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# Working Memory Costs of Task Switching

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Liefooghe, Baptist; Barrouillet, Pierre Noël; Vandierendonck, André; Camos, Valérie

# Working Memory Costs of Task Switching

Baptist Liefooghe
Ghent University

Pierre Barrouillet
Université de Genève

André Vandierendonck
Ghent University

Valérie Camos
Université de Bourgogne and Institut Universitaire de France

Although many accounts of task switching emphasize the importance of working memory as a substantial source of the switch cost, there is a lack of evidence demonstrating that task switching actually places additional demands on working memory. The present study addressed this issue by implementing task switching in continuous complex span tasks with strictly controlled time parameters. A series of 4 experiments demonstrate that recall performance decreased as a function of the number of task switches and that the concurrent load of item maintenance had no influence on task switching. These results indicate that task switching induces a cost on working memory functioning. Implications for theories of task switching, working memory, and resource sharing are addressed.

*Keywords:* task switching, working memory, resource sharing, complex span tasks

An important aspect of cognitive control is our capability to flexibly allocate attention to several activities at the same time and to swiftly reallocate attention from one activity to another in a minimum of time. Although we can think of daily examples reflecting this flexibility (e.g., writing an article and switching attention to a telephone call, Monsell, 2003), performance during task switching is inferior compared with the performance during task repetition. Indeed, task switching is associated with longer latencies and higher error rates, which is known as the task *switch cost* (Allport, Styles, & Hsieh, 1994; Jersild, 1927; Meiran, 1996; Rogers & Monsell, 1995).

While the effect of task switching on general performance measures has been extensively studied, the impact of task switching on working memory functioning remains underspecified. This is a rather surprising state of affairs because, on the one hand, several accounts of task switching have postulated working memory processes as the main source of the switch cost (e.g., Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003; Mayr & Kliegl, 2000, 2003; Rubinstein, Meyer, & Evans, 2001), and on the other hand, switching is supposed to be a key process within working memory functioning (Barrouillet, Bernardin, & Camos, 2004; Cowan, 2005). Accordingly, the aim of the present study was to investigate the impact of task switching on working memory functioning and more precisely the effect of task switching on concurrent maintenance of information within working memory.

## Task Set Reconfiguration and Task Switching

The view of working memory functioning as the main source of the switch cost is mainly endorsed by accounts emphasizing the role of control processes in task switching. More specifically, working memory would be involved in the configuration and the maintenance of the different task settings needed to perform an upcoming task (i.e., *task set reconfiguration*; Rogers & Monsell, 1995). For instance, some authors proposed that only one task set can be present at the same time in working memory and that, in order to switch between two tasks, the relevant task set must be retrieved from long-term memory by means of executive processes and subsequently maintained in working memory (e.g., Mayr & Kliegl, 2000, 2003; Rubinstein et al., 2001), while the irrelevant task set is no longer active (Koch & Philipp, 2005; Schuch & Koch, 2003; Verbruggen, Liefooghe, Szmalec, & Vandierendonck, 2005; Verbruggen, Liefooghe, & Vandierendonck, 2006).

More direct evidence demonstrating such involvement of working memory and executive processes in task switching was reported by Baddeley et al. (2001). In a series of experiments based on the list-completion procedure (Jersild, 1927), both a verbal variant of the trials task and random letter generation interfered more with mixed lists with two tasks requiring switching than with the pure lists containing only one task and requiring no switching. As these secondary tasks typically involve executive control processes, these findings demonstrate that the central executive is involved in task switching. It has also been shown that the phonological loop is involved in the retrieval and maintenance of task sets (Emerson & Miyake, 2003; Liefooghe, Vandierendonck, Muyllaert, Verbruggen, & Vanneste, 2005; Miyake, Emerson, Padilla, & Ahn, 2004; Saeki & Saito, 2004a, 2004b) as well as in tracking sequential action plans (Bryck & Mayr, 2005). These

accounts thus converge on the assumption that working memory mediates task set reconfiguration (e.g., Mayr & Kliegl, 2000, 2003; Rubinstein et al., 2001).

Even though the view of working memory functioning as being an essential source of the switch cost has been frequently endorsed, its involvement in task switching has also been questioned. First, recent studies challenged the view that working memory is involved in the maintenance of task sets. More specifically, it has been suggested that task elements such as response codes are represented in the activated part of long-term memory rather than in working memory itself (e.g., Kiesel, Wendt, & Peters, 2007; Meiran & Kessler, 2008; Rubin & Meiran, 2005). Second, and more importantly, while accounts calling upon task set reconfiguration are prominent, it is not univocally accepted that such processes are necessary to explain switch costs. It has been demonstrated that switch costs also substantially issue from priming effects, which facilitate task repetition and interfere with task switching. Such priming effects are elicited by associations between tasks, stimuli, and responses (Allport & Wylie, 2000; Waszak, Hommel, & Allport, 2003, 2004, 2005; Wylie & Allport, 2000) or by the repetition of instructional cues indicating the task to be performed (Arrington & Logan, 2004; Logan & Bundesen, 2003, 2004; D. W. Schneider & Logan, 2005). However, although these priming accounts challenge the necessity of task set reconfiguration—and by consequence the involvement of working memory in such reconfiguration—they still recognize a more generic contribution of executive control during task switching (e.g., Allport & Wylie, 1999). On the one hand, it has been argued that switch costs cannot be explained only in terms of task set priming and that they probably arise from the interaction between task set priming and executive control processes (e.g., Gilbert & Shallice, 2002; Yeung & Monsell, 2003). For instance, Yeung and Monsell (2003) suggested that task set priming is influenced by top-down control biases, which ensure that the correct task is executed. On the other hand, D. W. Schneider and Logan (2005) suggested that while executive control may not be required on a trial-to-trial basis during task switching, it is still needed to set the cognitive system in a way that enables performance during task switching without frequent top-down intervention.

