

# Evidence for graded central processing resources in a sequential movement task

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**Abstract** In the present experiment, we examined slowing of the individual key presses of a familiar keying sequence by four different versions of a concurrent tone counting task. This was done to determine whether the same cognitive processor that has previously been assumed by the dual processor model (DPM) to initiate familiar keying sequences and assist in their execution, is involved also in the central processes of a very different task (viz. identifying tones and counting target tones). The present results confirm this hypothesis. They also suggest that in this particular situation the central processing resources underlying the cognitive processor can be distributed across the central processes of different tasks in a graded manner, rather than that they continue to behave like a single, central processor that serially switches between the central processes of the concurrently performed tasks. We argue that the production of highly practiced movement sequences can be considered automatic in the sense that execution of familiar movement sequences can continue without cognitive control once they have been initiated.

## Introduction

Over the years, the study of reaction times produced many indications that information processing at the perceptual, central (i.e., cognitive), and motor level is independent (e.g., Anderson, Bothell, Byrne, Douglass, & Qin 2004; Detweiler & Schneider, 1991; Kahneman, 1973; Meyer & Kieras, 1997a; Salvucci & Taatgen, 2008). This implies that at these three processing levels different pieces of information can be processed concurrently. The main purpose of the present study is to examine whether, in a similar vein, processing at the central level can occur simultaneously in case of two concurrently executed tasks.

Below, we first outline how earlier research on discrete sequence skill resulted in the dual processor model (DPM; Verwey, 2001; for reviews see Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013; Rhodes, Bullock, Verwey, Averbek, & Page, 2004). This model is based on the workings of a cognitive processor in direct interaction with a dedicated motor processor, with the former being responsible for sequence selection (using perceptual or stored information) and sequence preparation, and the latter being primarily responsible for the execution of familiar (i.e., well-trained) movement sequences of limited length. According to the DPM, the cognitive processor is a versatile processing unit at the central level that can switch as a whole between different processes. These processes may underlie either a single task or concurrently performed tasks. Next, we establish on the basis of existing literature that processing resources at the central level may indeed behave like a single, unified processor performing one process at the time. Yet, we also present indications that these central processing resources are sometimes allocated in a graded fashion across different central processes that operate in parallel.

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Finally, we report an experiment with the discrete sequence production (DSP) task that aims to specify how the DPM's cognitive processor behaves in a dual-task situation. It examined whether (a) during execution of a fixed keying sequence the DPM's cognitive processor is involved also in concurrent, cognitively demanding processes like tone identification and counting targets. In addition, the experiment was designed to determine whether (b) in case of concurrent, central processing of two tasks this processor can be envisaged as a processing unit that switches between processes of different tasks (as originally proposed in the DPM), or whether it involves a pool of central processing resources that may be distributed in a graded fashion across the central processes of simultaneously performed tasks.

### The dual processor model

The DPM was originally proposed by Verwey (2001) to explain an observation with participants who had first extensively practiced several fixed sequences of up to six key presses in the DSP task. It appeared that selecting a forthcoming action (a single key press or a familiar keying sequence) slowed ongoing sequence execution, but this slowing was unaffected by the load of the selection process itself (when manipulated in terms of stimulus–response compatibility and reversing a learned stimulus–sequence association, Verwey, 1995, 2001). As a single processor (or, resource) model cannot account for this insensitivity to selection load, it was explained by a dual processor model. This model assumes that preparing the information processing system and selecting forthcoming movement sequences are carried out by a cognitive processor, while execution of the ongoing sequence is done primarily by a motor processor (for a recent description, see Abrahamse et al., 2013). The distinction between a cognitive and a motor processor seems reasonable as it fits seamlessly with many indications for such a distinction in a broad range of research paradigms (e.g., Anderson et al., 2004; Detweiler & Schneider, 1991; Meyer & Kieras, 1997a; Norman & Shallice, 1986; Pashler, 1994; Schwartz, 2006; Shaffer, 1991; Sigman & Dehaene, 2008; Sternberg, 1998). It is in line also with earlier indications that attentional costs are greater during movement preparation than movement execution (Glencross, 1980; Posner & Keele, 1969).

According to the DPM, the cognitive processor initially engages in translating each key-specific stimulus of the DSP task into a response. This is called the reaction mode. While limited practice induces priming of successive reactions (i.e., the associative mode, Verwey & Abrahamse, 2012), with extensive practice successive responses become represented by a so-called motor chunk. This representation has been proposed by various researchers to

explain sequential movement skills (e.g., G. A. Miller, Galanter, & Pribram, 1960; Paillard, 1960; Rhodes et al., 2004; Sakai, Kitaguchi, & Hikosaka, 2003; Verwey, 1996). Sequence execution is then based primarily on the motor processor using these motor chunks, and is said to occur in the chunking mode. The motor processor is autonomous in the sense that cognitive guidance is not needed once it has been supplied by the cognitive processor with a motor chunk and has started executing the sequence.

An important feature of the DPM is its assumption that, perhaps due to the typical speed instruction in reaction time tasks such as the DSP task, execution of familiar keying sequences usually involves a race between the cognitive processor translating individual key-specific stimuli, and the motor processor using motor chunks to trigger each response (Verwey, 2001, 2003b; cf. Logan, 1988). This is a reasonable assumption given that early in practice (i.e., in the reaction mode) the cognitive processor had already carried out the sequence by responding to the key-specific stimuli. The motor processor is assumed to be solely responsible for familiar sequence execution only when the cognitive processor is allocated to another task (like when selecting a forthcoming action or counting tones), and when actions are executed without cognitive monitoring (e.g., absent-mindedness may result in so-called action slips if deviations from familiar movement sequences are required, Norman & Shallice, 1986; Reason, 1992).

### Central processing resources: unified or graded?

The cognitive processor of the DPM was originally understood as a unit that switches between processes, performing one process after the other (Verwey, 2001). However, an alternative possibility is that the cognitive processor of the DPM is based on a pool of central processing resources that can be distributed across concurrently active processes in a graded fashion (e.g., Kahneman, 1973; Miller, Ulrich, & Rolke, 2009; Tombu & Jolicœur, 2005). Indications for graded central processing resources have been found even in research paradigms that traditionally were thought to support the notion of an integrated central processor or unified central processing resource.

