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Timing is affected by demands in memory search, but not by task switching

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Running Head: MEMORY SEARCH, TASK SWITCHING AND TIMING

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Abstract

Recent studies suggest that timing and tasks involving executive control processes might require the same attentional resources. This should lead to interference when timing and executive tasks are executed concurrently. This study examines the interference between timing and task switching, an executive function. In four experiments, memory search and digit classification were performed successively in four conditions: search-search (search followed by search), search-digit, digit-search and digit-digit. In a control reaction-time condition, participants provided RT responses in each of the two tasks. In a time-production condition, an RT response was provided to the first stimulus, but the response to the second stimulus, S2, was given only when participants judged that a previously presented target duration had elapsed. When responding to S2 required a switch, RTs to S2 were longer but produced intervals were unaffected. These results show that memory search affects concurrent timing, but not task switching. Task switching seems therefore to be one executive function not interfering with timing.

Keywords: timing, task switching, interference, scheduling, memory search, digit classification

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Many studies have demonstrated the critical role of attention when one is deliberately estimating an ongoing duration, mostly by showing interference between timing and other concurrent tasks (Brown, 1997, 2006; Coull et al, 2004). It has been suggested recently that the interference may reflect a significant contribution of executive control processes to estimation of duration (Brown, 1997, 2006; Rammsayer & Ulrich, 2005; Zakay & Block, 2004) and thus, that concurrent tasks involving executive processes would be especially likely to interfere with timing. Executive control processes (hereafter named executive processes) coordinate working memory sub-systems, focus and switch attention, and activate representations within long-term memory, but are not directly involved in temporary storage (Baddeley & Logie, 1999; Smith & Jonides, 1999).

Interference between timing and task switching has been reported (Zakay & Block, 2004). This is of particular interest since this interference effect may help specify which attentional processes are involved in timing. Another potential impact of interference between timing and task switching concerns the scheduling of mental processes, which depends on estimated durations of processes (e.g., Conway, Maxwell & Miller, 2003). In a model of Thomas and Brown (1974) an estimate of the duration of a mental process is available after the process is carried out. However, if time estimates are distorted during a task switch, this could lead to distorted estimates in compound tasks, thus resulting in less efficient schedules. The purpose of the present study was therefore to examine the issue of interference between timing and task switching.

In a study of executive processes in timing, Zakay & Block (2004) tested whether time estimates were influenced by manipulation of demands in two executive tasks, (1) resolving syntactic ambiguity in reading and (2) task switching. Timing was done concurrently with each of the two tasks in two separate experiments. In the task switching experiment, participants reproduced 12-s intervals while switching between two different versions of a Stroop task, naming colors or naming words. Colors and words could be represented by a single stimulus (name of a color printed in another color). In a difficult version of the task, the participants either had to provide the name or the color of the word. In an easy version of the task, the stimulus in the naming task appeared in white on the screen and the color was a colored square. In a prospective timing condition, when the participants were informed in advance that they had to estimate a time interval within which the task trials took place, reproductions were shorter when there were three task changes during the 12-s interval than when there was only one task change, and this effect seemed independent of task difficulty. This suggests a specific cost of task switching on timing.

Shorter temporal reproductions when there is interference during the estimated time interval are predicted by accumulator models of timing integrating attentional control (Brown, 1997, 2006; Coull et al., 2004; Gibbon, Church, & Meck, 1984; Lejeune, 1998; 2000; Zakay & Block, 1996): attention sharing between timing and the interfering task would result in loss of accumulated temporal information, hence in shorter perceived duration.

Whereas accumulator models predict shorter reproductions when there is interference during an estimated duration, longer temporal productions are predicted when interference takes place during the interval production. A recent example of this effect may be found in a study on interference between executive cognitive functions and prospective timing (Brown, 2006). In that study, series of 5-s intervals were produced concurrently with generating random numbers at a regular pace. Generating random numbers during time production made the series of produced intervals longer and more variable. Moreover, generated numbers were less random when they were provided concurrently with time production. This suggests that common resources must be shared when timing and executive-level tasks are performed concurrently. The basic idea is the following. According to an accumulator model of timing, a clock produces pulses at a regular rate. To produce a time interval of a target duration, the participant sets a criterion to the total number of pulses needed to produce the target duration. At the start of the produced interval, pulses begin to be accumulated. When the accumulation reaches the criterion, the response is made to end the produced interval. An accumulator model of timing integrating attentional control makes the further assumption that while attention is diverted to a secondary process (such as a task switch) pulses are not accumulated. Hence, time intervals are longer when they are produced concurrently with an attention demanding secondary task.

Similarly, produced time intervals are longer when memory search (i.e., comparing a probe to memory items) is performed during a time interval production, and the lengthening is proportional to the duration of memory processing (e.g., Fortin & Rousseau, 1987; Fortin, Champagne, Poirier, 2007). Timing seems to be interrupted during memory search, suggesting that common mechanisms are used in both tasks. In contrast, simple maintenance of information in memory had no or little effect on concurrent timing under some conditions, for example, maintenance of memory items while producing a time interval (Field & Groeger, 2004, Fortin & Breton, 1995; Fortin, Champagne, Poirier, 2006; Rammsayer & Ulrich, 2005). Holding material in storage seems to differ from carrying out executive processes in working memory (Smith & Jonides, 1999; Baddeley & Logie, 1999).

The primary goal of the present study was to examine the issue of interference between timing and task switching, a specific executive process related to task management (Smith &

Jonides, 1999). In the paradigm used in the present study, participants are asked to switch between two tasks: memory search and classification of a digit as being odd or even. Interference between memory search and timing has been demonstrated in numerous studies (e.g., Fortin, Champagne, Poirier, 2007; Neath & Fortin, 2005). This finding gives another reason to expect switching between memory search and another task would generate interference on concurrent timing. When a stimulus is presented for a task different from the task just carried out, the participant must use a different stimulus-response mapping. Something like a different rule (e.g., Rabbit & Vyas, 1973) or a different pathway (e.g., Dreher & Grafman, 2003) must be found in memory. If searching for a different mapping behaves like searching through items, then a task switch would interfere with timing.

However, although searching a set of verbal items in memory and switching from one task to another are both said to be working memory functions, they may not require the same resources. In an fMRI study, Postle, Berger and D'Esposito (1999) found a dissociation between effects of (1) increasing the size of a verbal memory set in a search task and (2) requiring alphabetization of such a memory set. In their study, the left perisylvian cortex was sensitive to the former manipulation, while the dorsolateral prefrontal frontal cortex was sensitive to the latter. Strictly mnemonic demands were dissociated anatomically from executive demands. In our study the strictly mnemonic demands are similar to those of Postle et al. (1999), and it is possible that they will be dissociated in their effects on timing from our executive demands of a task switch.

Two main general conditions were used in all the following experiments, a “time-production condition” and a “reaction-time condition”. In both conditions, two stimuli were presented successively, and the participant responded successively to each of these two stimuli.

In both conditions, the participant was asked to respond as quickly as possible to the first stimulus in the sequence. The main difference was in responding to the second stimulus: in the reaction-time condition the participant was asked to respond as quickly as possible to this second stimulus (as to the first stimulus), but in the time-production condition the participant was asked to respond to the second stimulus only when he/she judged that a target time interval had elapsed. Therefore, whereas a reaction time response was required in responding to the second stimulus in the reaction-time condition, responding to the second stimulus involved a time interval production in the time-production condition. This means that responding to the second stimulus only required processing the second stimulus in the reaction-time condition whereas in the time-production condition, time had to be estimated simultaneously with processing the second stimulus.

The time-production and reaction-time conditions were tested in two different groups of participants. In both conditions, each of the two stimuli could be either a letter or a digit. If it was a letter, the participant had to indicate whether it was a member of a previously memorized set of letters. If it was a digit, the participant was asked to indicate whether it was odd or even. In both conditions, two stimuli (letter-letter, letter-digit, digit-letter or digit-digit) were processed successively, resulting in four possible sequences of two tasks: memory search followed by memory search (MM trials), memory search followed by digit classification (MC trials), digit classification followed by memory search (CM trials), and digit classification followed by digit classification (CC trials). In the MM and CC sequences, performing the second task in the sequence did not entail a task switch, but in the MC and CM sequences, the participant had to switch from one task to another in order to perform the second task. Therefore, MM and CC trials were no-switch trials, MC and CM trials were switch trials. The types of task sequences (i.e., involving switch and no-switch) were mixed within blocks of trials in Experiments 1, 2, and 3. In Experiment 4, blocks in which the task sequences were mixed were compared to blocks with pure task sequences, that is, blocks in which there were only no-switch trials. This last experiment allowed us to compare the effect of no-switch trials in pure-sequence blocks, with no uncertainty as to the second task to be performed in the sequence, to the effect of no-switch trials in mixed-sequence blocks, with uncertainty relative to the next task.

The switch/no-switch manipulation allowed us to test whether there would be a switch cost on concurrent timing in the time-production condition. The same manipulation in the reaction time condition was used as a control, to ensure that switch costs could be observed in the task sequences used in the present study. As usual in task-switching studies, we expected that a switch cost would be detected in the reaction-time condition through longer reaction times to the second stimulus in switch trials than in no-switch trials. In the time-production condition, accumulator models of time estimation integrating attentional control (Brown, 1997; Gibbon, Church & Meck, 1984; Zakay & Block, 1997) predict interference between timing and task switching. This interference should result in longer time intervals, produced concurrently with processing the second stimulus, in switch trials than in no-switch trials. This is because in switch trials, there should be a disruption in accumulating temporal information during the task switch. This disruption should delay the time at which the subjective target interval to produce is reached, and hence delay the time at which the temporal production is ended (Brown, 1997).

Experimental trials are illustrated in Figure 1 in the two main experimental conditions, reaction-time (Figure 1a) and time-production condition (Figure 1b). A row of asterisks was first displayed on the screen on each trial. When ready, participants in both conditions began the trial by pressing the “0” key. This triggered the successive presentation of three consonants (one per second) to be memorized by the participants. The word “Ready” appeared on the screen after the last consonant. (Messages were in French; translations are given here.) When ready to see the first stimulus in the task sequence, the participants pressed the “0” key, which made the first stimulus in the sequence (S1) appear 500 ms later. A response to S1 was required. Eight hundred ms after the first response (Figures 1a and 1b), the second stimulus in the sequence (S2) appeared and a second response was required. The two responses in the sequence were labeled RT1 and RT2 in the reaction-time condition respectively, since they were both reaction-time responses. In the time-production condition, the two successive responses were labeled RT and TP (time production) since the first response was a reaction-time response and the second response marked the end of a time interval production. In effect, in the time-production condition, the response to S2 was provided when the participant judged that a tone, which started just before the onset of S2, had reached a target time interval (see Figure 1b). Note that the tone was presented in both the reaction-time and the time-production conditions to ensure the equivalence of stimulus conditions.

Figures 1a and 1b about here

The main hypotheses concerned response times to S2. In the reaction-time condition, it was expected that a switch cost would be revealed by longer reaction times to the second stimulus (RT2) in switch than in no-switch trials. In the time-production condition, interference between timing and a task switch would lead to longer time productions (TP) in switch than in no-switch trials, according to accumulator models of time estimation integrating attentional control.

The experimental design was similar in all experiments. In Experiment 1, the delay between the first response in the task sequence and the onset of the second stimulus, S2, was longer than in the three other experiments. In Experiments 3 and 4, two factors were manipulated during an experimental trial, memory load and task switching, so that effects of memory search and of a task switch on concurrent time production could be contrasted. Increasing demands in memory search usually leads to increased interference on timing; it was therefore expected that increasing memory load would lead to longer time productions in those experiments. In the first three experiments, switch and non-switch trials were mixed in all blocks of trials. Experiment 4 included pure blocks composed of non-switch trials only.