In sum, switch costs can be explained with and without task set reconfiguration, or even through the combination of both views in the assumption that switch costs consist of several components with each component having a different source (e.g., Meiran, Chorev, & Sapir, 2000; Monsell, 2003). Moreover, as we have seen, working memory related processes can play a role in these different views, albeit in a varying degree of importance. The question is thus not whether working memory is involved in task switching or not, but to what extent working memory is involved in task switching.

## Task Switching and Working Memory

Logan (2004) addressed this issue by testing the hypothesis that working memory and task switching share a single common set of resources. To that end, the task span procedure was used (Logan, 2004, 2006, 2007; D. W. Schneider & Logan, 2006). This procedure consists of two parts. In a first step, the study phase, participants have to memorize a series of task names such as *Hi–Low* (indicating a magnitude judgment, is the number greater than or less than 5?), *Odd–Even* (indicating a parity judgment, is the number odd or even?), or *Digit–Word* (indicating a form judgment, is the number a digit or a word?). In the second step, the test phase, a list of targets (a series of digits) is presented. This digit series is of the same length as the corresponding series of task names presented in the study phase. Logan (2004) compared three conditions. In the perform condition, for each digit in the target list, the corresponding task had to be performed by retrieving the task name from the memorized list and applying it to the presented digit. On the basis of this performance, the task span (i.e., the maximum number of correctly remembered and executed tasks) was calculated. In the recall condition, participants recalled the names of the corresponding tasks without applying them to the target stimulus (memory span for task names). In the control condition, participants performed the same task throughout the list of targets in the absence of a memory load. The primary finding of this research is that task spans and memory spans were equal. Importantly, conditions in which task names required task switching after every target stimulus (e.g., *Hi–Low, Odd–Even, Hi–Low, Odd–Even, Hi–Low, Odd–Even*) and conditions requiring only one task switch (i.e., *Hi–Low, Hi–Low, Hi–Low, Odd–Even, Odd–Even, Odd–Even*) yielded the same span. The latter results clearly suggest that task switching, operationalized as the number of task switches made, has no impact on working memory functioning, and Logan (2004) suggested that task switching and working memory maintenance do not share a single set of resources.

More recently, Kane, Conway, Hambrick, and Engle (2007) have reported several studies in which they investigated the connection between working memory capacity and switch costs. Although their "executive attention" theory of working memory capacity predicts such a connection (Engle, Kane, & Tuholski, 1999), they failed in four successive experiments to find any significant difference in switch costs between high- and low-span participants. The authors explained this unexpected result by suggesting that task set switching may not be the executive measure it is widely assumed to be, and they endorsed the aforementioned accounts, which claim that switch costs result from priming effects rather than from task set reconfiguration (e.g., Allport & Wylie, 2000; Logan & Bundesen, 2003). Thus, working memory capacity would not have any impact on switch cost because most task switching paradigms do not tap volitional, executive control processes.

These findings are corroborated by many correlational studies. Some of these studies reported a clear relation between task switching and working memory. Lehto (1996) reported fairly high correlations between performance on the Wisconsin Card Sorting Test (Berg, 1948)—often assumed to be a test of switching between task settings—and performance on complex span tasks such as the reading span task (Daneman & Carpenter, 1980) and the operation span task (Turner & Engle, 1989). However, Miyake et al. (2000) observed that the latent variable underpinning different measures of task switching was not related to the latent variable underlying the performance on complex span tasks. Additionally, Friedman et al. (2006) found no significant relation between task switching and measures of fluid intelligence, whereas there are well-known relations between fluid intelligence and working memory (Engle, Tuholski, Laughlin, & Conway, 1999). Thus, most of the correlational studies equally suggest an independence between task switching and working memory.

## Dual-Task Paradigms and Time Control

The above section offers a rather pessimistic perspective with respect to the possible impact of task switching on working memory functioning. However, such a conclusion is highly surprising. Of course, it could be assumed that task switching does not interfere with storage, either because task switching does not call upon working memory resources in a sufficient way (Kane et al., 2007) or because task switching and storage tax different resources (Logan, 2004). This latter view implies (a) the rejection of unitary conceptions of working memory that assume a unique resource shared between processing and storage, and (b) the adoption of a multicomponent view in which processing and storage rely on separate resources and supplies. However, the process of switching is an essential property of executive functioning (Collette & Van der Linden, 2002; Miyake et al., 2000), being referred to as the "gold-standard measure of executive control" (Kane et al., 2007, p. 35). It is thus difficult to imagine that switching could occur without central executive involvement. As a consequence, even within the multicomponent view of working memory, task switching should at least interfere with those working memory activities implicating the central executive. For example, the processes underpinning the completion of complex span tasks (performing a secondary task while maintaining items to be recalled) are known to involve the central executive, and the ensuing spans—like reading, counting, or operation spans—are usually considered as central executive measures. It can be noted that the task span procedure is akin to a complex span task (maintaining a list of tasks while performing them), and it is thus puzzling that the results issuing from this procedure did not indicate any effect of switching on performance.

One reason for this finding could reside in the procedure used. The clearest evidence for a direct relation between working memory and switching relies upon studies using selective interference procedures (e.g., Baddeley et al., 2001; Emerson & Miyake, 2003; Liefooghe et al., 2005). A common feature of such studies is the demand to perform primary and secondary tasks at virtually the same time. For instance, when Baddeley et al. (2001) combined task switching with a letter span, the participants had to encode one letter every second. In Emerson and Miyake (2003), participants had to make articulations every 500 or 750 ms. These constraints may create a tight temporal window in which the primary and the secondary tasks are forced to compete with each other, necessitating control and coordination by the central executive. Alternatively, if there are no strong temporal constraints, participants can engage in each step at their own pace and there is less need for competition because there is more time to delay some aspects of one task in order to process another task.

The importance of temporal constraints in examining the coordination of the processing and the maintenance of information has recently been stressed by Barrouillet and colleagues, who created computer-paced *continuous span tasks* in which time parameters are carefully controlled (Barrouillet et al., 2004; Lépine, Bernardin, & Barrouillet, 2005). This procedure revealed that even fairly simple tasks performed under temporal constraints could have a highly disruptive effect on concurrent maintenance (Lépine et al., 2005).

