpacking may not only develop with practice at the first element of a movement sequence but also at the second of a three element sequence. No evidence was obtained that after practice response selection was carried out concurrently with sequence execution. Dual task interference was obtained during preparation as well as during execution of the movement sequence. Interference hardly reduced with practice suggesting that practice leads to increased amounts of concurrent unpacking so that no capacity comes available for other tasks.

References