Experiment 1

Experiment 1 tested whether a task switch would interfere with timing, in which case time productions should be longer in switch trials than in no-switch trials. The reaction-time condition was used as a control condition, to verify whether the paradigm induces a switch cost, and to estimate its magnitude, that is, the difference in reaction time between the switch and no-switch conditions. If there is a switch cost in the reaction-time condition, RT2 should be longer in the switch than in the no switch condition. If this time required for switching interferes with timing, TP should be correspondingly longer in the switch than in the no-switch condition in the time-production condition. The critical comparison was therefore between the switch cost on reaction times (RT2 in Figure 1a) in the reaction-time condition and the switch cost on time productions (TP in Figure 1b) in the time-production condition.

Method

Participants. Fifteen young adults, mostly students at Université Laval, received a small honorarium ($5) for their participation in one experimental session of about 35 minutes. The sample was composed of 8 women and 7 men (mean age = 24.3, *SD* = 6.3). Eight participants were randomly assigned to the reaction-time condition, seven to the time-production condition. They were all naïve to the purpose of the experiment. No participant took part in more than one experiment in the study.

Apparatus and stimuli. A PC-compatible computer running E-Prime software controlled stimulus and feedback presentations, as well as data recording. The participants were seated in front of a computer screen, at a distance of about 70 cm from the monitor screen (VGA, 20 x 27 cm). Stimuli were displayed in white on a black background, and the size of each character was equivalent to 14 characters per inch. Instructions, stimuli, fixation points and feedback appeared in the middle of the screen. The right hand of the participants rested on the numerical keyboard of the computer. Presentation of some displays in a trial was controlled by the participants, who pressed the “0" key to make the display appear. The “1” and “3” keys were used to respond in the two tasks. The “1” key served to indicate that the target stimulus was present in the memory set in the memory search task, and to indicate that the digit was even in the digit classification task. The “3” key was used to indicate that the target stimulus was absent in the memory set and that the digit was odd. The experiment took place in a sound-attenuated test chamber, dimly lighted with a 40-Watt bulb. The auditory stimulus (550 Hz) used in experimental trials was emitted through two speakers, each speaker being at a distance of about 10 cm, on each side of the screen. Each participant was tested individually.

Procedure. In the reaction-time condition, there was one experimental session including two 56-trial blocks of experimental trials. In the time-production condition, there was one experimental session including two 45-trial blocks of time production practice trials followed by two 56-trial blocks of experimental trials. The number of memory-memory (MM), memory-classification (MC), classification-memory (CM) and classification-classification (CC) sequences was balanced within blocks of trials so half of the trials were switch trials (MC and CM) and the other half were no-switch trials (MM and CC). In switch trials, the number of MC and CM sequences was balanced, as was the number of MM and CC sequences in no-switch trials. Within these constraints, the four types of trials were presented randomly within a block of trials. When the presented stimulus was a consonant, the presence/absence of the target letter in the memory set was balanced in a block of trials, as was the use of even/odd digits.

In the time-production condition, the 2-s target interval to be produced throughout the experiment was presented in demonstration trials, which started with five asterisks displayed in the center of the screen. When ready, the participants pressed the “0” key, which started the 2-s tone presentation. The participants were asked to pay attention to the tone duration because they would have to produce the same duration themselves throughout the experiment. After five demonstration trials, practice trials began. A practice trial also started with the five asterisks followed by the participants pressing the “0” key when ready. A tone presentation started, which the participants ended by pressing the “1” or the “3” key when they judged that the duration presented in the demonstration trials was reached. There was no mention of the tone duration value in time units (e.g., seconds). Participants were asked to use the “1” and “3” for an approximately equal number of times. In the first block of practice trials, feedback followed each interval production, informing the participants whether the interval was too short, too long, or correct, within a temporal window of 10% (± 100 ms) centered on the target interval. The feedback consisted of a visual message, “Too short”, “Too long” or “Correct” presented in the center of the screen. No feedback was provided in the second block of practice trials. In the following experimental blocks, participants performed the two tasks successively as described earlier and illustrated in Figure 1, in the reaction-time (Figure 1a) or in the time-production (Figure 1b) condition.

Results

Before performing the analyses, trials with errors in memory search or in digit classification were removed. Outliers (± 3 *SD* from the mean) were then computed with individual means and standard deviations of each participant for reaction times and temporal productions and were removed from the data sets. For each participant, mean reaction times and mean produced intervals in the two blocks including experimental trials were computed at each level of the switch/no-switch factor; those means were submitted to the analyses.

The critical statistical tests, regarding the main hypotheses of this experiment, were the following. In the *reaction-time condition*: 1) the difference in reaction times in responding to S2 (RT2 in Figure 1a), in switch and no-switch trials and 2) the difference in percent errors in responding to S2. In the *time-production condition*: 3) the difference in time productions (TP in Figure 1b) in switch and no-switch trials and 4) the difference in percent errors in responding to S2. In the reaction-time condition, an analysis of variance including one within subjects factor with two levels, switch and no-switch was performed on RT2. The same ANOVA was performed on percent errors in responding to S2. Time productions (TP) were then submitted to an analysis of variance including one within subjects factor with two levels, switch and no-switch. The same test was carried out on percent errors in responding to S2 in the time-production condition. Means and standard deviations of reaction times to S1 (labeled RT in the time-production condition and RT1 in the reaction-time condition respectively) were computed.

Reaction-time condition. Participants made 2.25% errors in responding to S1 and 3.81% in responding to S2. Outliers represented 2.00% and 1.22% of the remaining data in responses to

S1 and to S2 respectively. The ANOVA with one within subjects factor, switch/no switch, revealed that the mean reaction time to the second stimulus (S2), RT2, was significantly longer in switch than in no-switch trials, $F(1, 7) = 87.14$, $p < .001$, MSE = 273, $\eta^2_p = .93$, as shown in Figure 2a. Percent errors in responding to S2 were not different in switch ($M = 3.52\%$) and no-switch ($M = 4.10\%$) trials, $F(1, 7) = .36$, $p = .57$, MSE = .0003, $\eta^2_p = .05$.

On average, RT2 was 885 ms in switch trials and 808 ms in no-switch trials, revealing a switch cost of 77 ms. Means and standard deviations of reaction times to S1, RT1, were 847.88 ms and 265.55 ms respectively.

Time-production condition. There were 3.68% and 1.67% errors in responses to S1 and to S2, respectively. Outliers represented 0.81% and 0.79% of the remaining data in responses to S1 and to S2 respectively. Time productions did not differ in switch and no-switch trials, $F(1, 6) = .42$, $p = .54$, MSE = 1190, $\eta^2_p = .06$ (see Figure 2b). Percent errors in responding to S2 were not different in switch ($M = 2.01\%$) and no-switch ($M = 1.34\%$) trials, $F(1, 6) = .56$, $p = .48$, MSE = .0003, $\eta^2_p = .09$. The mean and standard deviation of reaction times to S1, RT, were 1134.49 ms and 432.60 ms respectively.

In the two time production practice blocks of trials, mean intervals produced in the first block with feedback and in the second block without feedback were respectively 1916 ms (*SD* = 268) and 2123 ms (*SD* = 493).

Figures 2a and 2b about here

Discussion

The critical finding in Experiment 1 is that even though there was a clear switch cost on reaction times in the reaction-time condition, there was no corresponding switch cost on produced time intervals in the time-production condition. These results suggest that although the paradigm in the present experiment induces a significant switch cost on reaction time, the time required to switch from one task to another may be performed concurrently with no interference on timing.

Overall, analyses on errors in the memory and digit classification tasks revealed that errors in responding to S2 were not different in switch and no-switch trials in the time-production condition. There was therefore no evidence of speed-accuracy trade-off that could explain the lack of interference from switching on time productions.

In Experiment 1, the delay between the response to S1 and the onset of S2 was 800 ms, which is relatively long. The cost of a task switch decreases as the interval following the previous task increases (Meiran, 1996; Meiran, Chorev & Sapir , 2000; Rogers & Monsell, 1995; Ruthruff, Remington & Johnston 2001). The decreased cost may be the result of more available time for the previous task set to dissipate, see Monsell (2003). A larger task switch cost might be produced in our paradigm by shortening the response-stimulus interval. One could argue that the relatively long response-stimulus interval of Experiment 1 reduced or eliminated the very component of task switch cost that interferes with timing. Moreover, an ample response-stimulus interval might be especially useful during time interval production, because a time interval response is not speeded as a reaction time response is. In order to rule out these possibilities, the same experimental conditions as in Experiment 1 were used in Experiment 2, except that the delay between the response to S1 and the onset of S2 was reduced.

Experiment 2

The goal of Experiment 2 was to test whether a switch cost on timing would be observed when the response-stimulus interval is considerably shorter than in Experiment 1. This interval, which was 800 ms in Experiment 1, was thus shortened to 200 ms in Experiment 2. Experimental trials were otherwise identical. The number of experimental trials and the number of time production practice trials were increased in Experiment 2 relative to Experiment 1 in order to reduce variability in temporal performance and thus, to increase the probability of detecting a potential effect of switching on timing.

Method

Participants. Twenty-two participants, 14 women and 8 men (mean age = 24.9, *SD* = 6.5) were tested in this experiment. Ten participants were randomly assigned to the reaction-time condition, twelve to the time-production condition.

Apparatus and stimuli. The apparatus and stimuli were identical to those in Experiment 1.

Procedure. In the reaction-time condition, there were four experimental sessions, each session including two 64-trial blocks.

In the time-production condition, there were two sessions of practice of time interval production followed by two experimental sessions. Each time production practice session included five 48 trial-blocks. In the first four blocks, feedback was provided after each temporal production, as in practice trials with feedback in Experiment 1. There was no feedback in the last block of trials in the practice sessions.

Each of the two experimental sessions that followed began with the target interval, which was presented five times in the form of a 2-s tone. This was followed by a 45-trial block of practice on time interval production with feedback. There was then a 20-trial practice block of time production without feedback. After these two blocks of practice, there were two 64-trial experimental blocks. In experimental trials, the sequence of events was identical to that in Experiment 1 (see Figure 1), except that the delay between the response to S1 and the onset of S2 was 200 ms in Experiment 2.

In both the reaction-time and the time-production conditions, no more than two sessions could be completed during the same day. If there two sessions were completed the same day, there was a minimum delay of one hour between the two sessions.

Results

The analyses were conducted as in Experiment 1.

Reaction-time condition. There were 2.30% errors in responses to S1, 3.67% in responses to S2. Outliers represented 1.80% and 1.58% of the remaining data in responses to S1 and to S2 respectively. An ANOVA with switch/no-switch as within subjects factor confirmed that RT2 was significantly longer in switch than in no-switch trials, $F(1, 9) = 52.62$, $p < .001$, MSE = 818, $\eta^2_p = .85$ (see Figure 3a). Mean RT2 was 742 ms in switch trials and was 649 ms in no-switch trials, for a switch cost of 93 ms. Percent errors in responding to S2 were not different in switch ($M = 4.26\%$) and no-switch ($M = 3.09\%$) trials, $F(1, 9) = 1.40$, $p = .27$, MSE = .0005, $\eta^2_p = .14$.