Barrouillet et al. (2004) accounted for these phenomena by proposing the time-based resource-sharing model, which suggests

a unitary view of working memory. This model assumes that both processing and maintenance of information within working memory require attention, a limited resource that must be shared. Those items of knowledge that are inside the focus of attention receive activation, but when attention is switched away, their activation suffers from a time-related decay. These memory traces can be refreshed through a covert retrieval process that requires attention (Cowan, 1995; Cowan et al., 1994). However, following Pashler (1998), it is assumed that there is a central bottleneck that constrains central processes and that attention can be allocated to only one thing at a time (Garavan, 1998; Oberauer, 2003). As a consequence, attention must be switched away from processing to refresh the decaying memory traces of the information to be maintained. Barrouillet et al. assume that this attentional switching occurs throughout processing, attention being frequently diverted for short pauses during which other items can be focused upon and memory traces refreshed. In other words, there is a time-based resource sharing through a frequent and rapid switching of attention from processing to storage. In this account, any activity that occupies attention would have a detrimental effect on storage because it impedes, at least for short periods of time, the refreshment of the decaying memory traces. More precisely, if we define the cognitive cost of a given activity as the detrimental effect it has on other activities to be concurrently performed, cognitive cost corresponds to the proportion of time during which this activity occupies attention and impedes other activities. By comparing continuous span tasks, which involve different processing tasks presented at the same computer-controlled rate, we can investigate the detrimental effect that cognitive processes have on working memory storage (Barrouillet et al., 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Gavens & Barrouillet, 2004; Lépine et al., 2005). The differences in recall performance offer a measure of the cognitive cost that investigated processes place on working memory. Thus, the present study took advantage of the continuous span task procedure to assess the cognitive cost of task switching.

## The Present Study

In the present article, we report on a series of four experiments in which the relationship between task switching and working memory was investigated. More precisely, the cognitive load of task switching was examined by incorporating task switching in a continuous span task. In each experiment, participants were presented with time-constrained tasks in which they had to switch between two digit judgments while remembering letters. The question was raised whether the number of switches impaired the concurrent maintenance of items. In Experiment 1, we compared recall performance from continuous span tasks in which participants had either to apply the same task to each target (e.g., either a magnitude or a parity judgment) or to systematically alternate between the two tasks. Experiment 2 evaluated more precisely the effect of task switching. Participants had to switch between the two tasks in both conditions, but one condition involved only a few task switches whereas the other condition involved a lot of task switches. In Experiment 3, the results of Experiment 2 were generalized to a preload procedure (Sternberg, 1967). Finally, Experiment 4 tested the hypothesis that the effect of task switching on storage is commensurate with the time during which task

switching occupies attention. For this purpose, we compared the effect of task switching on storage to the effect of stimulus degradation, which is equally attention demanding but independent of task switching (e.g., Rubinstein et al., 2001).

As we have seen, many accounts evoked above do not predict any effect of task switching on maintenance. By contrast, following the unitary conception of working memory and the time-based resource-sharing model, we expected a clear impairment of task switching on working memory storage. Because task switching requires attention that is no longer available for refreshing decaying memory traces, the extra time of attentional occupation it induces would thus impair the maintenance of the to-be-recalled items. As a consequence, in all experiments, we predicted that recall would be poorer when more task switches were required.

## Experiment 1

Experiment 1 was based on the list-completion procedure (e.g., Allport et al., 1994; Jersild, 1927). In this procedure three types of lists are presented: (a) a pure list containing only Task A, (b) a pure list containing only Task B, and (c) a mixed list in which participants have to alternate between Task A and Task B. The switch cost is computed as the difference between the mean latencies (and error rates) of both pure lists and the mixed list. Although this method has proven to be useful in many investigations of task switching (e.g., Baddeley et al., 2001; Emerson & Miyake, 2003; Saeki & Saito, 2004a, 2004b), it is important to note that the cost observed in this situation does reflect a broad range of demands and processes that are not all specific to task switching. For this reason, it is more appropriate to refer to this cost as a *global switching cost* (e.g., Kray & Lindenberger, 2000; Mayr, 2001). An advantage of this method is that the difference between pure and mixed lists is large and robust. In view of the present purpose, namely finding evidence for an effect of task switching on working memory storage, it seems appropriate to start with such a large effect. If no difference is observed under these conditions, the search for a cognitive cost associated with more fine grained measures of task switching is futile.

The present experiment compared recall performance in continuous span tasks including either pure lists or mixed lists of tasks. Participants were presented with a number of consonants to be remembered. After each consonant, they were presented with a series of digits to be processed according to the list completion paradigm. Pure lists involved either parity or magnitude judgments, whereas mixed lists required participants to alternate between parity and magnitude judgments of the digits. We predicted poorer recall in the mixed list than in the pure list conditions.

### Method

*Participants.* Nineteen first-year psychology students at Ghent University participated for course requirements and credit. All participants had normal or corrected-to-normal vision, were right-handed, and were naïve to the purpose of the experiment.

*Tasks and material.* A continuous span task designed by Barrouillet et al. (2004) was used. During a continuous span task, two constituent tasks need to be coordinated. Participants were presented with series of three to six consonants to be remembered. Consonants in each series were drawn from 13 groups with low intergroup confusability based on their Dutch pronunciation (Vandierendonck, De Vooght, & Van der Goten, 1998). These groups were: (*B, D, P, T*), (*C*), (*F, S*), (*G*), (*H, K*), (*J*), (*L*), (*M, N*), (*Q*), (*R*), (*V, W*), (*X*), (*Z*). After each consonant, a series of eight digits (from 1 to 9, without 5) colored in either red or blue was sequentially displayed on screen. These series were randomly generated with the restriction that immediate stimulus repetition was avoided. When the digit was red, the participants had to decide whether it was larger or smaller than 5, by pressing a right or a left key, respectively. If it was blue, participants judged its parity by pressing the right or the left key for even and odd numbers, respectively. Previous research has shown that these response mappings are consistent with the mental representations of numbers in long-term memory, thus avoiding spurious compatibility effects (Dehaene, Bossini, & Giraux, 1993; Nuerk, Iversen, & Willmes, 2004). For both judgments the right hand had to be used.