One such research paradigm is the additive factors method (AFM; Sternberg, 1969). Following the 20 years of AFM research that followed Sternberg's (1969) seminal article, a model was proposed postulating that information in a choice reaction time task is processed in seven serial processes (in that context referred to as processing stages). Of these, the best known are stimulus identification, response selection and motor programming (Sanders, 1990). To explain how the massively parallel human neural system accomplishes discrete serial processes, Sternberg (1998) proposed two possibilities. Either there is a single, central

processor that deals with one process at the time, or different processes are carried out by different central processors and seriality is enforced by the need of one processor, performing one process, to wait for the results provided by another processor that performs another process. Important in this respect is that a few AFM studies found indications that sometimes one central process may start before the previous central process has ended (e.g., Miller & Hackley, 1992; Sackur & Dehaene, 2009; Stanovich & Pachella, 1977). In terms of Sternberg's (1998) proposal, this can be explained only by the notion that central processing resources can be distributed across parallel central processes, as if there is more than one central processor.

In the so-called psychological refractory period (PRP) paradigm, participants perform two choice reaction time tasks in rapid succession (Pashler, 1994; Welford, 1952). Research with the PRP task suggested that a particular central process, response selection, can deal with only one task at the time so that selecting the response for the second task has to wait for response selection of the first task to finish (Pashler, 1994). It later appeared that other processes, such as memory retrieval and classifying stimuli according to an uncommon rule, may be subject to this bottleneck as well (Johnston & McCann, 2006; Ruthruff & Pashler, 2001). The fact that several central processes are subject to a single processing bottleneck has been explained by the notion that those processes are carried out by a single processor at the central level (Meyer & Kieras, 1997b; Pashler, 1994). However, in the PRP task, too, data have been observed suggesting that at the central level multiple processors sometimes work in parallel (Hommel, 1998; Sackur & Dehaene, 2009; Tombu & Jolicœur, 2005). This has in fact been observed with highly practiced and nonarbitrary stimulus–response mappings (Greenwald, 2003; Lien, McCann, Ruthruff, & Proctor, 2005; Lien, Proctor, & Allen, 2002), when stimulus onset asynchronies are expected to be short (Miller et al., 2009), and when participants are instructed to process in parallel (Lehle, Steinhauser, & Hübner, 2009). So, at least two well-known research paradigms show that central processing resources usually behave like a unified processor that switches between serially executed processes, but when these processes are used in independent tasks, and/or one of these processes is highly practiced, these resources may be shared between parallel, central processes.

### Concurrent counting

Recently, we examined the contribution of the DPM's cognitive processor to the production of keying sequences by having participants count target tones that were presented while they were carrying out fixed sequences of six key presses (Verwey, Abrahamse, & De Kleine, 2010).

Tone counting was used because it is highly suitable for studying the cognitive involvement in discrete sequence skill: it requires central processing at an experimenter determined moment in time, while it is unlikely to interfere with sequence execution at the perceptual or response levels (e.g., McLeod, 1977; Wickens, 1984). The results of this recent study were consistent with the notion that the cognitive processor—that according to the DPM is involved both in initiating, and executing keying sequences by racing with the motor processor—is responsible for identifying tones too. This is in line with findings that classifying a tone in an arbitrary way requires central processing (Johnston & McCann, 2006).

However, the Verwey et al. (2010) study showed also that target tones did not interfere with sequence execution any more than distracter tones. This could be taken to suggest that (silent) counting of targets is carried out by another than the cognitive processor. However, given that counting relies on short-term memory, it seemed more likely that counting is a central process that for some reason was postponed until the sequence had been completed (a similar flexibility has been observed in writing, Olive, Alves, & Castro, 2009, cf. Lehle et al., 2009). Therefore, the first purpose of the present study was to show that counting can indeed concur, and interfere, with sequence execution if we use an adapted design relative to the previous study. This design involved four procedural adjustments relative to the Verwey et al. (2010) procedure. First, the interval between successive sequences was relatively short for half the participants. We expected that this would be a potent way to prevent participants from postponing counting until after sequence completion. Second, we increased the pitch difference of the target and distracter tones because participants in the previous study had had difficulty distinguishing them. That may have increased the cognitive load of identifying the pitch and may have caused participants to postpone counting. Third, we used seven instead of six-key sequences. This gave participants more time during sequence execution for the dual task than in our previous study with six-key sequences (cf. Garcia-Colera & Semjen, 1988). Fourth, due to balancing familiar and unfamiliar sequences in the test phase of the previous study half of those participants started with the unfamiliar sequence. This may have stimulated them to use a strategy of postponing counting. In the present study, the unfamiliar sequence condition was eliminated.

If these adjustments are successful, interkey intervals (IKIs) of the familiar sequences should on average be longer in case tone identification is followed by counting, than when it is not. This is the typical slowing that is expected when the dual task becomes more demanding. In anticipation of the results, we can say that we did observe this indication for counting during sequence execution.

## Graded central processing resources

This brings us to the second, and major, purpose of the present study: to determine whether the counting-based interference pattern would be in line with a switching central processor—as originally proposed in the DPM—or with a graded sharing of central processing resources across the simultaneously performed tasks. To that end, participants first practiced two discrete sequences involving seven key presses. They then performed these sequences in four test conditions while either a single target tone, a single distracter tone, or no-tone was presented (each occurring with a 0.33 chance). The names of these four test conditions reflect the moment of tone presentation (during or before sequence execution), and the participants' task (ignore tones, identify tones, count target tones). Like in the previous study, we examined the times to execute each response in the During/Count condition to determine whether these responses would be slowed more following target tones (that were to be identified and counted) than following distracter tones (that were to be identified but not counted). While the no-tone trials in the During/Count condition served as control condition for when no tone was presented, the During/Ignore condition was used as a control condition to examine whether tones may still have a slowing effect when they are to be ignored.

Two further test conditions were included to obtain additional evidence that tone identification and target counting separately load the same central processing resources that contribute to sequence execution. In the During/Identify condition, participants were to indicate immediately after each sequence whether the tone had been a target or not. This was expected to induce only tone identification during sequence execution, so that target and distracter tones would yield similar sequence slowing (relative to the no-tone condition). In contrast, in the Before/Count condition the tone was presented just before onset of the first key-specific stimulus so that tone identification could occur before sequence initiation. Here, we expected only target counting to occur during sequence execution, so that only target tones would slow the (earlier part of the) sequence.

As mentioned above, the DPM claims that a cognitive processor races with a motor processor to produce the next response. This benefits performance even after extensive practice, but implies also that a dual task that uses the cognitive processor slows sequence execution. If the DPM's cognitive processor is indeed a unified central processing resource that performs only one process at the time—but may switch between processes—tone presentation in the During/Count condition should slow more key presses in case of a target than of a distracter tone. Yet, the amount of slowing at each of the individual responses should be the

same for target and distracter tones. This prediction arises from the fact that any central processing induced by a dual task eliminates for some time this processor's contribution to sequence execution, which is then left entirely to the motor processor. So, when tones are counted the identification process is followed by a counting process, and it takes longer (and more ongoing responses) before the cognitive processor can switch back to racing with the motor processor than when a tone is identified but not counted.