Time-production condition. There were 5.70% and 3.06% errors in responding to S1 and to S2, respectively. Outliers represented 1.83% and 0.54% of the remaining data in responses to S1 and to S2, respectively. Time productions did not differ in the switch and no-switch conditions, $F(1, 11) = .02$, $p = .90$, MSE = 1012, $\eta^2_p = .002$ (see Figure 3b). Percent errors in responding to S2 were not different in switch ($M = 3.13\%$) and no-switch ($M = 2.99\%$) trials, $F(1, 11) = .17$, $p = .69$, MSE = .00006, $\eta^2_p = .02$. The mean and standard deviation of reaction times to S1, RT, were 785.89 ms and 371.41 ms respectively.

In the time production practice sessions, mean intervals produced in blocks with feedback on time production accuracy and in the last block without feedback were 1983 ms (*SD* = 257) and 1972 ms (*SD* = 393) respectively. In experimental sessions, intervals produced in the block of practice trials with feedback were, on average, 1998 ms (*SD* = 206), whereas productions in the practice block without feedback were 2054 ms on average (*SD* = 276).

The mean and standard deviation of RT1 were 736.97 ms and 76.97 ms respectively.

Figures 3a and 3b about here

Discussion

Even with a much shorter delay between the response to S1 and the onset of S2, which reduced the possibility of preparing for switching, the difference between the effects of a task switch on reaction times and on time productions was replicated in Experiment 2. This supports the main conclusion of Experiment 1 according to which switching from one task to another seems to be performed concurrently with no interference on timing, despite a clear switch cost on reaction times when the same task is executed in a reaction-time condition. Again, analyses of errors in the memory and digit classification tasks revealed no speed-accuracy trade-off that could account for the lack of effect of switching on timing.

It is possible that in the paradigm used in Experiment 1 and Experiment 2, the switch/no-switch manipulation did not induce an effect large enough to influence time productions. This possibility appears unlikely because effects of memory set size, of about the same magnitude as the switch cost found here, have consistently led to effects on timing (e.g., Fortin & Rousseau, 1987). To verify this possibility however, effects of memory processing and of a task switch on timing were contrasted within the same task in Experiment 3.

Experiment 3

This experiment used the same paradigm as Experiment 2, except that the memory load in the search task varied from trial to trial instead of being constant: the memory set could include two, four or six consonants. Based on earlier literature (e.g., Fortin, Rousseau, Bourque & Kirouac, 1993) such increases in set size should lead to increases in reaction times in the reaction-time condition, and should also lead to a significant lengthening of produced intervals in the time-production condition. Furthermore, on the basis of the results in Experiments 1 and 2, reaction times should be significantly longer in switch than in no-switch trials, but time productions should not differ in those trials. The objectives of Experiment 3 were thus (1) to verify that an increase in set size and a task switch would have effects of about the same magnitude on reaction times, thus showing similar demands in terms of processing time, and (2) to test whether an increase in set size and a task switch would also have effects of about the same magnitude on time productions, thus showing similar interference effects on concurrent timing.

Method

Participants. Twenty participants, 15 women and 5 men (mean age = 23.5, *SD* = 8.2) were tested in this experiment. Eight participants were randomly assigned to the reaction-time condition, twelve to the time-production condition.

Apparatus and stimuli. The apparatus and stimuli were identical to those in Experiments 1 and 2.

Procedure. In the reaction-time condition, there were four experimental sessions, each session including four 48-trial blocks. In the time-production condition, there were two sessions of practice of time interval production followed by two experimental sessions. Each time production practice session included five 48 trial-blocks. In the first four blocks, feedback was provided after each temporal production, as in practice trials with feedback described in the Method section of Experiment 1. There was no feedback in the last block of trials in the practice sessions.

Each of the two following experimental sessions began with presenting the target interval five times with a 2-s tone. This was followed by a 45-trial block of practice of time interval production with feedback. A 20-trial block of practice of time production without feedback then followed. The participants were tested in three successive blocks of experimental trials including 48 trials each. In experimental trials, the sequence of events was identical to that in Experiment 2, with a 200-ms delay between the response to S1 and the onset of S2, except that the number of consonants presented at the beginning of each trial varied from trial to trial. In each trial, the memory set could include 2, 4 or 6 consonants.

Results

The analyses are similar to those of Experiments 1 and 2 except that memory-set size was included as an additional within subjects factor in each ANOVA.

Reaction-time condition. There were 3.3% and 6.6% errors in responses to S1 and S2, and outliers represented 1.9% and 1.7% of the remaining data in responses to S1 and S2 respectively.

A repeated-measures ANOVA with two factors, memory-set size (2, 4, 6) and switch/no-switch was carried out on RT2. This analysis confirmed that the increase in RT2 with increasing set size shown in Figure 4a was significant, $F(2, 14) = 22.99$, $p < .001$, MSE = 921, $\eta^2_p = .77$ and that RT2 was significantly longer in switch than in no-switch trials, $F(1, 7) = 36.20$, $p = .001$, MSE = 2284, $\eta^2_p = .84$. RT2 was, on average, 721 ms in switch trials and 638 ms in no-switch trials, for a switch cost of 83 ms. The corresponding cost of increasing set size in the memory task was comparable: mean RT2 was 715 ms at set size = 6 and 642 ms at set size = 2, for an overall cost of memory processing of 73 ms. The interaction between task switching and memory set size was also significant, $F(2, 14) = 4.28$, $p = .04$, MSE = 177, $\eta^2_p = .38$. The form of the interaction is that RT2 is particularly short in the no-switch condition, when there were only two items in the memory set. Tests of simple main effects showed however that the effect of set size was significant in both the switch and no-switch conditions (both *p*s < .01).

An ANOVA with two within subjects factors, memory-set size and switch/no-switch, showed that percent errors increased with set size, $F(2, 14) = 23.82$, $p < .001$, MSE = .04, $\eta^2_p =$ .77. The effect of the switch/no-switch factor was not significant, $F(1, 7) = 1.47$, $p = .27$, MSE = .15, $\eta^2_p = .17$, but set size interacted with switching, $F(2, 14) = 4.28$, $p = .04$, MSE = .04, $\eta^2_p =$ .38. In the switch condition, when 2, 4, and 6 letters were included in the memory set, percent errors were 6.3, 5.6 and 9.9% respectively, whereas the corresponding errors in the no-switch condition were 2.6, 6.3, and 8.9%. The interaction shows that the percentage of errors was especially low when the set size was small (2 items), in no-switch trials. Tests of simple main effect showed that the effect of set size was statistically significant ($p < .01$) with both switch and no switch trials.

The ANOVA with set size as single factor showed that RT1 increased with set size (654, 704, 747 ms at set size = 2, 4, and 6, respectively), $F(2, 14) = 14.49$, $p < .001$, MSE = 1185, $\eta^2_p =$ .67. The same analysis on percent errors in responding to S1 showed that errors also increased with set size (4.4, 5.9, 9.4% at set size = 2, 4, and 6, respectively), $F(2, 14) = 23.82$, $p < .001$, MSE = .001, $\eta^2_p = .77$.

Figures 4a and 4b about here

Time-production condition. Errors in memory search or digit classification led to elimination of 5.7% of the trials with responses to S1 and 3.1% of the trials with responses to S2. Outliers were then eliminated, representing 1.8% and 0.5% of the remaining data in responses to S1 and S2 respectively.

Four ANOVAs were performed: one on time productions with set size and switch/no-switch as within subjects factors, and one on percent errors in responding to S2 (errors committed in the digit or memory task while producing the time interval), with set size and switch/no-switch as within subjects factors also. ANOVAs were performed on responses to S1, one on RT and one on percent errors. Because the switch/no-switch factor is irrelevant in responding to S1, these ANOVAs included the set size factor only.

The repeated-measures ANOVA with two within subjects factors, memory-set size (2, 4, 6) and switch/no-switch showed that produced intervals lengthened with increasing set size in the memory set, $F(2, 22) = 10.70$, $p = .001$, MSE = 3539, $\eta^2_p = .49$, but did not differ in switch and no-switch trials, $F(1, 11) = 1.12$, $p = .31$, MSE = 2623, $\eta^2_p = .09$, as shown in Figure 4b. The interaction between set size and switch/no-switch was also nonsignificant, $F(2, 22) = 1.30$, $p = .29$, MSE = 1812, $\eta^2_p = .11$.

The repeated-measures ANOVA on percent errors in responding to S2 with two within subjects factors, memory-set size (2, 4, 6) and switch/no-switch, showed that more errors were made when responding to Stimulus 2 when set size increased (1.1, 2.6, 5.6% at set size = 2, 4, and 6, respectively), $F(2,22) = 16.30$, $p < .001$, MSE = .013, $\eta^2_p = .60$. However, neither the task switch effect (3.2% and 3.0%, for switch and no-switch trials, respectively), $F(1,11) = 0.17$, $p =$

.69, MSE = .001, η^2_p = .02, nor the interaction between set size and task switch, $F(2,22) = 2.31$, $p = .12$, MSE = .001, η^2_p = .17, were significant.

In order to test whether increasing set size would have the usual effect on reaction times to the first stimulus, an ANOVA with one factor, set size, was performed on reaction times to S1, RT. RT increased significantly with increasing set size (703, 754, 794 ms at set size = 2, 4, and 6, respectively), $F(2, 22) = 32.02$, $p < .001$, MSE = .001, η^2_p = .74. Besides, an ANOVA on percent errors in responding to S1, with set size as a within subjects factor, showed that errors also increased significantly with increasing set size (4.1, 4.3, and 8.1% at set size = 2, 4, and 6, respectively), $F(2, 22) = 8.61$, $p = .002$, MSE = .001, η^2_p = .44.

In the two practice sessions, mean intervals produced in the three blocks with feedback and in the block without feedback were respectively 1975 ms (*SD* = 307) and 2093 ms (*SD* = 312). In experimental sessions, mean intervals produced in the block of practice trials with feedback and the practice block without feedback were respectively 2006 ms (*SD* = 278) and 2058 ms (*SD* = 238).

Discussion

The critical finding in this experiment was a clear distinction between effects of memory search and of a task switch on time production: increasing processing times in memory search lengthened time intervals produced concurrently, but a comparable increase in processing time due to a task switch had no effect on produced intervals. Processing times in memory search and in the task switch were estimated in control reaction time conditions, revealing comparable costs related to memory search and a task switch. Despite these comparable costs, effects on concurrent timing were completely different: increasing set size in the memory task lengthened significantly produced intervals whereas time productions were similar whether or not the participants had to switch between tasks during the interval. These results confirm that a task switch, as used in the present experiment as well as in Experiments 1 and 2 of the present study, does not interfere with timing. More importantly, comparable demands in terms of processing time in memory search did affect concurrent time production, showing specific interference between timing and memory search in the present experiment.

In the reaction-time condition, errors in responding to the second stimulus increased with set size, but the effect was more pronounced in the no-switch than in the switch condition. This interaction is due to the fact that errors were especially low when the memory set included two items in no-switch trials, showing that when set size was small, performing memory search twice repeatedly led to very few errors. This may be due to the fact that searching a small set of memory items a first time consolidates item representations, leading to very few errors in the second search. More importantly regarding the objectives of the present study, there was no effect of switching, and no interaction involving the switch factor on errors in responding to the second stimulus in the time-production condition. Therefore, in the time-production condition, neither produced intervals nor errors in processing the second stimulus during the interval production were affected by a task switch.