Three types of digit lists were created: (a) 8 lists containing only parity judgments; (b) 8 lists containing only magnitude comparisons, and (c) 16 mixed lists in which the participants had to alternate between the parity and the magnitude tasks. In this way, for each length of the letter sequence (three, four, five, or six consonants), 4 simple and 4 mixed lists were presented. This resulted in a total of 32 lists to be performed.

*Procedure.* The participants were tested in groups of two by means of Pentium III personal computers with 17-inch color monitors running the Tscope experimentation software (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). The instructions were presented on-screen and paraphrased if necessary. A practice session of three blocks preceded the experimental sessions. In the first practice block, one letter series of each length was presented, and participants had to memorize the consonants without processing the digits presented after each consonant. In the second block, participants processed the digits without memorizing the consonants, whereas in the last block, both letter memorization and digit processing had to be performed.

After these three practice blocks, the experiment proper started. The letter–digit lists were presented in a random order. The course of events for each list was as follows: First, the length and the type of the list were announced in the middle of the screen (e.g., "4 consonants—magnitude task"). Second, a consonant was presented for 1,500 ms, followed by a 300-ms blank. Next, a digit appeared for 900 ms followed by a 300-ms blank. When the eight digits were presented, the next consonant appeared, and so on. The time course of these events was fixed. Even when participants did not respond to the digits, the sequence continued. At the end of a list, participants had to recall the consonants in the correct order by typing the letters on the keyboard with their left hand. The recalled consonants were presented on a display on-screen. Whenever the participants had forgotten an item, they pressed the spacebar and a question mark appeared instead of a letter. The experiment lasted about 1 hr.

### Results

The specific impact of task switching on working memory maintenance was investigated by considering the recall performance, the quality of digit processing, and the size of the switch cost as a function of the different lists' lengths. These latter analyses focused on the last series of digits in each series of letters

because it is only there that the memory load equated the length of the series of letters.

*Recall performance.* We first computed the average span for the pure and the mixed lists by summing the number of correctly recalled consonants for both types of lists across all list lengths (Friedman & Miyake, 2005). The average span was higher for the pure lists (63.68 out of 72) compared with that for the mixed lists (58.32), $F(1, 18) = 5.07$, $p < .05$. Next, the quality of recall was considered for each list length. First, the absolute recall performance was computed. For each series the proportion of recalled consonants in absolute correct order was calculated. For instance, when presented *P, Q, R, D* and recalling *P, Q, R, D*, the score was 4 out of 4 and the recall proportion was 1. However, when *P, D, Q, R* was recalled, the score was 1 out of 4 (proportion .25) because only the first consonant matched its presentation position. Because this is a very strict measure of recall, we also considered relative recall quality. Following a method used by Vandierendonck, Kemps, Fastame, and Szmalec (2004) and Szmalec, Vandierendonck, and Kemps (2005), Kendall's tau rank correlation between the presented series and the recalled series was weighted with the recall performance without consideration of the correctness of the ranking.[1] Both measures were separately subjected to a 2 (pure lists vs. mixed lists) by 4 (list length) multivariate analysis of variance (MANOVA). Absolute recall was poorer for mixed lists (.82) compared with pure lists (.90), $F(1, 18) = 7.57$, $p < .05$, and decreased as a function of list length (.89, .92, .86, and .77), $F(3, 16) = 10.59$, $p < .001$ (see Table 1). These effects did not interact, $F(3, 16) = 1.31$, $p = .31$. The relative recall performance mirrored these findings. The relative recall was lower for the mixed lists (.88) compared with the pure lists (.92), $F(1, 18) = 8.88$, $p < .01$, and recall performance decreased as a function of the increasing list length (.90, .94, .89, and .87), $F(3, 16) = 11.75$, $p < .001$. No interaction was observed, $F < 1$.

*Digit processing.* Performance on the numerical judgment tasks can be analyzed in terms of latency and accuracy. First, we studied the average amount of time participants focused on the processing of the digits in each list. For each list, the total time spent on average on the processing of the digits between the presentation of two consecutive consonants was calculated irrespective of whether the digits' judgments were correct or not. These digit processing times were then averaged according to the type and the length of the lists. A 2 (pure lists vs. mixed lists) by 4 (list length) MANOVA was conducted on these mean processing times (see Table 2). The digit processing times were larger (5,966 ms) for the mixed lists than for the pure lists (4,667 ms), $F(1, 18) = 77.91$, $p < .001$, and did not increase with list length, either for the pure list, $F < 1$, or for the mixed list, $F(1, 18) = 2.08$, $p = .17$.

The average number of errors produced while processing the eight digits between two consecutive consonants was also subjected to a 2 (pure lists vs. mixed lists) by 4 (list length) MANOVA (see Table 2). The mean number of errors was larger for the mixed lists (1.92) compared with the pure lists (.88), $F(1, 18) = 55.31$, $p < .001$, and increased with the list length (1.28, 1.37, 1.39, and 1.57), $F(3, 16) = 3.49$, $p < .05$. These effects did not interact, $F < 1$.

*Memory load by task switching.* In the next step, we focused on the possible influence of working memory load on task switching performance by conducting a 2 (pure list vs. mixed list) by 4 (list length) MANOVA on the average latencies of the last sequence of digits for each list length. For this analysis, trials that were incorrect, trials immediately following incorrect trials, and trials including latencies smaller than 100 ms or larger than 1,200 ms (overlapping with the next digit) were discarded from the data analyses. Also, trials following trials with latencies larger than 1,200 ms (overlaps from previous responses) were discarded. A total of 16% of the trials were removed, and the remaining latencies were free of spurious effects and provided a more pure indication of task switching performance (see Table 3). The latencies were longer for the mixed lists (708 ms) than for the pure lists (567 ms), $F(1, 18) = 62.86$, $p < .001$, resulting in a mixed list cost of 141 ms. The latencies also increased as a function of list length (626 ms, 629 ms, 645 ms, and 650 ms), $F(3, 16) = 3.58$, $p < .05$. These effects interacted, $F(3, 16) = 5.04$, $p < .05$. However, this interaction did not result in an increase but in a decrease of the mixed list cost with the number of letters to be maintained. This was due to the fact that only the latencies within the pure lists increased as a function of list length, $F(1, 18) = 29.24$, $p < .001$, whereas there was no significant effect on the latencies within the mixed lists, $F < 1$ (see Figure 1).