In contrast, the DPM's cognitive processor may be based on central processing resources that can be split up in a graded fashion between racing with the motor processor and tone identification and/or counting (e.g., Kahneman, 1973; Miller et al., 2009; Tombu & Jolicoeur, 2005). In that case, individual responses may be slowed more with concurrent identification and counting than with just concurrent identification (and no counting). The number of responses that are slowed can be predicted to be about similar for both target and distracter tones because the extra counting process is accounted for already in terms of additional slowing per response for a target tone.

In short, the present study was designed (a) to test whether counting target tones can occur during execution of familiar keying sequence, just like identifying tones. This would be indicated by slower sequence execution when targets are identified and counted, than when tones are only identified or only counted. (b) Assessing the number of slowed responses and the amount of slowing for each response in case of distracter and target tones, was expected to indicate whether the DPM's cognitive processor involves a unified, switching processor at the central processing level, or central processing resources that are distributed across execution and tone processes in a graded manner. In the present study, we used sequences that were likely to involve segmentation of the sequences into two successive motor chunks. This was done to study dual-task effects on the expected transition between motor chunks (see [Discussion](#)).

## Method

### Participants

In exchange for course credits 48 right-handed undergraduate students took part (average age of 20, range 18–25; 24 women). The study had been approved by the ethics committee of Faculty of Behavioural Sciences of the University of Twente.

### Apparatus

Stimulus presentation, timing, and data collection were achieved using the E-prime<sup>®</sup> 2.0 experimental software

package on a standard Pentium<sup>®</sup> IV Windows XP<sup>®</sup> PC. Unnecessary Windows services were shut down to improve response time (RT) measurement accuracy. Stimuli were presented on a 17 in. Philips 107T5 display running at 1,024 × 768 pixel resolution in 32-bit color, and refreshing at 85 Hz. The viewing distance was approximately 50 cm, but this was not strictly controlled. Tones were presented with a Sennheiser HD202 over-the-ears headphone.

### Procedure

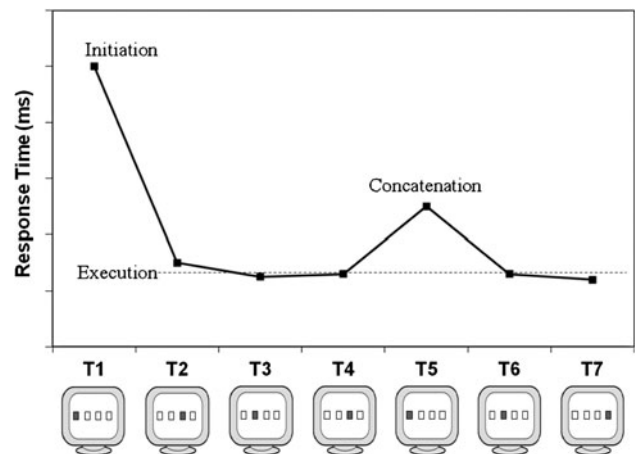
Upon entering the lab, participants filled out an informed consent form and received a written instruction on the task to be performed which, if necessary, was extended orally by the experimenter. Then the six practice blocks were carried out. The ensuing test phase started off by participants putting on headphones to hear the dual-task tones. The duration of the experiment was approximately two and a half hours.

### The sequencing task

The sequencing task involved two 7-key sequences carried out with the four fingers of the left hand (see Fig. 1). The task involved presentation of four black 0.9 × 0.9 cm square placeholders horizontally in the center of the computer screen against a white background. To mimic the positions of the response keys on the key board there were 0.7-cm gaps between the four placeholders. Participants sat with their left hand fingers resting lightly on the CVB and N keys of a regular computer key board. A stimulus involved filling of one placeholder with green after which the participants responded by pressing the spatially compatible key. When the correct key had been pressed, the color in the square changed back to the background color (white). Errors resulted in the message “wrong key” (in Dutch) for 500 ms after which the correct key was to be depressed any way.

Stimuli were presented in two fixed series of seven (i.e.,  $S_1$ – $S_7$ ), thus requiring two fixed sequences of seven key presses ( $R_1$ – $R_7$ ). The term trial is used to denote an entire sequence. The two 7-key sequences were always presented in random order. The time between stimulus  $n$  and response  $n$  is indicated by  $T_n$  (e.g., the RT between  $S_2$  and  $R_2$  is  $T_2$ <sup>1</sup>). In case of response–stimulus interval (RSI) 0 this RT equals the IKI.

<sup>1</sup> We prefer using the name ‘response time’ over ‘reaction time’ to prevent the suggestion that participants explicitly react to each key-specific stimulus, which is not likely in a practiced DSP sequence (cf. Luce, 1986; Verwey, Abrahamse, Ruitenberg, Jiménez, & De Kleine, 2011).



**Fig. 1** A prototypical example of a seven-key discrete keying sequence for which each element is labeled by the processes it is assumed to involve (i.e., initiation, concatenation, and in case of all elements, execution). Below the RT graph, stimuli of a typical sequence are displayed (stimulus locations at each sequential position are balanced across finger for different participants)

Participants performed a prestructured and an unstructured sequence. A prestructured sequence includes a temporal structure in that there is a pause between  $R_4$  and  $S_5$  (Verwey & Dronkert, 1996). This pause consisted of a non-aging response stimulus interval that lasted 300–2,000 ms. Non-aging intervals have a larger probability of shorter intervals to prevent participant from inferring when the interval ends (see Gottsdanker, Perkins, & Aftab, 1986 for a discussion). In the test conditions, this pause was removed but participants typically continue to have a slow response at the location of the pause, suggesting development of two motor chunks. The unstructured sequence did not include such a pause. Apart from the pause, all response–stimulus intervals were zero.

The two sequences of each participant were selected from a set of four versions. Across participants, each sequence was used as often as prestructured and unstructured sequence in the practice phase. The four sequences were created by mapping the numbers of the series 1323124 to each of the four keys so that, across participants, each finger occurred equally often at a particular sequential position. For example, one participant had VNBVBC and NVCV-NCB (‘-’ indicating the pause in the practice phase), while the next participant had CBVBCVN and BCNC-BNV.

Both sequences involved a key pressing order that in an earlier study had spontaneously induced a relatively long  $T_5$  (De Kleine & Verwey, 2009). This was taken to suggest that with this particular key pressing order, most participants spontaneously divide this sequence into two successive motor chunks with the transition between  $R_4$  and  $R_5$ , even when there is no pause.