In Experiments 1, 2 and 3, switch and no-switch trials were mixed within blocks of trials. Even when there is no switch from one trial to the next in a mixed block, response times tend to be longer than for the same task in a pure block of trials of the task (see Monsell, 2003, for a brief review). This mixing cost indicates that there are long-term as well as transient costs of a task switch. In a mixed block, participants have to be ready on every trial to perform both tasks, hence incurring long term costs such as task uncertainty and related coordination of task resources. It is possible that the long term costs of mixing affect timing, while the transient costs, such as inhibition and activation of task sets, do not. Experiments 1, 2, and 3 showed a cost of switching on reaction times, but not on time productions. In those experiments, switch and nonswitch trials were compared in mixed blocks so an estimate of the mixing cost is not available. The purpose of Experiment 4 was to verify that there is a mixing cost on reaction times (as reported in earlier literature) and, if so, to test whether it interferes with concurrent time productions.

Experiment 4

Two main conditions were compared in Experiment 4: a *mixed-sequence condition* and a *pure-sequence* condition. As in Experiments 1, 2, and 3, task sequences involving a switch (memory-classification and classification-memory- MC and CM) were mixed with task sequences not involving a switch (memory-memory and classification-classification- MM and CC) within blocks of trials in the mixed-sequence condition. In the pure-sequence condition, blocks of trials were composed of no-switch trials only (MM or CC), so that blocks of trials included only MM or only CC trials. In an experimental session, all blocks were mixed in the mixed condition and all blocks were pure in the pure condition. The main comparison of interest concerned no-switch trials (MM and CC) in pure and mixed conditions: task uncertainty and the need of task resource coordination were present in no-switch trials in the mixed condition, but absent in the pure condition.

The comparison between pure and mixed conditions was made separately in no-switch trials with the memory task (MM) and with the digit classification task (CC). In no-switch MM trials, the pure and mixed conditions only differed in terms of uncertainty about the task to be performed in the sequence and as a result of this uncertainty, of demands in task coordination. In MM trials of both pure and mixed conditions, memory search was followed by memory search, so a set of items had to be memorized at the beginning of each trial. In contrast, in CC trials, participants had to memorize items at the beginning of trials in the mixed condition only since in that condition, no-switch CC trials were mixed with switch (MC or CM) trials. There was no memory set presented in CC trials of the pure condition to eliminate any possible uncertainty about the task to be performed. Therefore, in MM trials, task uncertainty and task resource coordination were present in the mixed condition, but not in the pure condition. In CC trials, task uncertainty, task resource coordination and memory load were present in the mixed condition, but not in the pure condition. Consequently, any difference in MM trials between reaction times to S2 or between time productions in the pure and mixed conditions would reflect effects of task uncertainty and task resource coordination. In CC trials, a difference between RT2 or between produced intervals in the pure and mixed conditions could be caused not only by task uncertainty and demands in task coordination, but also by memory demands.

Method

Participants. Twenty-three participants, 16 women and 7 men (mean age = 20.7, *SD* = 2.0) completed this experiment. Thirteen participants were randomly assigned to the reaction-time condition, 10 to the time-production condition.

Apparatus and stimuli. The apparatus and stimuli were identical to those in Experiments 1, 2 and 3.

Procedure. There were three experimental sessions in the reaction-time condition, two sessions in the pure-sequence condition (one session with MM trials only and one session with CC trials only) and one session in the mixed-sequence condition (with MM, CC, MC and CM trials). The two sessions in the pure condition were completed successively in counter-balanced order, with half of the participants beginning with MM trials, the other half beginning with CC trials. In order to eliminate any possibility of uncertainty about the task to be executed in the pure-sequence condition, this condition was always tested before the mixed-sequence condition. The participants were therefore tested in the pure-sequence condition in the first two sessions, and in the mixed-sequence condition in the third session. Each of the first two sessions in the pure-sequence condition included 48-trial practice block followed by three 48-trial experimental blocks of trials. The third session (in the mixed condition) included one 48-practice block of trials followed by six experimental 48-trial blocks. There was no feedback on memory or classification performance in practice trials.

In the time-production condition, there was a first practice session which included demonstration trials followed by time production practice trials: there were five demonstration trials followed by four 48-trial blocks of time production with feedback, and then one 48-trial block of time production without feedback. After this first session, there were four experimental sessions, two sessions in the pure-sequence condition (Sessions 2 and 3) with concurrent time production, two sessions in the mixed-sequence condition (Sessions 4 and 5) with concurrent time production. In each experimental session (Sessions 2, 3, 4, and 5), there were, successively: one 24-trial block of practice of time production alone with feedback, one 24-trial block of practice of time production alone without feedback, one 24-trial practice block of task sequences (with no concurrent time production as in the reaction-time condition). These blocks were followed by one 24-trial practice block of task sequences with concurrent time production. The three experimental blocks were then performed, each of these blocks including 48-trial experimental blocks of task sequences with concurrent time production. Overall, there were four practice blocks followed by three experimental blocks of trials in Sessions 2, 3, 4 and 5; only data from trials in these three experimental blocks were included in statistical analyses. In the time-production condition, pure sequences with the memory task only or the digit task only were used in Sessions 2 and 3, these two sessions being completed in counter-balanced order. Mixed sequences were used in Sessions 4 and 5; these sessions were always completed after the pure-sequence sessions (Sessions 2 and 3). There was no feedback on performance in task-sequence practice trials, as in the reaction-time condition.

To ensure that the participants understood well the specific task to be performed in the various types of blocks, a brief message was displayed on the screen ("Please fetch the experimenter.") just before the block of practice task-sequence trials, and just before the block of practice trials of task-sequence with concurrent time production. When the message appeared, the participant opened the door of the testing room and the experimenter, who was next to the door, entered to verify whether the participant understood well the next task to be performed. The message remained present on the screen until the experimenter pressed the space bar to resume the experiment.

All other aspects of the procedure, target interval, feedbacks, pauses between blocks of trials, were identical to those in Experiments 1, 2, and 3. Each experimental session lasted between 30 and 45 minutes.

In the both the reaction-time and time-production conditions, each participant performed 144 experimental trials in the pure-sequence memory task condition (MM trials), 144 experimental trials in the pure-sequence digit task condition (CC trials) and 288 experimental trials in the mixed-sequence condition (MM, CC, MC, CM trials).

Results

The main comparisons of interest in the time-production condition were 1) between no-switch trials in the pure condition and no-switch trials in the mixed condition, the comparison being made separately for MM trials and CC trials, 2) between switch trials and no-switch trials in the mixed-sequence condition. Contrasting performance in MM trials of the pure and mixed conditions allowed us to verify whether task uncertainty and task resource coordination affect concurrent timing: in that case, produced intervals should be longer in MM trials of the mixed condition than in the pure condition. Contrasting performance in CC trials of the pure and mixed conditions allowed us to examine the effect of adding memory load to task uncertainty and task resource coordination on concurrent timing. The test of difference between switch and no-switch trials in the mixed condition was the same as the tests of differences in switch and no-switch trials in Experiments 1, 2, and 3, and permitted to test whether switching from one task to another interfered with timing. In the reaction-time condition, the same comparisons as those performed in the time-production condition were carried out on RT2.

Tests were therefore computed on data in no-switch trials to compare performance in the pure- and mixed-sequence conditions. In the time-production condition, differences in produced intervals and in percent errors in responding to S2 were tested in MM, and then in CC trials. In the reaction-time condition, the same tests were performed on reaction times and errors in responding to S2. Furthermore, ANOVAs were carried out as in Experiment 3 in order to test the effects of switching and of memory search in the mixed-sequence condition. In both the reaction-time and time-production conditions, ANOVAs were performed on reaction times and on errors in responding to S1 to verify the effect of set size on performance.

Because Experiment 4 was specifically designed to test the difference between no-switch trials in pure- and mixed-sequence conditions, results pertaining to this difference are presented first. Analyses testing the effect of a task switch in Experiment 4 are then presented.

Finally, an omnibus ANOVA using data from all experiments of the present study was performed. Merging the relevant data from all experiments increases statistical power considerably, which might reveal a general effect of a task switch on time productions that could not be detected in each experiment considered separately. The difference between produced intervals in switch and no-switch trials in all experiments was therefore tested, as were errors in responding to S2 in the time-production conditions. The same tests were carried out on corresponding measures in the reaction-time conditions of the four experiments, RT2 and errors in responding to S2.

Figures 5a and 5b about here

Effect of pure/mixed sequence - Reaction-time condition. Errors in responding to S1 and S2 represented 3.5% and 4.9% errors respectively, and there were 1.8% and 1.6% of outliers in the remaining responses to S1 and S2 respectively.

Figure 5a shows RT2 in no-switch MM trials, in the pure- and mixed-sequence conditions. Reaction times to S2 were longer in the mixed than in the pure condition, $F(1, 12) = 4.90$, $p = .05$, MSE = 1610, $\eta^2_p = .29$. In those MM trials, percent errors in responding to S2 were not different in the mixed ($M = 6.2\%$) and in the pure ($M = 4.9\%$) conditions, $F(1, 12) = 2.08$, $p = .17$, MSE = .001, $\eta^2_p = .148$.

In no-switch CC trials, mean RT2 was significantly shorter in the pure than in the mixed condition as shown in Figure 5b, $F(1, 12) = 14.99$, $p = .002$, MSE = 514, $\eta^2_p = .56$. In those CC trials, there were also more errors in responding to S2 in the pure ($M = 4.9\%$) than in the mixed ($M = 1.1\%$) condition, $F(1, 12) = 20.15$, $p = .001$, MSE = .001, $\eta^2_p = .63$.

Effect of pure/mixed sequence - Time-production condition. Because of errors in memory search or digit classification, 5.7% of the trials with responses to S1 and 3.1% of the trials with responses to S2 were eliminated. Outliers, representing 1.5% and 0.4% of the remaining data in responses to S1 and S2 respectively, were then eliminated.

As shown in Figure 6a, time productions in no-switch MM trials did not differ in the pure- and mixed-sequence conditions, $F\ (1, 9) = 0.02, p = .97$, MSE = 203810, $\eta^2_p = .0001$. In those trials, percent errors in responding to S2 tended to be higher in the mixed- ($M = 6.4\%$) than in the pure-sequence (4.4%) condition, but this effect did not reach statistical significance $F(1, 9) = 4.92, p = .054$, MSE = .0001, $\eta^2_p = .35$.

In contrast, in CC trials, time productions were longer in the mixed- than in the pure-sequence condition as shown in Figure 6b, $F(1, 9) = 22.21, p < .001$, MSE = 41728, $\eta^2_p = .71$. There were very few errors in responding to S2 in those CC trials, but the percentage of errors was significantly higher in the pure- ($M = 0.5\%$) than in the mixed-sequence ($M = 0.0\%$ - no error) condition, $F(1, 9) = 7.21, p = .025$, MSE = .0001, $\eta^2_p = .45$.

Figures 6a and 6b about here

Figures 7a and 7b about here

Effect of a task switch in mixed-sequence condition – Reaction-time condition. The ANOVA on RT2 confirmed that RT2 increased with increasing set size as shown in Figure 7a, $F(2, 24) = 50.59, p < .001$, MSE = 283, $\eta^2_p = .81$, and was longer in switch than in no-switch trials, $F(1, 12) = 127.71, p < .001$, MSE = 1798, $\eta^2_p = .91$. Mean RT2 was 698 ms in switch and

590 ms in no-switch trials, for a switch cost of 108 ms. Mean RT2 was 661 ms at set size = 6, 617 ms at set size = 2, for an overall cost of memory processing of 44 ms. The interaction between task switching and memory set size was nonsignificant, $F(2, 24) = 2.53$, $p = .101$, MSE = 465, $\eta^2_p = .17$.