The error rates of the last sequence of each list were also subjected to a 2 (pure lists vs. mixed lists) by 4 (list length) MANOVA (see Table 3). The error rates were higher for the mixed lists (.18) than for the pure lists (.08), $F(1, 18) = 37.94$, $p < .001$,

[1] Kendall's tau is a measure of ranked correlation that measures the level of disarray for a pair of samples. The value of Kendall's tau lies between +1 (complete concordance between both samples) and –1 (complete disagreement). In the present study, Kendall's tau was used to calculate ranking correctness by comparing the order of the presented consonants with the order of recalled consonants. This calculation is based on the position of a consonant relative to the other consonants in the string, so it captures more of the data than an absolute determination of correct position. To avoid attenuated ranges, we subjected this rank correlation to an arcsine transformation and linearly rescaled this outcome in order to obtain an index between 0 and 1. Hence, negative values were avoided. This was of importance when multiplying this transformed tau with the free recall performance. For example, when presented *P, Q, R, D* and recalling *P, R, Q, D,* the relative recall is .73, while the absolute recall is .50. Although only the first and the last consonant matched their presentation order, relatively seen, only the *R* was recalled incorrectly compared with the *Q.*

Table 1

*Absolute and Relative Recall Performance of Experiment 1 as a Function of List Length and List Type*

| | List length | | | | | | | | |
| | 3 | | 4 | | 5 | | 6 | | |
| Variable | M | SD | M | SD | M | SD | M | SD | M |
|---|---|---|---|---|---|---|---|---|---|
| Absolute recall | | | | | | | | | |
| Pure list | .96 | .15 | .96 | .07 | .89 | .15 | .79 | .16 | .90 |
| Mixed list | .82 | .22 | .88 | .13 | .83 | .23 | .74 | .25 | .82 |
| Relative recall | | | | | | | | | |
| Pure list | .96 | .16 | .96 | .06 | .92 | .11 | .85 | .13 | .92 |
| Mixed list | .87 | .16 | .91 | .10 | .86 | .19 | .89 | .21 | .88 |

and they increased as function of list length (.11, .12, .12, and .16), $F(3, 16) = 8.21$, $p < .001$. The two factors did not interact, $F < 1$.[2]

## Discussion

The results of Experiment 1 were twofold. First, recall performance was significantly poorer for mixed lists than for pure lists. The presence of task switches thus impaired working memory maintenance. The analyses clearly indicated that participants were engaged in processing digits for a larger amount of time with mixed lists than with pure lists. Hence, the cognitive load induced by mixed-list processing was higher than the average cognitive load due to pure lists, and this resulted in a more detrimental effect on the maintenance of letter series in mixed lists.

We also observed an influence of the concurrent memory load on pure lists but not on mixed lists, resulting in a decrease of the global switching cost under memory load. It is possible that due to different attentional demands, mixed and pure lists were affected in a different way by the concurrent load. Because pure lists involved a single task and hence simpler processing activities, it is possible that participants were more prone to postpone the treatment of the digits while refreshing the memory traces of the letters in the pure lists than in the more complex mixed lists, in which they prioritized digit processing rather than refreshment. This kind of a strategy-related effect has already been observed in dual tasks (Camos & Barrouillet, 2004). Such a discrepancy would account for the fact that reaction times increased with memory load in pure lists but remained unchanged in mixed lists. Experiment 2 further examined this issue.

Taken together, the results of Experiment 1 showed a neat relation between task switching and working memory by demonstrating that task switching impedes the maintenance of consonants in working memory. In the next experiment, we wanted to replicate this finding by using a more fine grained operationalization. To this end, the number of switches was varied parametrically, ranging from lists with a few switches to lists with many switches, and the task switches were made less predictable.

## Experiment 2

In contrast to Experiment 1, Experiment 2 used a task-cueing procedure in which participants alternate between two or more

### Table 2
*Response Times (in Milliseconds) and Mean Number of Errors (out of 8) of the Digit Processing in Experiment 1 as a Function of List Length and List Type*

| | List length | | | | | | | |
| | 3 | | 4 | | 5 | | 6 | |
| Variable | M | SD | M | SD | M | SD | M | SD |
|---|---|---|---|---|---|---|---|---|
| Response time | | | | | | | | |
| Pure list | 4,682 | 753 | 4,614 | 579 | 4,573 | 686 | 4,800 | 674 |
| Mixed list | 5,942 | 814 | 6,062 | 857 | 5,926 | 825 | 5,933 | 925 |
| Errors | | | | | | | | |
| Pure list | 0.82 | 0.67 | 0.80 | 0.52 | 0.85 | 0.57 | 1.04 | 0.44 |
| Mixed list | 1.73 | 0.91 | 1.94 | 0.79 | 1.92 | 0.94 | 2.10 | 0.85 |