## Practice phase

The practice phase involved six practice blocks, each including 90 unstructured and 90 prestructured sequences, yielding a total of 540 practice trials for each sequence. During practice the inter-sequence interval amounted to 1,750 ms. Each practice block lasted 10–15 min and was followed by a 7 min rest period. Halfway through each practice block there was a 20 s break.

## The test phase: dual-task conditions

The test phase involved four blocks, each with another version of the dual task but always involving the execution of the two familiar sequences (24 trials with each sequence) in a random order while a tone could be presented. The order of the four test blocks was counterbalanced across participants by rotating their order across participants. The test phase started off with an introduction on the screen about the four dual-task versions.

In each dual-task condition, every keying sequence involved presentation of either one 100 ms target tone, one 100 ms distracter tone, or no-tone (all  $ps = 0.33$ ). So, two-thirds of the sequences involved presenting a tone. These tones were either a 698 Hz (scientific pitch notation: F5) distracter tone, or a 440 Hz (A4) target tone (which in Verwey et al., 2010 had been 660 Hz, E5). At the start of the test phase and at the start of each of the four test blocks these two tones were presented five times in alternation for familiarization. There was no pause in between the four test phase blocks other than a short instruction on the next dual task. A brief dual-task reminder remained visible at the bottom of the screen during each test block.

In the During/Count, the During/Ignore and the During/Identify conditions onset of the (target, distracter or no-) tone concurred with onset of one randomly selected key-specific stimulus. In the During/Count condition participants were instructed to count target tones across a block of trials. At the end of the block they typed in the number of target tones they had counted. This was immediately followed by feedback about the actual number of target tones. In the During/Identify condition, the participants were asked after each sequence whether they had heard a target tone (pressing with the unused right hand ‘L’ and ‘Enter’) or not (i.e., pressing just ‘Enter’ after distracter and no-tone trials). This was followed by performance feedback too. In the During/Ignore condition participants were instructed to ignore all tones.

Finally, in the Before/Count condition the tone was presented before  $S_1$  onset. The actual moment of tone presentation depended on the inter-sequence interval (see below). Participants entered the number of counted target tones at the end of the Before/Count test block (just like in

the During/Count condition). This was followed by performance feedback, too.

For half of the participants the interval between successive sequences (i.e., between  $R_7$  and  $S_1$ ) in the test phase was relatively short in all four test conditions, while it was relatively long for the other half. Specifically, in the During/Count and During/Ignore conditions the inter-sequence interval amounted to 700 ms for the short inter-sequence interval group and 2,000 ms for the long inter-sequence interval group. These intervals were fixed to stimulate participants to develop a strategy of counting either during or following sequence execution. In the Before/Count condition—where tones were presented in between sequences—the interval between tone offset and  $S_1$  onset was also 700 or 2,000 ms. Here, the 100 ms tone was preceded by an interval of 200 ms in the short and 1,500 ms in the long inter-sequence interval condition. This yielded a total inter-sequence interval of 1,000 ms (=200 + 100 ms tone + 700 ms) for the short inter-sequence interval group, and 3,600 ms (=1,500 + 100 + 2,000 ms) for the long inter-sequence interval group. In During/Identify the inter-sequence interval was participant paced as the computer waited until the participant had indicated the identity of the tone. Here, the tone identity response (pressing L + Enter, or just Enter) was followed by either a 1,700 or 3,000 ms interval before onset of  $S_1$  of the next sequence.

## Results

Sequences of which the total execution time exceeded the grand mean across all sequences plus 2.5 times the standard deviation (i.e., >3,600 ms in practice and test phases) were removed from the RT analyses. This concerned less than 3 % of the sequences in the practice and the test phases. Sequences with errors in sequence execution and the first two sequences of each (sub-)block were also excluded from the RT analyses. In the prestructured and unstructured sequences  $T_1$  was the initiation interval, and  $T_2$ – $T_7$  made up the IKIs.

## Practice phase

The development of sequencing skill in the practice phase was examined with a 2 (structure: prestructured vs. unstructured)  $\times$  6 (block)  $\times$  7 (key) within-subject ANOVA on RTs. In addition to block and key main effects,  $F(5,235) = 412.3$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.90$ , and  $F(6,282) = 106.3$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.69$ , respectively, it revealed a key  $\times$  block interaction,  $F(30,1410) = 20.9$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.31$ . This interaction showed that improvement differed across the different key presses. For the unstructured

sequences, a planned comparison confirmed the expected spontaneous development of segmentation in that  $T_5$ —the longest IKI—reduced less with practice than the regular IKIs  $T_2T_3T_4T_6T_7$ ,  $F(5,235) = 6.5$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.12$  (cf. De Kleine & Verwey, 2009). Indeed, in blocks 5 and 6 the longest IKI of the unstructured sequence had become reliably longer than the five regular IKIs,  $F(1,47) = 17.3$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.27$ . (This was not examined for pre-structured sequences because there  $T_5$  involved responding under time uncertainty).

An ANOVA with the above design was used to examine arcsine square-root transformed error proportions per key. It showed a slight increase in error proportion with block, from 2.5 % in block 1 to 3.2 % in block 6,  $F(5,235) = 10.2$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.18$ . A key main effect,  $F(6,282) = 15.1$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.24$ , and a structure  $\times$  key interaction,  $F(6,282) = 3.8$ ,  $p < 0.01$ ,  $\eta_p^2 = 0.07$ , indicated that especially in the prestructured sequence, error proportion was relatively high for  $R_2$  (4.5 vs. <3.2 % for the other responses).

### Test phase

The RTs obtained in each dual-task condition are depicted in Fig. 2 as a function of the tone presented. These RTs were analyzed using a mixed 2 (group: long vs. short inter-sequence interval)  $\times$  2 (structure during practice: pre-structured vs. unstructured)  $\times$  4 (dual task: During/Count, During/Ignore, During/Identify, Before/Count)  $\times$  3 (tone: target, distracter, no-tone)  $\times$  7 (key) ANOVA on RTs with group as between-subject variable (this particular ANOVA ignored tone position, but below we report effects of tone position, too).