An ANOVA on percent errors in responding to S2 was performed with two within subjects factors, memory-set size and switch/no-switch. Percent errors increased with set size, $F(2, 24) = 12.79$, $p < .001$, MSE = .001, $\eta^2_p = .52$, and were higher in switch than in no-switch trials, $F(1, 12) = 6.62$, $p = .02$, MSE = .004, $\eta^2_p = .36$ (7.4% and 3.6% and in switch and no-switch trials respectively). The interaction between the two factors was significant, $F(2, 24) = 5.48$, $p = .01$, MSE = .001, $\eta^2_p = .31$. Tests of simple main effects showed that errors increased significantly with set size in no-switch trials ($p < .001$), but not in switch trials ($p = .18$); percent errors were, at set size = 2, 4, and 6 respectively, 1.0, 2.3, 7.5% in no-switch trials, 7.0, 6.7, 8.7% in switch trials. As in Experiment 3, the interaction shows that the percentage of errors was especially low when the set size was relatively small (2 or 4 items), in no-switch trials.

The usual effect of set size was found on RT1 (636, 670, 702 ms at size = 2, 4, and 6, respectively), $F(2, 24) = 26.01$, $p < .001$, MSE = 562, $\eta^2_p = .68$. Percent errors in responding to S1 also increased with set size (2.7, 3.9, 6.8% at size = 2, 4, and 6), $F(2, 24) = 7.60$, $p = .003$, MSE = .001, $\eta^2_p = .39$.

Effect of a task switch in mixed-sequence condition – Time-production condition. Mean produced intervals are shown as a function of memory-set size in switch and no-switch trials in Figure 7b. The repeated-measures ANOVA showed that produced intervals lengthened significantly with increasing set size, $F(2, 18) = 16.75$, $p < .001$, MSE = 8767, $\eta^2_p = .65$, but did not differ in switch and no-switch trials, $F(1, 9) = 1.28$, $p = .29$, MSE = 2187, $\eta^2_p = .13$. The interaction between set size and switch/no-switch was also nonsignificant, F (2, 18) = .74, p = .49, MSE = 2969, η^2_p = .08.

The repeated-measures ANOVA on percent errors in responding to S2 with set size (2, 4, 6) and switch/no-switch factors showed that errors increased with set size (0.9, 2.6, 5.6% at set size = 2, 4, and 6, respectively), F(2,18) = 11.50, p = .005, MSE = .001, η^2_p = .56. Neither the switch/no-switch factor (3.2% and 2.9%, for switch and no-switch trials, respectively), F(1,9) =.15, p = .71, MSE = .001, η^2_p = .02, nor the interaction between set size and task switch, F(2,18) = .956, p = .40, MSE = .001, η^2_p = .10, were significant.

RT to S1 increased significantly with increasing set size (645, 674, 704 ms at set size = 2, 4, and 6, respectively), F(2, 18) = 28.54, p < .001, MSE = 296.8, η^2_p = .76. This result shows that increasing set size has the usual effect on reaction times to S1. Errors also increased significantly with increasing set size (3.8, 4.9, 7.2% at set size = 2, 4, and 6, respectively), F(2, 18) = 3.64, p =.05, MSE = .001, η^2_p = .29, as confirmed by an ANOVA on percent errors in responding to S1, with set size as single factor.

In the practice session, mean intervals produced in the three blocks with feedback and in the block without feedback were respectively 1977 ms (*SD* = 210) and 2197 ms (*SD* = 360). In experimental sessions, mean intervals produced in the block of practice trials with feedback and the practice block without feedback were respectively 2022 ms (*SD* = 224) and 2288 ms (*SD* = 399).

Omnibus ANOVAs - Effect of a task switch – Time-production and Reaction-time conditions

The difference between mean intervals produced in switch and no-switch trials of the four experiments was tested, including produced intervals from the 41 participants of the present study. The repeated-measures omnibus ANOVA showed that general means of produced intervals did not differ in switch and no-switch trials (2962.5 and 2964.4 ms in switch and no-switch trials respectively), $F(1, 40) = 0.08$, $p = .78$, MSE = 920.20, $\eta^2_p = .002$. Accuracy in responding to S2 was not different in switch and no-switch trials either since mean percent errors in responding to S2 did not differ (2.9 vs. 2.7% in switch and no-switch trials), $F(1, 40) = 0.03$, $p = .59$, MSE = 0.001, $\eta^2_p = .007$. In contrast, the data from the 39 participants in the reaction-time conditions showed that reaction times in responding to S2 were significantly longer in switch than in no-switch trials (752.0 vs. 659.3 ms), $F(1, 38) = 257.32$, $p < .0001$, MSE = 651.64, $\eta^2_p = .87$. There were also more errors in responding to S2 in switch than no-switch trials overall (5.8 vs. 4.0%), $F(1, 38) = 6.74$, $p = .01$, MSE = .001, $\eta^2_p = .15$.

Discussion

The objective of Experiment 4 was to verify whether task uncertainty and related task resource coordination, in no-switch trials of a mixed-sequence condition, could perturb timing. A straightforward answer to this question was provided by comparing produced intervals in MM trials, in the pure- and mixed-sequence conditions; in those conditions, task uncertainty, demands in task coordination and memory load were identical. Items had to be memorized in both pure and mixed conditions, but whereas participants had to be ready for the memory task only in the pure-sequence conditions, they also had to prepare for the digit task in the mixed-sequence condition. Time intervals produced during processing of the second target in the pure and mixed conditions did not differ, showing that timing was unaffected by task uncertainty and the corresponding requirements in task coordination. In contrast, reaction times were shorter in the pure than in the mixed condition, confirming that increased uncertainty and coordination demands led to longer reaction times.

In no-switch CC trials, produced intervals in the time-production condition as well as reaction times to the second stimulus in the reaction-time condition were longer in the mixed- than in the pure-sequence condition. In the mixed condition, a memory set was presented at the beginning of each trial, but not in the pure-sequence condition. Although searching the memory set was not required in no-switch CC trials, there could have been some processing of memory items as suggested by longer reaction times and time productions in the mixed condition. Longer time productions are consistent with the interfering effect of increasing memory load on concurrent timing found here in Experiment 3 as well as in previous studies on timing (e.g., Fortin & Breton, 1995; Fortin & Massé, 1999; see also Fortin, 1999, for a review).

In the reaction-time as well as in the time-production condition, response times (RT2 and time productions) to the second stimulus were longer in the mixed than in the pure condition in CC trials, but there were more errors in the pure than in the mixed condition in those trials. This suggests that when digit classification was performed twice in succession with no memory load, the participants adopted a fast mode of responding, leading to a greater number of errors. This was especially true in the reaction-time condition since in the time-production condition, there was no temporal pressure to respond as quickly as possible. This may explain why in the time-production condition, the percentage or errors was extremely low (0.25% on average).

Comparing performance in switch and no-switch trials in the mixed-sequence condition allowed us to replicate the distinction found in Experiment 3 between effects of memory search and a task switch on concurrent time production. As in Experiment 3, produced intervals were lengthened by increasing load in memory search, but not by a task switch. This result is especially interesting since the increase in reaction times caused by switching is undoubtedly produced by an executive function. This confirms that in the present study, switching between memory search and digit classification did not disturb concurrent timing whereas a less demanding manipulation in terms of processing times, increasing set size in memory search, affected timing.

The main results in the reaction-time condition are identical to those in Experiment 3. Reaction times to the second stimulus increased as memory load increased, and were longer in switch than in no-switch trials, showing that the paradigm was used successfully to induce comparable costs of switching and of increasing memory load.

As in Experiment 3, errors in responding to the second stimulus increased with set size in the reaction-time condition, the increase in errors being stronger in no-switch than in switch trials: errors were especially low when the memory set included fewer items in no-switch trials. This may possibly be due to some consolidation of memory representations when a small set is searched in memory, hence the very low percentage of errors in the second search. As in Experiment 3 however, the most important result concerning the objectives of the present study was that there was no effect of switching, and no interaction involving the switch factor on errors in responding to the second stimulus in the time-production condition. This shows again that in the time-production condition, neither produced intervals nor errors in processing the second stimulus during the interval production were influenced by a task switch.

Finally, time productions did not differ in switch and no-switch trials when time production data from the four experiments were analyzed in an omnibus analysis of variance, confirming that timing was not perturbed by switching between memory search and digit classification.

General Discussion

Our main hypothesis was that a switch cost would be observed on timing when a task switch takes place during a concurrent time interval production. More specifically, in accordance with accumulator models of time estimation integrating attentional control, it was predicted that produced intervals would be longer when there was a task switch during the interval than when there was no task switch. In the four experiments of the present study, there was no switch cost on timing since productions did not differ in switch and no-switch trials. In contrast, as in previous studies (e.g., Fortin & Rousseau, 1987; Fortin, Champagne, Poirier, 2007), increasing load in concurrent memory search led to a regular and significant lengthening of produced intervals. Given that the time cost of a task switch and of increasing set size in memory search were comparable in reaction time conditions, we can conclude that there was a clear distinction between effects of a task switch and of memory search on concurrent timing in the present study, suggesting a dissociation between cognitive resources used in memory search and task switching in regard to timing.

This conclusion concerns the specific process of switching from one task to another since the critical comparison was between switch and no-switch trials in otherwise identical conditions. Besides, although this comparison reveals a distinction between effects of memory search and of switching on timing in the present study, they do not imply of course that timing could never be perturbed by processes related to task switching in other experimental conditions.

One variant of task switching requires switching between naming colors and naming words in the Stroop task (see, e.g., Allport, Styles, & Hsieh, 1994; Yeung & Monsell, 2003). Interference from switching between color and word naming on timing was reported recently (Zakay and Block, 2004). From the brief summary given of the procedure and analysis, it seems that several differences may explain why interference was found in that study but not in the present study. For example, in the study summarized by Zakay and Block (2004) time was estimated throughout a 12-s experimental trial during which word and color naming were performed repeatedly, whereas in the present study, a single response was provided during a time production of about three seconds in the present study. It is known that estimation of short (i.e., less than around 5 seconds) and long time intervals seem to involve different processes (Fraisse, 1984; Pöppel, 1988). Moreover, performing the Stroop task repeatedly for long intervals may be more attention demanding than our tasks and make participants more sensitive to additional demands imposed by a switch. Finally, in one condition in which interference between switching and timing was found with the Stroop task, bivalent stimuli (stimuli used in both tasks) were used, whereas the stimuli in the present study were univalent (digits in the digit task and letters in the memory task). This raises the possibility that it might be easier to observe interference between timing and switching with bivalent stimuli, which leads generally to higher switch costs (Monsell, 2003). Note however that interference between timing and the easy version of the Stroop task was also reported by Zakay and Block (2004). In their study, the easy version was equivalent to a switch condition with univalent stimuli.

Although using other task switching paradigms and other timing tasks might generate interference between switching and timing, contrasting effects of switching and of memory search yielded an unambiguous finding in the present study: approximately equal time costs in a task switch and memory processing led to radically different patterns of interference with producing short time intervals. Produced intervals were unaffected by a task switch whereas increasing memory load in item recognition regularly lengthened concurrently produced intervals. The lengthening of time productions with increasing concurrent demands is predicted by accumulator models of time estimation integrating attentional control. In such models, when a time interval is produced, temporal information is accumulated. Interfering operations interrupt temporarily the accumulation, which delays the moment when the subjective target duration to be produced is reached (Brown, 1997, 2006; Coull et al., 2004; Gibbon, Church, & Meck, 1984; Lejeune, 1998; 2000; Zakay & Block, 1996). As in previous studies (e.g., Fortin & Rousseau, 1987; Fortin, Champagne, Poirier, 2007), the results of Experiments 3 and 4 suggest that memory search systematically interrupts timing: increasing memory load lengthened produced intervals, a result accounted for by an interruption/accumulation interpretation. In contrast, intervals did not differ in switch and no-switch trials, suggesting that a task switch could be performed in parallel with timing. It can therefore be concluded that memory search interrupts timing but that a task switch does not. Although task switching may be considered similar to searching for items in memory because a task switch implies identifying and activating a different rule (e.g., Rabbit & Vyas, 1973) or a different pathway (e.g., Dreher & Grafman, 2003) in memory, its impact on concurrent timing is definitely different from that of memory search.