### Table 3
*Reaction Times (in Milliseconds) and Error Rates of the Task-Switching Performance During the Digit Processing of Experiment 1 as a Function of List Length and List Type*

| | List length | | | | | | | |
| | 3 | | 4 | | 5 | | 6 | |
| Variable | M | SD | M | SD | M | SD | M | SD |
|---|---|---|---|---|---|---|---|---|
| Reaction time | | | | | | | | |
| Pure list | 550 | 75 | 549 | 61 | 572 | 75 | 599 | 81 |
| Mixed list | 703 | 115 | 710 | 110 | 719 | 111 | 702 | 126 |
| Alternation cost | 157 | | 161 | | 147 | | 102 | |
| Errors | | | | | | | | |
| Pure list | .06 | .04 | .07 | .04 | .08 | .06 | .11 | .07 |
| Mixed list | .17 | .10 | .17 | .10 | .18 | .07 | .21 | .10 |

choice reaction tasks according to a pattern that is unpredictable and controlled by cues (Meiran, 1996). The switch cost is defined as the difference between trials that repeat the same task as the previous trial, and trials that involve a different task from the previous trial. This methodology offers some advantages compared with the list-completion procedure. Previous research argued that the difference between pure and mixed lists does not only concern the systematic switching between two tasks, but also the maintenance of two task sets as compared with only one task set in pure lists (Rogers & Monsell, 1995), higher demands on interference control (Rubin & Meiran, 2005), and the tracking of task sequences (Bryck & Mayr, 2005). In contrast, the task-cueing procedure constitutes a different situation, since task repetitions and task switches are both performed within the context of a mixed list. Hence, as both task sets are present throughout a mixed list, the situation is more similar for repetition and switch trials. This difference in methodology could be crucial for the present research question. The difference in recall performance we observed in Experiment 1 could reflect different working memory demands of pure and mixed lists that are independent of the processes underlying task switching per se. For example, the need to keep an additional task set active in a mixed list could have disrupted the maintenance of consonants and produced poorer recall.

In Experiment 2, we compared recall performance on two continuous span tasks that differed only in the number of switches involved by their processing component. Both conditions contained the same series of digits, the order of which was manipu-

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[2] In order to further investigate the influence of a concurrent memory load on task switching, we conducted an additional analysis in which the digit-processing task was divided into two blocks by grouping the first four and the last four trials. Switch costs in both blocks were then compared. The underlying idea was that switch costs may increase as a function of the number of concurrent consonants in only the first block and not in the second block. The reason for this is that participants would rehearse the concurrent items only when processing the first digits but not afterward. However, the interaction between list lengths, list type, and block was not significant for either the latencies, $F < 1$, or the error rates, $F < 1$. The absence of such interactions thus suggests that the influence of the consonants on digit processing was similar for the beginning and the end of the last processing phase.
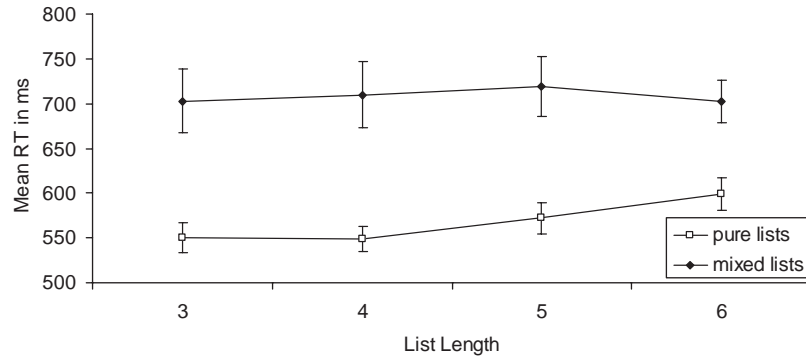
*Figure 1.* Mean reaction times (and standard errors) per item within the last interletter interval as a function of the experimental condition (either pure or mixed lists) and the length of the memory list in Experiment 1. RT = reaction time.

lated to create high- and low-switch lists in the same way as in Logan (2004; Experiment 4). If the difference in recall performance observed in Experiment 1 was only due to the maintenance of an additional task set in the mixed lists, no difference in recall performance should appear in the present experiment. By contrast, our hypothesis was that it is task switching performance that involves a cognitive cost and not the presence of an additional task set. Thus, we predicted that recall performance would be more impaired for high-switch lists compared with the low-switch lists. Second, we further investigated the influence of concurrent loads on the switch cost. If the previous results are due to the nature of the mixed lists and their induction of a higher priority for processing, the decrease in switch costs that we observed in Experiment 1 should not be replicated, because mixed lists were presented in both conditions of Experiment 2.

## Method

*Participants.* Nineteen first-year psychology students at Ghent University participated for course requirements and credit. All participants met the same criteria as in the previous experiment and did not participate to the previous experiment.

*Materials and procedure.* The procedure and the materials were identical to those in Experiment 1 except that only two types of lists were created, by manipulating the order of appearance of the colored digits: 16 low-switch lists with two or three switches per eight digits, and 16 high-switch lists with five or six switches. The distribution of the switches along a sequence of digits was random in both types of lists, with the restriction that the occurrence of both tasks was in balance within each list. For each list length, 4 low-switch and 4 high-switch lists were presented, resulting in a total of 32 lists to be performed. For each sequence, the list length was announced but not the number of switches. The experiment lasted about 1 hr.

## Results

*Recall performance.* The average span was higher for the low-switch lists (56.16 out of 72) than for the high-switch list (52.84), $F(1, 18) = 5.78$, $p < .05$. A 2 (low-switch vs. high-switch lists) by 4 (list length) MANOVA was conducted on the absolute and relative recall performance (see Table 4). The absolute recall

performance was larger on low-switch lists (.80) than on high-switch lists (.75), $F(1, 18) = 7.39$, $p < .05$, and decreased as a function of list length (.86, .81, .75, and .70), $F(3, 16) = 12.06$, $p < .001$. These effects did not interact, $F < 1$. For the relative recall performance, the difference between both lists remained (.86 vs. .83), $F(1, 18) = 7.77$, $p < .05$, but recall performance did not decrease as a function of list length, $F(3, 16) = 1.61$, $p = .23$. The effects did not interact, $F < 1$.