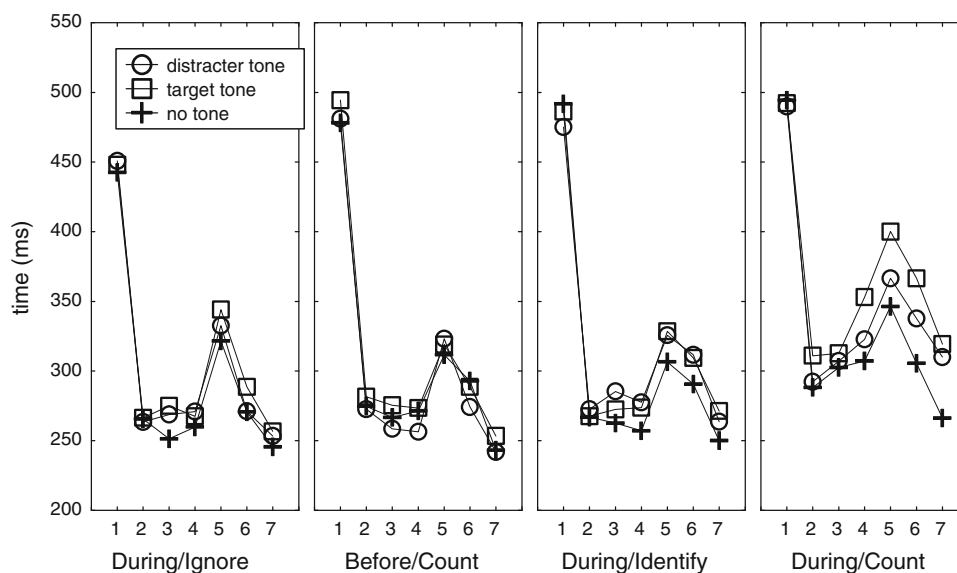
The ANOVA showed main effects of structure,  $F(1,46) = 23.9$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.34$ , dual task,  $F(3,138) = 27.9$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.38$ , tone,  $F(2,92) = 31.1$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.40$ , and of key,  $F(6,276) = 93.2$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.67$ . A dual task  $\times$  tone interaction confirmed that target, distracter, and no-tones had different effects in the four dual-task conditions,  $F(6,276) = 4.9$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.10$ . These effects were in line with the notion that, across all  $T_s$ , target counting slowed mean RT more in the During/Count ( $T_{\text{target tone}} - T_{\text{distracter tone}} = 18$  ms) and Before/Count conditions ( $T_{\text{target tone}} - T_{\text{distracter tone}} = 11$  ms), than in During/Ignore (5 ms), and During/Identify (0 ms). Furthermore, this interaction suggested that tone identification slowed mean RT more in During/Count ( $T_{\text{distracter tone}} - T_{\text{no-tone}} = 17$  ms) and During/Identify (12 ms), than in During/Ignore (8 ms), and Before/Count (−4 ms).

The dual task  $\times$  key interaction,  $F(18,828) = 5.0$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.10$ , was in line with the notion that (at least some of the) key presses past the first were especially slow in the During/Count condition (see Fig. 2). In addition, the dual task  $\times$  key  $\times$  tone interaction,  $F(36,1656) = 1.9$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.04$ , suggested that this slowing differed as a function of the tone that had been presented. Below we test our hypotheses more specifically with planned comparisons.

### Effects on average execution rate ( $T_2$ – $T_7$ )

First of all, it should be mentioned that planned comparisons showed that the duration of the inter-sequence interval did not influence whether the tone was processed during or after sequence execution. Therefore, this variable was

**Fig. 2** RTs in the four dual-task conditions as a function of tone identity and key press within the sequence (across tone positions, inter-sequence interval, and sequence structures)



ignored in subsequent analyses. Next, planned comparisons in the no-tone conditions of all dual-task conditions showed that  $T_5$ s were longer than the regular IKIs  $T_2T_3T_4T_6T_7$  in both the unstructured and the prestructured sequences,  $F_s(1,46) > 22.0$ ,  $p_s < 0.001$ ,  $\eta_p^2 > 0.32$ . This confirmed that practicing with the pause between  $R_4$  and  $S_5$  in the prestructured sequence had led to segmentation, just as in the unstructured sequence. Despite the different causes for segmentation in the prestructured and the unstructured sequences, further planned comparisons showed that ‘pure execution’ IKIs ( $T_2T_3T_4T_6T_7$ ) and  $T_5$  were not differently slowed by the dual tasks ( $p_s > 0.20$ ). This implies for both types of sequences that the cognitive processor was not involved any more in executing  $R_5$  (and thus in concatenating motor chunks) than in  $R_2R_3R_4R_6R_7$ . This allowed unstructured and prestructured sequences to be pooled in all subsequent analyses.

A series of planned comparisons compared across all IKIs the effects of target tones, distracter tones, and no-tones in each of the four dual-task conditions. The results are presented in Table 1. Even though these planned comparisons include also the IKIs that precede tone presentation, this table already shows a highly consistent picture that confirms our hypothesis that both tone identification and target counting lengthened mean IKI.

Next, planned comparisons were carried out that compared the differences in each cell of Table 1 with those of the other cells in the same row. For example, we examined whether the difference between target tone and no-tone (first results row) was larger in During/Count (41 ms) than in During/Identify (15 ms), whether it was larger in During Identify (15 ms) than in Before/Count (5 ms), and so on. Similarly, we compared differences in the cells of each results column. For instance, the target tone vs. no-tone difference in the During/Count condition (of 41 ms, last column) was compared with the distracter tone vs. no-tone difference in the same dual-task condition (of 20 ms).

Without describing all these tests in detail, we can say that these planned comparisons almost entirely support the notions that sequence execution was slowed more in case of concurrent identification plus counting than in case of just concurrent identification, and that sequence execution was slowed more in case of concurrent identification than without concurrent identification.

One deviation from the predicted pattern was that in the Before/Count condition slowing was not different for the target tone and no-tone even though counting was expected to occur during sequence execution (upper results cell). We therefore examined whether perhaps only the first few responses were slowed (given that the tone always preceded sequence initiation). Indeed, when this planned comparison involved only  $T_2$ – $T_4$  it showed 10 ms more slowing with the target tone than with no-tone,  $F(1,46) = 5.3$ ,  $p < 0.05$ ,  $\eta_p^2 = 0.10$ . This is indicated in that particular cell too.

The other deviation was that tones that were to be ignored in the During/Ignore condition still caused some slowing (marked by ‘distraction?’ in Table 1). This slowing tended to be larger for participants encountering the During/Ignore condition later in the test phase,  $F(1,40) = 2.9$ ,  $p = 0.09$ ,  $\eta^2 = 0.07$ . This suggests development of automatic attention attraction by the tone during the test phase.