The distinction between effects of memory search and a task switch on timing in the present study is relevant to the issue of distinguishing executive control processes contributing to performance in memory search tasks. Using event-related fMRI, two categories of processes were dissociated in a working memory task: load-related mnemonic processes and nonmnemonic executive control processes (Postle, Berger & D'Esposito, 1999). In Postle et al.'s study, two tasks were compared. The first one consisted in identifying positions of letters in working memory and thus involved mnemonic processes. The other task also required identification of position but included an additional requirement of reordering memory items in alphabetical order. This specific alphabetization component of the task did not impose any memory load but involved control processes contributing to working memory function. Regions activated by mnemonic processes and by alphabetization were dissociated, mnemonic processes being primarily posteriorly mediated, and nonmnemonic executive control processes being primarily prefrontal cortex-mediated. More precisely, left perisylvian cortex showed sensitivity to load in the mnemonic task whereas dorsolateral prefrontal cortex showed specific sensitivity to alphabetization.

Similarly, Smith & Jonides (1999) distinguished mnemonic functions in item recognition from a set of executive processes such as scheduling processes in management of complex tasks, which requires switching focused attention between tasks. They noted that although executive processes often operate on short-term memory content, mnemonic functions and executive processes may be dissociated since neurological patients may have intact short-term memory functions but impaired executive processes and vice versa. In their review of neuroimaging studies using positron emission tomography (PET) or fMRI, they conclude that regions activated for short-term memory functions and for executive processes such as task switching differ. Regions activated in memory tasks differ depending on the type of information (verbal material, spatial information, object information) but task management specifically activated the dorsolateral prefrontal cortex.

Results of the present study provide a strong behavioral demonstration of a distinction between load-related memory functions and of a task switch, a nonmnemonic executive control process. This key finding contributes to define the specific attentional resources required in timing tasks. In fact, although attentional models of timing are supported by numerous studies showing interference between attention and timing tasks, attentional processes responsible for interference effects remain relatively unidentified. In a systematic analysis of concurrent temporal and nontemporal dual-task studies, Brown (2006) concluded that executive-level tasks seem especially likely to generate interference on concurrent timing. This conclusion was supported by results showing a robust interference effect between random number generation and timing. As noted by Brown, similarities between processes in both tasks may indeed be identified since they both emphasize ordering and sequencing. Our results show however that drawing general conclusions about interference between executive processes and timing may be premature, mostly because of the variety of processes associated to executive control. For example, in a study which specifically addressed the issue of diversity of executive functions, evidence for separability of random number generation and task switching was found (Fisk & Sharp, 2004; Miyake, Friedman, Emerson, Witzki, Howerter & Wager, 2000). This could explain why producing 5-s intervals was disturbed by random number generation (Brown, 2006), but that time production was not perturbed by a task switch in the present study.

A number of factors contribute to the fact that produced intervals in dual-task trials are notably longer than the 2-s target duration to be produced in the present study. First, there was no feedback on temporal accuracy in experimental trials; producing time intervals with no feedback generally result in intervals longer than target durations. This could be noticed, in the present study, in trials of practice of time production alone, with no dual task, performed at the beginning of experimental sessions. In the four experiments of the present study, mean intervals in those trials with no feedback were, on average, 2131 ms. When performed at the end of an experimental session, these productions are even longer because of the “lengthening effect”, the tendency of temporal productions to become longer across trials (e.g., Brown, 1997; Hicks & Allen 1979). Data from recent experiments in our laboratory showed this effect in single-task time production trials with no feedback. In two experiments, intervals produced at the beginning and at the end of experimental sessions were, on average, 2348 and 2656 ms respectively, but the target interval to be produced was two seconds as in the present experiment (Gaudreault & Fortin, manuscript in preparation).

Performing a concurrent task during a time interval production results in a general lengthening of produced intervals, the interference effect. This nonspecific cost of concurrency is often observed when one task such as random number generation (Brown, 2006), mental arithmetic (Brown, 1997), or memory search (Fortin & Massé, 1999) is interpolated in time interval production (see Brown, 1997, p. 1468, for a discussion). This is attributed to some distraction of attention from timing by the specific operations required in the task, the general requirements of the interpolated tasks, and by the need to coordinate operations in the temporal and nontemporal concurrent tasks. These demands, including executive demands related to task coordination, would interrupt timing, resulting in relative loss of temporal information accumulated during the interval production. Because of this loss, the participant must wait for a longer duration to reach the target interval to be produced, hence longer produced intervals. The present study shows that in addition to this general cost of concurrency, increasing memory load lengthens time productions further, but a task switch does not.

A noteworthy contribution of the present study is to demonstrate that timing may be used successfully to distinguish among working memory functions. In effect, searching a set of verbal items in memory and task switching are both working memory functions, but they obviously do not interact in the same way with timing. This differential sensitivity of timing could be exploited in order to analyze the issue of separability of executive functions. Recent evidence reveals separability of some executive processes, in particular of switching, updating and inhibition (e.g., Fisk & Sharp, 2004; Miyake, Friedman, Emerson, Witzki, Howerter & Wager, 2000). The clear distinction between memory search and task switching found in the present study implies that timing tasks might prove to be extremely useful in addressing the nature and function of the central executive, a critical issue in current research on working memory (Baddeley, 2007).

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Figure Captions

Figure 1. Experiment 1. An experimental trial in the reaction-time (1a) and in the time-production (1b) conditions. Three consonants were presented (1/s), followed by “Ready”. The participant pressed the “0” key when ready to see the first stimulus (S1). Five hundred ms later, S1 appeared. The participant responded as quickly as possible to S1, by pressing one of two keys depending on the response in the memory or digit task (RT1 in the reaction-time condition in Figure 1a, RT in the time-production condition in Figure 1b). Eight hundred ms after the first response (RT1 in the reaction-time condition or RT in the time-production condition), a second stimulus (S2) appeared. The participant responded as quickly as possible to this stimulus in the reaction-time condition by pressing one of two keys in the reaction-time condition (RT2). In the time-production condition, the participant also responded by pressing one of two keys, but only when he/she judged that the tone, started 400 ms before S2 onset, had reached its target duration; this was the time production (TP). A row of asterisks then appeared, marking the beginning of the next trial.

Figure 2. Experiment 1. Figure 2a) Mean reaction times to the second stimulus in switch and no-switch trials. Error bars represent the SEM computed with the MSE. Figure 2b) Mean produced intervals in switch and no-switch trials.

Figure 3. Experiment 2. Figure 3a) Mean reaction times to the second stimulus in switch and no-switch trials. Error bars represent the SEM computed with the MSE. Figure 3b) Mean produced intervals in switch and no-switch trials.

Figure 4. Experiment 3. Figure 4a) Mean reaction times to the second stimulus as a function of memory-set size, in switch and no-switch trials. Error bars represent the SEM computed with the

MSE. Figure 4b) Mean produced intervals as a function of memory-set size, in switch and no-switch trials.

Figure 5. Experiment 4 – Reaction-time condition: Figure 5a) Mean reaction times to the second stimulus in MM (memory search followed by memory search) no-switch trials. Figure 5b) Mean reaction times to the second stimulus in CC (digit classification followed by digit classification) no-switch trials. Error bars represent the SEM computed with the MSE.

Figure 6. Experiment 4 – Time-production condition: Figure 6a) Mean produced intervals in MM (memory search followed by memory search) no-switch trials. Figure 6b) Mean produced intervals in CC (digit classification followed by digit classification) no-switch trials. Error bars represent the SEM computed with the MSE.

Figure 7. Figure 7a) Mean reaction times to the second stimulus as a function of memory-set size in switch and no-switch trials. Error bars represent the SEM computed with the MSE. Experiment 4. Figure 7b) Mean produced intervals as a function of memory-set size, in switch and no-switch trials.

Figure 1a) Reaction-time condition

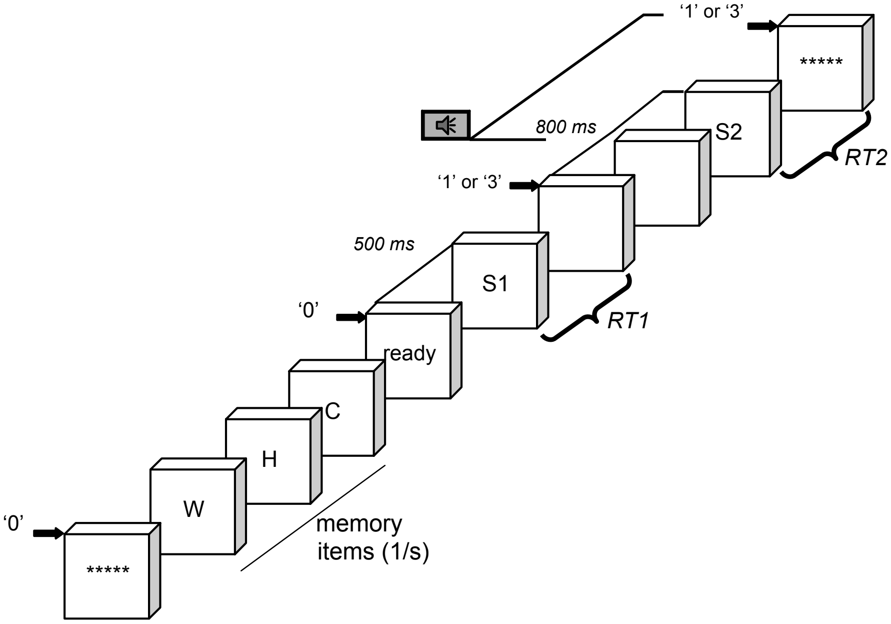
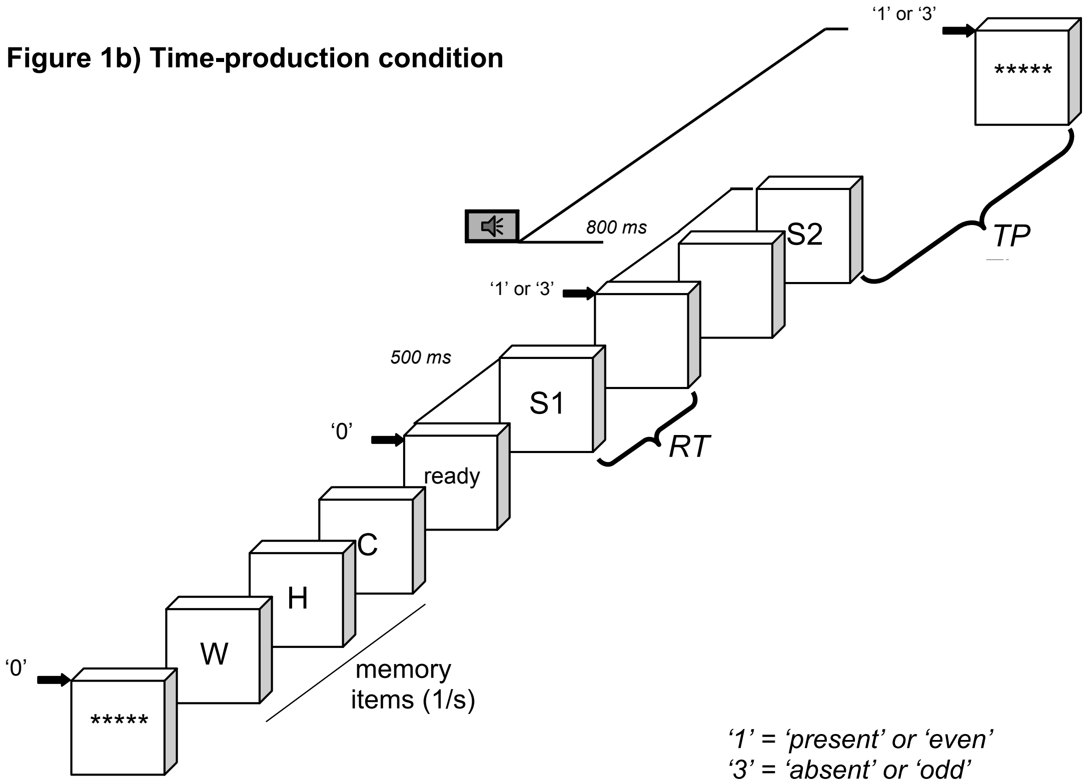