*Digit processing.* The digit processing times and the mean numbers of errors were computed as in Experiment 1. A 2 (low-switch vs. high-switch lists) by 4 (list length) MANOVA was performed on both the processing times and numbers of errors (see Table 5). The digit-processing times were longer for the high-switch list (5,908 ms) compared with the low-switch list (5,602 ms), $F(1, 18) = 29.93$, $p < .001$, and remained equal across the different list lengths, $F < 1$. The effects did not interact, $F < 1$. The number of errors was larger for the high-switch list (1.79) than for the low-switch list (1.52), $F(1, 18) = 12.23$, $p < .01$, and increased marginally with list length, $F(3, 16) = 2.47$, $p = .099$ (1.60, 1.68, 1.62, and 1.79). The effects did not interact, $F < 1$.

*Memory load by task switching.* In order to investigate the influence of memory load on task switching, the same exclusion criteria as in Experiment 1 were used, and 18% of the trials were removed. A 2 (low-switch vs. high-switch lists) by 2 (task repetition vs. task switching) by 4 (list length) MANOVA was con-

Table 4

*Absolute and Relative Recall Performance of Experiment 2 as a Function of List Length and List Type*

| | List length | | | | | | | | |
| | 3 | | 4 | | 5 | | 6 | | |
| Variable | M | SD | M | SD | M | SD | M | SD | M |
|---|---|---|---|---|---|---|---|---|---|
| Absolute recall | | | | | | | | | |
| Low-switch list | .86 | .21 | .83 | .22 | .79 | .16 | .71 | .25 | .80 |
| High-switch list | .85 | .19 | .78 | .27 | .70 | .29 | .68 | .26 | .75 |
| Relative recall | | | | | | | | | |
| Low-switch list | .88 | .12 | .87 | .18 | .88 | .17 | .82 | .19 | .86 |
| High-switch list | .87 | .15 | .83 | .17 | .82 | .10 | .81 | .21 | .83 |

Table 5

*Response Times and Mean Errors (out of 8) of the Digit Processing in Experiment 2 as a Function of List Length and List Type*

| | List length | | | | | | | |
| | 3 | | 4 | | 5 | | 6 | |
| Variable | M | SD | M | SD | M | SD | M | SD |
|---|---|---|---|---|---|---|---|---|
| Response time | | | | | | | | |
| Low-switch list | 5,722 | 731 | 5,744 | 809 | 5,664 | 683 | 5,724 | 700 |
| High-switch list | 5,926 | 772 | 5,890 | 794 | 5,895 | 616 | 5,921 | 691 |
| Errors | | | | | | | | |
| Low-switch list | 1.44 | 1.01 | 1.52 | 1.07 | 1.50 | 0.98 | 1.62 | 0.91 |
| High-switch list | 1.76 | 1.06 | 1.83 | 1.15 | 1.74 | 0.85 | 1.83 | 0.93 |

ducted on the last sequence of digits for each list length (see Table 6). The latencies were similar for the low- and the high-switch lists, $F < 1$. Repetition trials were performed faster than switch trials (636 ms and 697 ms, respectively), $F(1, 18) = 44.03$, $p < .001$, resulting in a 61-ms switch cost. The latencies did not vary across list length, $F(1, 18) = 1.35$, $p = .29$. None of the interactions were significant; the largest $F$ value was $F(3, 16) = 1.04$, $p = .40$, and the cost of switching remained unaffected by an increasing concurrent memory load (see Figure 2).

The error rates were analyzed in a similar way. The error rates were marginally larger for the high-switch than for the low-switch lists (.17 and .14, respectively), $F(1, 18) = 4.17$, $p = .056$. Fewer errors were made on repetition than on switch trials (.12 and .18, respectively), $F(1, 18) = 17.43$, $p < .001$. More errors were made when the list length increased (.14, .14, .16, and .18), $F(3, 16) = 5.50$, $p < .01$, and none of the interactions reached significance; the largest $F$ value was $F(3, 16) = 1.28$, $p = .31$.[3]

## Discussion

The results of Experiment 2 again indicated that task switching impaired working memory functioning. First, recall performance was poorer for high-switch lists than for low-switch lists. Because both list types involved the same tasks and differed only in the

Table 6

*Reaction Times During the Digit Processing of Experiment 2 as a Function of List Length, List Type, and Trial Type (Repetition or Switch)*

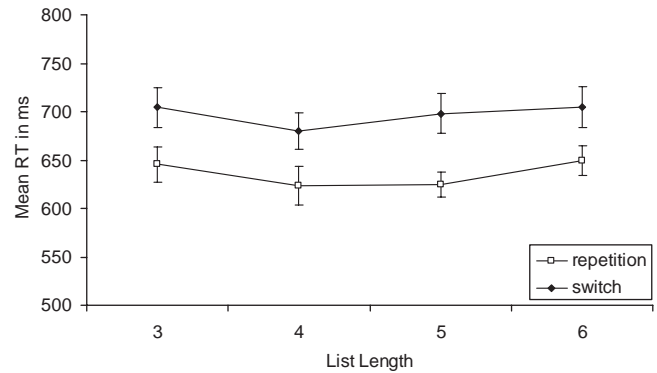| | List length | | | | | | | | |
| | 3 | | 4 | | 5 | | 6 | | |
| Variable | M | SD | M | SD | M | SD | M | SD | M |
|---|---|---|---|---|---|---|---|---|---|
| Low-switch list | | | | | | | | | |
| Repetition | 651 | 81 | 632 | 91 | 630 | 49 | 640 | 65 | 638 |
| Switch | 707 | 81 | 693 | 85 | 687 | 103 | 709 | 116 | 699 |
| Switch cost | 55 | | 61 | | 57 | | 69 | | 61 |
| High-switch list | | | | | | | | | |
| Repetition | 640 | 77 | 614 | 83 | 619 | 64 | 659 | 70 | 633 |
| Switch | 702 | 97 | 668 | 79 | 709 | 76 | 700 | 69 | 695 |
| Switch cost | 62 | | 54 | | 90 | | 42 | | 62 |



*Figure 2.* Mean reaction times (and standard errors) within the last interletter interval as a function of the type of trial (either repetition or switch) and the length of the memory list in Experiment 2. RT = reaction time.

number of task switches imposed by the task order, it can be concluded that task switching itself involves a cognitive load that leads to an impaired maintenance. The fact that the effect on recall was rather small compared with that in Experiment 1 suggests that in the previous experiment the impairment of working memory maintenance by task switching was overestimated due to the use of list completion. It should also be remembered that based on the time-based resource-sharing model, it is assumed that task switching impairs working memory maintenance because task switching occupies attention. As a consequence, the effect of this attentional occupation on maintenance cannot go beyond, and should be commensurate with, the extra time resulting from the increase in the number of switches, which was about 190 ms within a postletter interval. Thus, a large disruptive effect on recall could not be expected from so subtle a variation in attentional demand. Nonetheless, this variation proved to be sufficient to significantly impair the maintenance of the letters and impair their recall.