To assess the effect of the various dual-task conditions on sequence execution rate when no tone was presented, we performed a Tukey HSD post hoc test on the mean IKIs ( $T_2$ – $T_7$ ) of the four dual-task conditions without a tone. These mean IKIs amounted to 269 ms (During/Ignore), 277 ms (Before/Count), 272 ms (During/Identify), and 302 ms (During/Count). The post hoc test showed that IKIs were slower in During/Count condition than in each of the three other dual-task conditions,  $p_s < 0.01$ . No significant differences were observed between the three remaining dual-task conditions,  $p_s > 0.20$ .

**Table 1** The difference in mean execution times per key (across  $R_2$ – $R_7$ ) for each tone counting task condition between the two tone conditions indicated in column 1 (across  $R_2$ – $R_7$  and tone positions), and its significance levels

Tone condition	Tone counting condition			
	During/Ignore	Before/Count	During/Identify	During/Count
Target tone vs. no-tone	14 ms** (283 vs. 269 ms) (distraction?)	5 ms <sup>ns</sup> (282 vs. 277 ms) ( $T_2$ – $T_4$ : *) (counting)	15 ms ** (287 vs. 272 ms) (identification)	41 ms *** (344 vs. 303 ms) (identification and counting)
Distracter tone vs. no-tone	8 ms + (277 vs. 269 ms) (distraction?)	–6 ms <sup>ns</sup> (271 vs. 277 ms)	17 ms *** (289 vs. 272 ms) (identification)	20 ms *** (323 vs. 303 ms) (identification)
Target tone vs. distracter tone	6 ms <sup>ns</sup> (283 vs. 277 ms)	11 ms** (282 vs. 271 ms) (counting)	–2 ms <sup>ns</sup> (287 vs. 289 ms)	21 ms *** (344 vs. 323 ms) (counting)

Each cell also displays the mean RTs in the two tone conditions and the hypothetical cause

\*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$ ; \*  $p < 0.05$ ; +0.05 <  $p < 0.10$ ; ns  $p > 0.10$ ; dfs = (1,46)



### Effects on the responses following a tone

Our second research question made predictions about the number of slowed responses following a tone, and whether slowing of each of those responses was larger or not. This was tested with a mixed 6 (location:  $L_{-1}$ – $L_4$ )  $\times$  3 (dual task: During/Identify, During/Ignore, During/Count)  $\times$  3 (tone)  $\times$  2 (group)  $\times$  2 (structure) ANOVA on the IKIs, relative to the moment of tone presentation with group as between subjects variable (see Fig. 3). In this analysis,  $L_{-1}$  indicates the mean of all IKIs preceding the tone,  $L_0$  the RT immediately following tone presentation, and  $L_1$ – $L_4$  the ensuing four RTs. This ANOVA showed main effects of Dual task,  $F(2,92) = 41.1$ , structure,  $F(1,46) = 44.1$ , tone,  $F(2,92) = 35.3$ , and location,  $F(5,230) = 9.9$ , all  $ps < 0.001$ ,  $\eta_p^2 > 0.18$ . More importantly, according to a dual task  $\times$  tone interaction the slowing caused by the target, distracter and no-tones differed across the dual-task conditions,  $F(4,184) = 6.0$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.12$ . A location  $\times$  dual task interaction indicated that the IKIs following the tone were slowed differently in the three dual-task conditions,  $F(10,460) = 4.1$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.08$ .

A planned comparison showed that presentation of target and distracter tones did not significantly lengthen IKIs in the During/Ignore condition relative to no-tone,  $F(1,46) = 1.0$ ,  $p > 0.20$ ,  $\eta_p^2 = 0.02$  (see left panel of Fig. 3). For the During/Identify and the During/Count conditions (center and right panels of Fig. 3), planned comparisons showed that across  $L_0$ – $L_4$  IKIs following a (target and distracter) tone were longer than following no-tone, while this was not the case at  $L_{-1}$ ,  $F_s(1,46) > 34.4$ ,  $ps < 0.001$ ,  $\eta_p^2s > 0.43$ .

An important further finding was that in the During/Count condition responses at  $L_1$ – $L_4$  were slowed more by a target than by a distracter tone,  $F(1,46) = 10.5$ ,  $p < 0.01$ ,

$\eta_p^2 = 0.19$ , while this was not the case with the response at  $L_0$ ,  $F(1,46) = 0.80$ ,  $p > 0.20$ ,  $\eta_p^2 = 0.02$ . The effects of target and distracter tones reduced across  $L_0$ – $L_4$  in During/Identify and During/Count (relative to no-tones),  $F_s(5,230) > 8.3$ ,  $ps < 0.001$ ,  $\eta_p^2s > 0.15$ .

In short, it appeared that in the During/Count and During/Identify conditions the four or five responses following a tone were slowed, while this was not the case in the During/Ignore condition. Furthermore, whereas in the During/Count condition responses at  $L_1$ – $L_4$  were slowed more by a target tone than by a distracter tone, such a tone effect was not observed for the response at  $L_0$ .

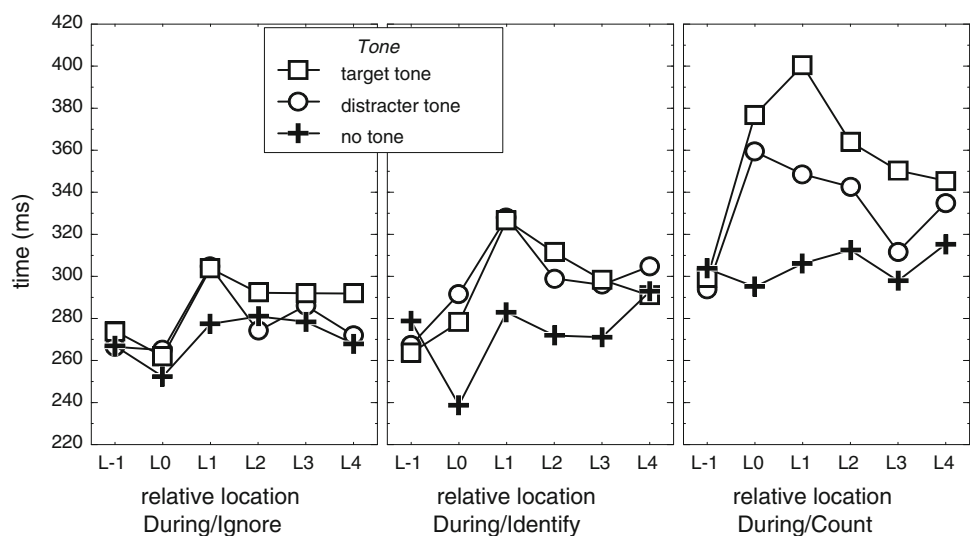
### Tone counting performance

In the Before/Count and During/Count conditions the number of target tones ranged between 5 and 25, and was 16 on average for each test block (with 48 trials). Counting performance appeared quite good: in the Before/Count condition 36 of the 48 participants (75 %) reported the correct number of target tones, and in the During/Count condition this was the case for 32 participants (67 %). In the During/Identification condition 98 % of the responses were correct.