Figure 1b) Time-production condition



'1' = 'present' or 'even'
'3' = 'absent' or 'odd'

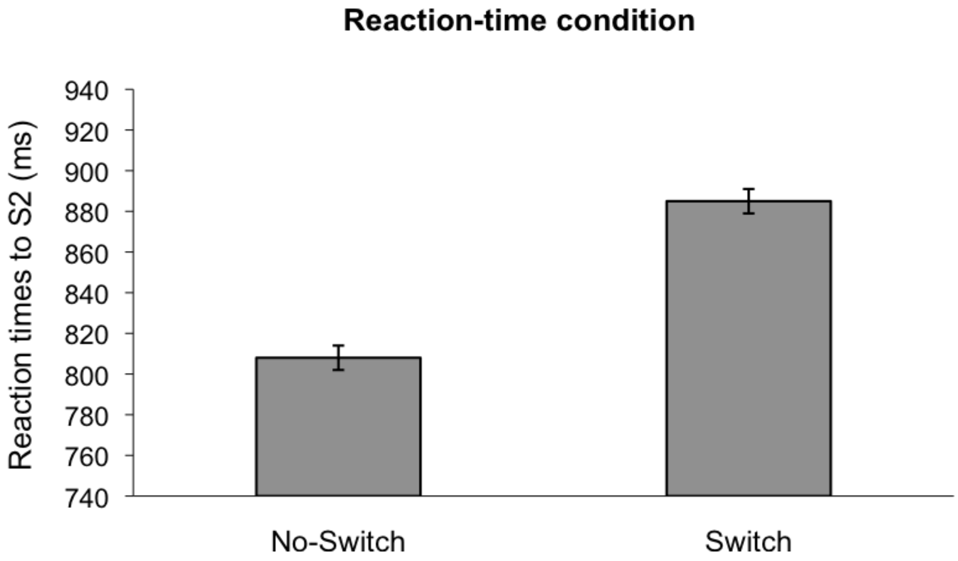


Figure 2a

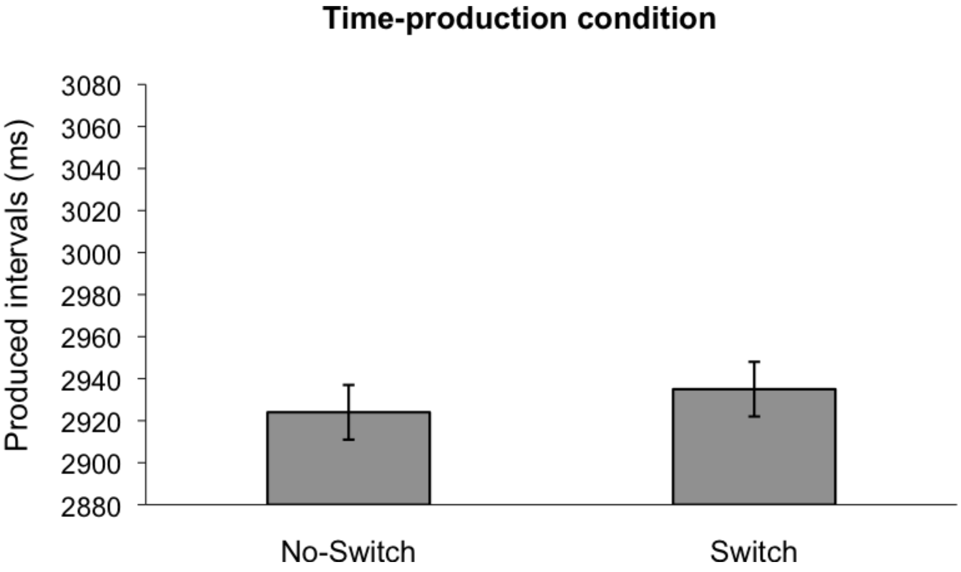
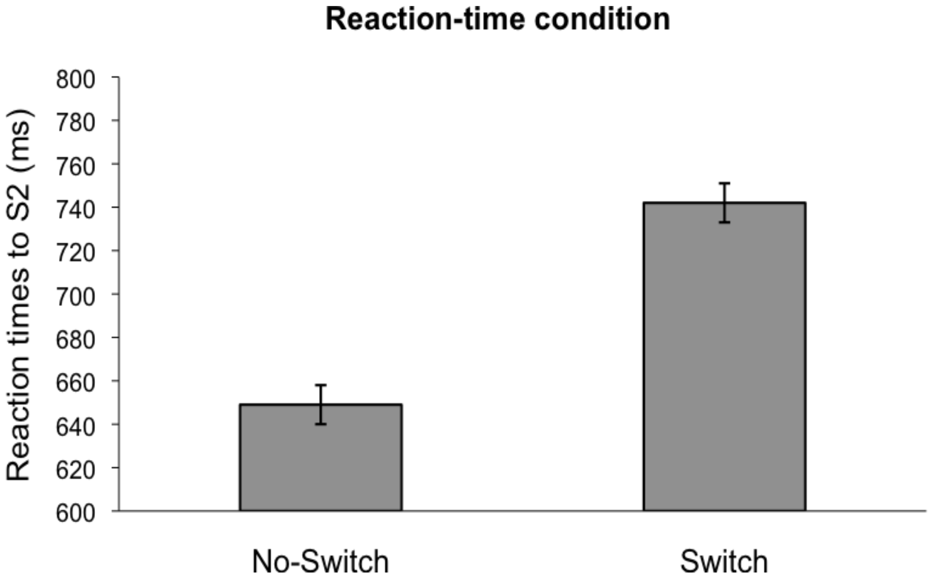


Figure 2b



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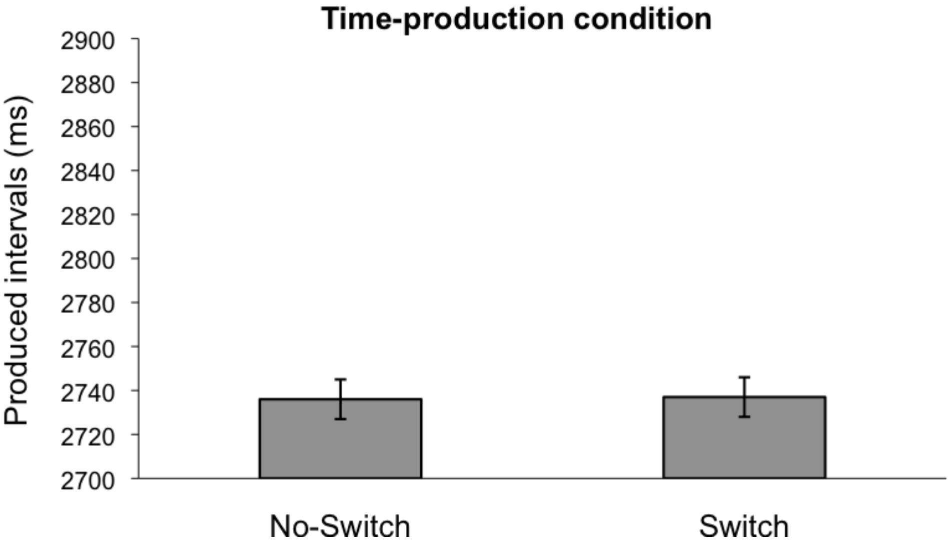

Figure 3b

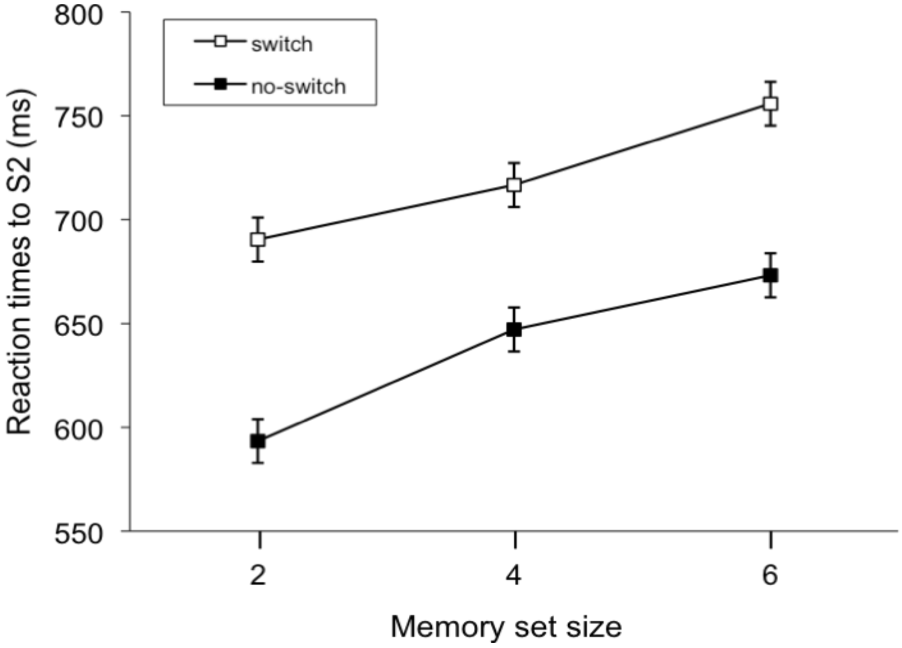

Figure 4a

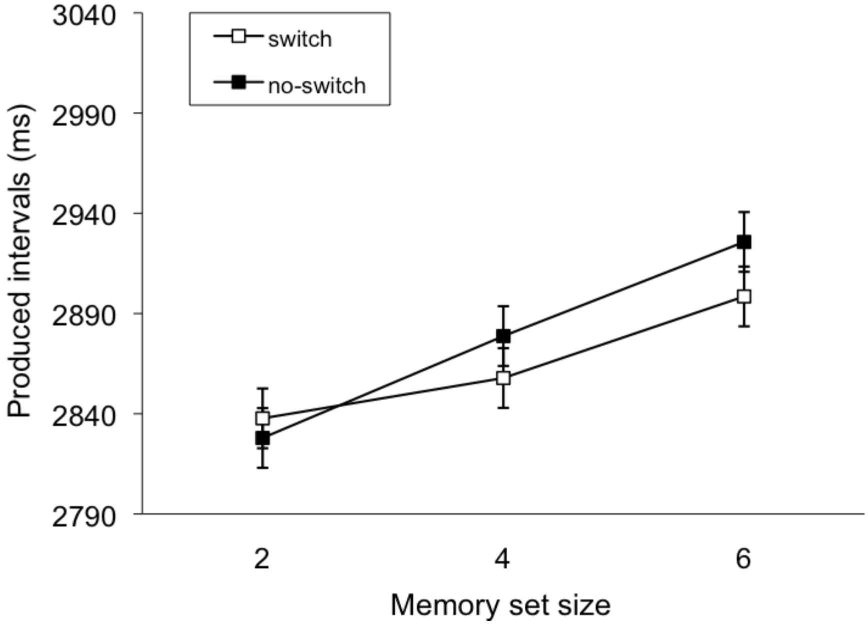

Figure 4b

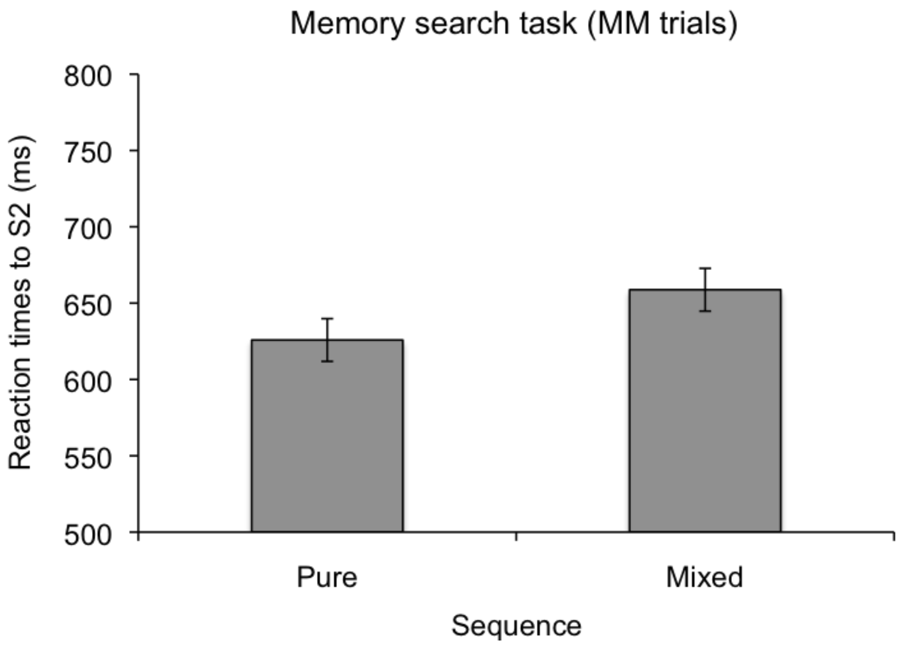

Figure 5a

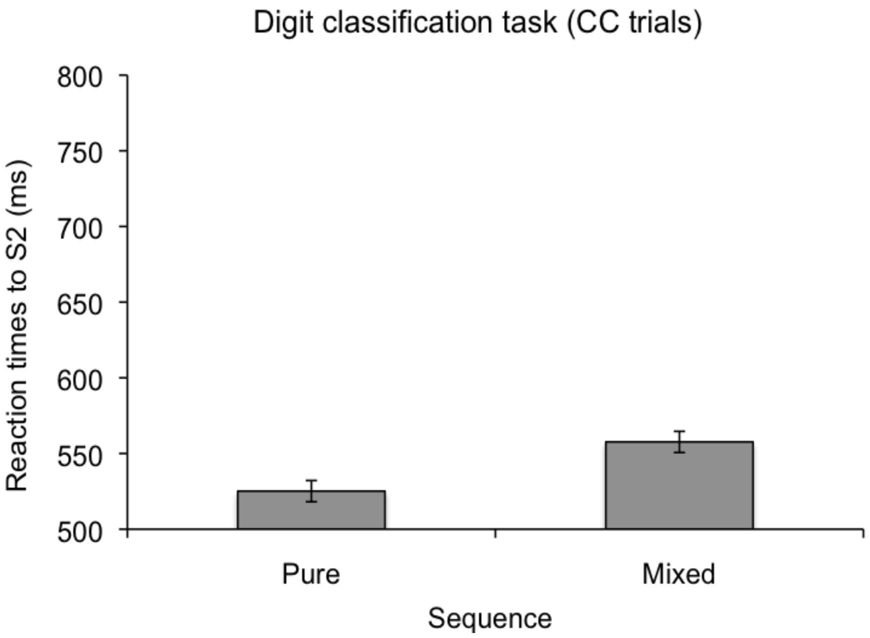

Figure 5b

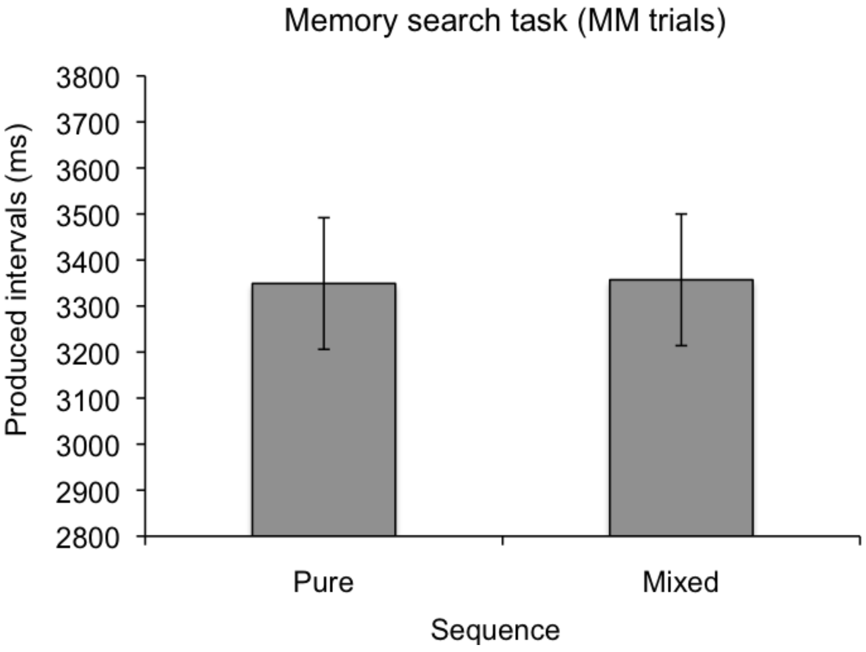

Figure 6a

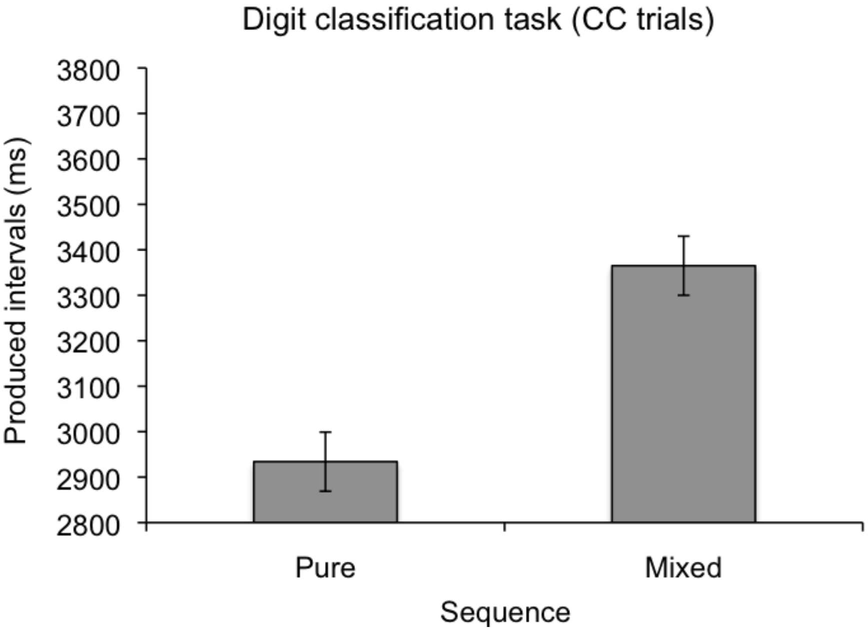

Figure 6b

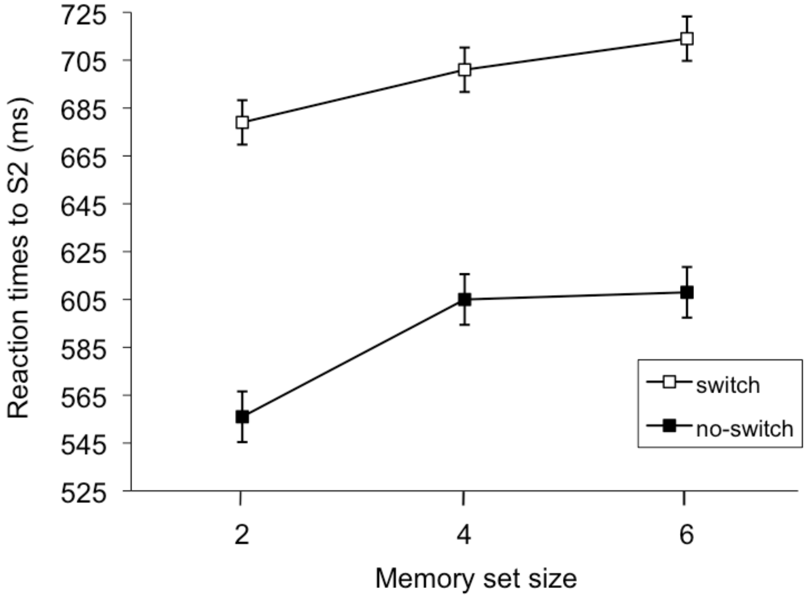

Figure 7a

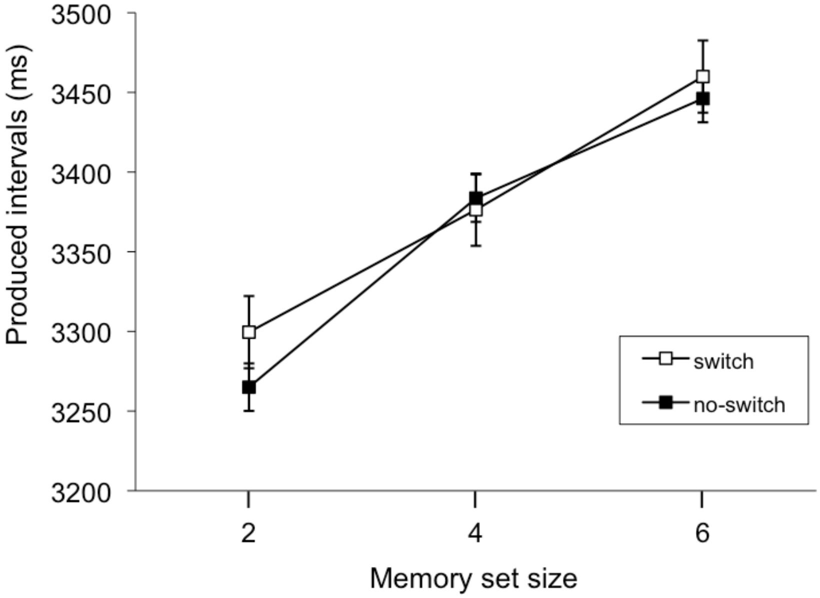

Figure 7b