### Errors

Arcsine square-root-transformed error proportions were analyzed with the above-mentioned mixed 2 (group)  $\times$  2 (structure)  $\times$  4 (dual task)  $\times$  3 (tone)  $\times$  7 (key) ANOVA. It indicated that (actual) error proportions differed for the dual-task conditions (During/Ignore, 3.3 % per key; During/Count, 3.1 %; During/Identification, 2.8 %; and Before/Count, 2.5 %),  $F(3,138) = 7.6$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.14$ . Error proportions were higher in prestructured

**Fig. 3** RTs as a function of tone identity, dual task, and position relative to tone presentation (tone onset coincided with onset of the key-specific stimulus evoking the response at  $L_0$ ).  $L_{-1}$  includes the mean of all IKIs that preceded tone presentation (thus excluding  $T_1$ )



than in unstructured sequences (3.2 vs. 2.6 %),  $F(1,46) = 11.1$ ,  $p < 0.01$ ,  $\eta_p^2 = 0.19$ , and error proportions were higher at  $R_6$  than at the other responses (4.6 vs. 1.5–3.3 %),  $F(6,276) = 12.8$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.22$ . Furthermore, error proportions increased more in case of a short inter-sequence interval with prestructured (from 2.6 % with the long, to 3.7 % with the short intervals) than with unstructured sequences (from 2.5 to 2.8 %),  $F(1,46) = 4.8$ ,  $p < 0.05$ ,  $\eta_p^2 = 0.09$ .

## Discussion

### Concurrent counting

The present results show that average RTs in the familiar keying sequence were lengthened when a dual-task tone was identified and when a dual-task target tone was counted, and that this lengthening was even larger when identification and counting processes both concurred with sequence execution. These findings confirm our expectation that not only the identification of a tone by the cognitive processor can occur while the motor processor is executing the keying sequence sequences (as already shown in Verwey et al., 2010), but that the cognitive processor can also perform the counting process while sequence execution continues. This suggests that in the Verwey et al. (2010) study counting had indeed been postponed until after sequence completion. The observation that sequence execution was slowed by both identification and counting supports the assumption that the same cognitive processor that was postulated by the DPM to race with the motor processor to trigger responses, is involved also in performing cognitive processes in very different tasks.

This interpretation receives support from the observation in the During/Count condition (Fig. 3) that the larger slowing caused by a target tone did not start at the first, but only at the second response after tone presentation. This is a direct indication that the counting process had to await identification of the tone and, hence, that counting followed tone identification. This observation suggests that the sequential nature of familiar keying sequences allows these keying sequences to be used also as a tool to determine the order of cognitive processes in a dual task.

Interference by the tone counting task with sequence execution had been caused by slowing of the four or five responses that followed each tone (see Fig. 3). This refutes the possibility that sequence slowing was caused by the memory load associated with the tone counting task as that should have delayed all responses rather than only these few responses following a tone. Further evidence against this possibility is that slowing was affected by the type of

tone. Conversely, an earlier DSP task study showed that a fairly demanding memory task, per se, does not slow execution of four- and six-key sequences (Verwey, 2003a).

It is not entirely clear which of our procedural changes, relative to Verwey et al. (2010), had caused participants to count during, instead of following, sequence execution. We expected the short interval between successive sequences to be decisive in this respect, but participants appeared to count during sequence execution even when the inter-sequence interval was relatively long. Consequently, concurrent counting seems to have been induced by the use of longer sequences, excluding unfamiliar sequences from the test phase, and/or the larger pitch difference. We now think the larger pitch difference was most important in this respect.<sup>2</sup>

### Graded central processing resources

In the “Introduction” we argued that central processing resources may be distributed across the central processes of two concurrent tasks when these tasks are independent, and one of these central processes is highly practiced and/or compatible.<sup>3</sup> Detailed analyses showed that the enhanced slowing in case identification and counting both concurred with sequence execution, concerned the same responses as those that were slowed by just concurrent identification and just concurrent counting. Concurrent identification and counting did not slow more responses. This supports the notion that the DPM’s cognitive processor is based on central processing resources that can be allocated to different parallel processes in a graded fashion. So, the DPM’s original assumption of a unified cognitive processor that switches between processes (Verwey, 2001) seems not to hold when a dual task is performed during execution of a movement sequence. Future research might investigate whether such a graded distribution of central processing resources is perhaps possible only when one central process

<sup>2</sup> Verwey et al. (2010) used discrimination of 660 and 698 Hz tones. The frequencies of these tones differ by about 6 % (= 38 Hz). In the present study, the difference between the 440 and 698 Hz tones amounted to 45 % (= 258 Hz). Pakarinen, Takegata, Rinne, Huotilainen, and Näätänen (2007) reported RTs to tone pairs that differed with various magnitudes around a standard tone of 523 Hz. In their study a deviation of 6 % (= 34 Hz) increased RT by about 65 ms relative to the largest deviation of 30 % (= 160 Hz). So, in retrospect, participants in the Verwey et al. (2010) study may have postponed counting because of the relatively long time and effort needed to properly identify tones with similar frequencies.

<sup>3</sup> Other determinants may be the joint use of a common process in the two tasks (Joliceur & Dell’Acqua, 1999; Kahneman, 1973; Norman & Shallice, 1986; Pashler, Johnston, & Ruthruff, 2001), the likelihood that codes in the two tasks can be confused (Hirst & Kalmár, 1987; Zwicker, Grosjean, & Prinz, 2010), and a high task complexity that is likely to require all central processing capacity (like when tones are hard to distinguish, Sigman & Dehaene, 2008).

is simple, like when stimulus–response compatibility is high (e.g., Lien et al., 2005).

#### Additional issues

The present data raise several interesting further issues. First, the result that counting may occur during sequence execution suggests that in our previous study participants had opted to postpone counting until after sequence completion. If so, why did they not postpone tone identification too? One explanation is suggested by a model of auditory memory stores (Cowan, 1984, 1988). It asserts that auditory information is initially stored in a volatile, precategorical echoic trace that lasts for no more than 200–300 ms. If so, this suggests that after presentation tones had to be translated immediately into a more stable code that could last until after sequence completion. The indication that even distracter tones were followed by slowed responses indicates that the translation of this echoic trace—by ‘our’ tone identification process—was a cognitive task too. This is consistent with indications that classification according to an uncommon rule requires cognitive processing (Johnston & McCann, 2006).

Second, the Verwey et al. (2010) study showed that the three responses following a tone were slowed. In the present study this was observed with four or five responses, even in case of a distracter tone. We speculate that the number of slowed responses was higher in the present study because, once the tone had been identified, a decision was needed to initiate the counting process (just like a response needs to be selected before it is initiated). In our previous study, that decision could be postponed along with counting until after sequence completion so that sequence execution was slowed only by tone identification. Yet, given the strategy to count during sequence execution, participants in the present study had to decide during sequence execution. This occurred even when a distracter tone had been presented. This reasoning suggests that the decision to count requires cognitive processing resources too, and that participants can schedule whether this decision process occurs during or after sequence execution.

Third, post hoc comparisons of mean execution rates across  $R_2$ – $R_7$  in the sequences of the four dual-task conditions without a tone, showed no rate differences between During/Ignore, Before/Count, and During/Identify. However, the sequences in these three conditions were executed significantly faster than in the During/Count condition without tone. This slowing cannot be attributed to the memory load of the target counter or to processing tones. Instead, it may have been caused by the additional executive control demands of keeping two dual-task processes prepared (identification and counting) instead of only one such process (just identification or just counting).

Fourth, participants in the present experiment performed an unstructured and a prestructured sequence. The reason for this manipulation was that earlier research had shown that participants tend to spontaneously segment sequences exceeding four- or five-key presses in two motor chunks (e.g., Kennerley, Sakai, & Rushworth, 2004; Povel & Collard, 1982; Sakai et al., 2003; Verwey, Lammens, & van Honk, 2002). For the present sequences, the transition between successive chunks was observed to spontaneously develop at the fifth response (De Kleine & Verwey, 2009). To compare this spontaneous transition with an experimenter-imposed transition, we inserted in the prestructured sequence during practice a pause before the fifth stimulus (Verwey, 1996; Verwey, Abrahamse, & Jiménez, 2009). We wondered whether or not concatenation between successive motor chunks at the fifth response in these two sequence types would be slowed more by the tone counting task than the other responses. Our recent study did not find such an additional increase in slowing at transition points induced by pauses (Verwey et al., 2010). This suggested that motor chunks are concatenated without cognitive involvement. The present results confirmed this in that, even though the fifth response was relatively slow in both types of sequences, in both structured and unstructured sequences this response was not slowed more by the dual task than the other responses. This confirms that triggering the response at this concatenation position involved the same cognitive contribution as the other responses, and hence that in these fixed sequences the concatenation process itself does not involve cognitive processing.

#### On automaticity

Single resource models (Kahneman, 1973; Moray, 1967; Telford, 1931) assert that processing is automatic when there is no interference with a concurrent task. Later, researchers have argued that processing would be automatic when it occurs without intention, effort, and awareness (for recent overviews, see Moors & De Houwer, 2006, 2007; Saling & Phillips, 2007). Problematic is that such features of automatic processing often do not co-occur. Several theorists have tried to resolve this problem by arguing that the prime criterion of automatic processing is autonomy in the sense that processes are not cognitively monitored (e.g., Bargh, 1992; Tzelgov, 1997). Interestingly, the concept ‘automatic processing’ continues to evoke interest in contemporary theorists (Ashby & Crossley, 2012; Ashby, Turner, & Horvitz, 2010; Moors & De Houwer, 2007; Saling & Phillips, 2007).

We believe that the DPM is consistent with the autonomy criterion for automaticity, and that absence of dual-task interference is indeed a poor indicator for automaticity of sequential motor skills. According to the DPM, reduced

cognitive involvement is possible because motor chunks are coded in an efficient, movement related way and cognitive processes are not essential for execution once the sequence has been initiated (e.g., Hikosaka et al., 1999; Saling & Phillips, 2007; Verwey, 2001). The DPM does acknowledge, however, that execution of familiar movement sequences usually involves a cognitive component (Glencross, 1980; Posner & Keele, 1969). The use of motor chunks at the motor level unburdens the cognitive processor, but it comes at the price that familiar movement patterns are sometimes carried out when they should not be used. This results in action slips that are typically attributed to habitual action patterns being produced in inappropriate situations because the performer is distracted or absent minded (Botvinick & Bylsma, 2005; Norman & Shallice, 1986; Reason, 1992). So, in line with the autonomy criterion of automatic processing, the DPM suggests that (a) sequential movement skills can be considered automatic in the sense that cognitive involvement is not required for execution once the sequence has been initiated, and that (b) in the domain of sequential action skills dual-task interference does not imply that sequencing skill is not automatic.

Apart from the automatic execution of movement sequences, the present data also provide an indication that the control of information processes automated within the test phase. Table 1 shows that slowing of responses in the During/Ignore condition by the to-be-ignored target tones was of a comparable magnitude as when the target tones were actually processed in the other dual-task conditions. This may suggest that in three of the four test conditions an automatic tendency had developed to process each tone. If so, this tendency would have to be stronger for participants who encountered the During/Ignore condition later in the test phase (due to balancing the order of test conditions). This was confirmed by a marginally significant increase of slowing by tones as participants got the During/Ignore condition later in the test phase. In this case, automaticity is suggested by the tendency to continue a practiced order of processes (rather than responses).

## Conclusions

The present results confirmed our expectation that not only the identification of a tone by the cognitive processor can occur while the motor processor is executing the keying sequence sequences (as had already been shown in Verwey et al., 2010), but that the cognitive processor can perform also the counting process while sequence execution continues. Detailed analyses of the individual responses following a tone revealed that the central processing resources underlying the cognitive processor can, in certain situations, be distributed in a graded fashion across the central

processes of these two concurrent tasks. This indicates that the DPM's cognitive processor may not always behave as a unified unit, but may sometimes be split up between parallel processes at the central processing level. Together with earlier findings (Verwey et al., 2010), the present results suggest that the resources underlying central processing are responsible for the cognitive processes used in sequence production (including preparing and initiating keying sequences, and triggering individual key presses), and in tone counting (identifying tones, incrementing a counter in memory, and perhaps even deciding to count, and keeping identification and counting processes ready for use). The triggering of individual responses in a familiar keying sequence by the motor processor, and the concatenation of successive motor chunks within a familiar sequence do not seem to require these central processing resources. These sequence execution processes at the motor level can be considered automatic in the sense that, once the sequence has been initiated, they occur autonomously and require no cognitive involvement.

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