In line with the interpretation of Camos and Barrouillet (2004), switch costs remained unaffected by the concurrent memory load. Whatever the number of letters to be maintained, the switch cost remained essentially constant. This result suggests that the decrease in mixing cost associated with the increase in the number of letters to be maintained that was observed in Experiment 1 was probably due to the fact that the two conditions under comparison involved different list types, which in turn induced different strategies in our participants. The lack of effect of the concurrent memory load on the switch cost is at odds with previous studies, where it was observed that concurrent articulatory suppression affected the size of the switch cost (e.g., Liefooghe et al., 2005; Miyake et al., 2004). As a possible interpretation, this lack of effect of verbal load on task switching could be attributed to an insufficiently strong manipulation of the size of the verbal load. For example, it could be that the number of items to be concur-

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[3] As in Experiment 1, an additional analysis was conducted in order to find out whether the observed load effects were similar for the beginning and the end of the last processing phase. Again the interaction between list lengths, trial type, and block failed to be significant both for the latencies, $F(3, 16) = 1.89$, $p = .17$, and the error rates, $F(3, 16) = 1.92$, $p = .17$.

rently maintained (six consonants) was not large enough to find any effect. Moreover, it has been suggested that in a complex span task the load that is induced by the maintenance of items could be undermined by using strategies involving long-term memory storage (e.g., Saito & Miyake, 2004). In view of these possibilities, Experiment 3 employed a paradigm in which participants had to maintain a memory preload while processing a series of only eight digits and recall the preload immediately afterward. This way, the amount of time between the presentation of the preload and the recall of the preload was drastically reduced, thus minimizing the possible involvement of strategies based on long-term memory storage. At the same time, it was possible to increase the number of consonants to be maintained up to eight.

## Experiment 3

As in the previous experiment, we contrasted the recall performance on high- and low-switch lists, but we used preloading instead of a continuous span task design. First, participants were presented with a sequence of consonants immediately followed by a series of eight digits to be processed at a pace fixed by the computer. After processing this series, participants recalled the consonants in the correct serial order. With the aim of increasing the maintenance demands on working memory, six list lengths ranging from three to eight consonants were presented. The prediction was the same as in the previous experiments. We expected poorer recall performance for high-switch lists than for low-switch lists. Additionally, we investigated whether the switch cost also remained unchanged across the different sizes of the memory preload.

### Method

*Participants.* Twenty-four first-year psychology students at Ghent University participated for course requirements and credit. All participants met the same criteria as in the previous experiment.

*Materials and procedure.* The materials in Experiment 3 were identical to those of Experiment 2 except that the consonants were presented as a list before the digits and the list length now varied from three to eight consonants. The course of events for each list was essentially the same as in Experiment 2. The consonants were serially presented at a rate of 1,500 ms per consonant followed by

a 300-ms blank. For each list type (high switch or low switch) and length (three, four, five, six, seven, or eight consonants), four lists were presented, resulting in the presentation of 48 lists. The experiment lasted about 45 min.

### Results

*Recall performance.* The average recall score was larger for the low-switch lists (98.7 out of 132) than for the high-switch lists (93.38), $F(1, 23) = 8.28$, $p < .01$. A 2 (low-switch vs. high-switch lists) by 6 (list length) MANOVA was conducted on absolute and relative recall performance (see Table 7). Absolute recall was higher for the low- than for the high-switch lists (.78 and .75, respectively), $F(1, 23) = 7.79$, $p < .05$, and decreased with list length (.92, .91, .83, .69, .71, .58, and .46), $F(5, 19) = 25.04$, $p < .001$. This decrease was similar for both types of lists, $F(1, 23) = 1.21$, $p = .28$. For the relative recall performance, the difference between the low- and high-switch lists was also significant (.77 vs. .74, respectively), $F(1, 23) = 4.99$, $p < .05$, and recall also decreased as a function of list length (.94, .94, .86, .76, .58, and .46), $F(5, 19) = 43.77$, $p < .001$. The effects did not interact, $F < 1$.

*Digit processing.* The digit processing times were obtained in the same way as in the previous experiments. A 2 (low-switch vs. high-switch list) by 6 (list length) MANOVA was performed on times and error rates (see Table 8). The digit-processing times were longer for the high-switch lists (6,159 ms) than for the low-switch lists (5,801 ms), $F(1, 23) = 43.98$, $p < .001$, with no significant effect of list length, $F(5, 19) = 1.07$, $p = .41$, and no interaction, $F(5, 19) = 1.24$, $p = .33$. The mean number of errors was larger for the high-switch lists compared with the low-switch lists (1.81 and 1.33 out of 8, respectively), $F(1, 23) = 27.73$, $p < .001$, and remained unaffected by list length, $F < 1$. These effects did not interact either, $F(5, 19) = 1.63$, $p = .20$.

*Memory load by task switching.* The exclusion criteria of the previous experiments were used, and 18% of the trials were removed. A 2 (low-switch vs. high-switch lists) by 2 (task repetition vs. task switching) by 6 (list length) MANOVA was performed (see Table 9). The latencies were marginally longer for the high-switch list (697 ms) than for the low-switch list (685 ms), $F(1, 23) = 4.09$, $p = .055$. Task repetition was faster than task switching (656 ms and 725 ms, respectively, with a switch cost of 69 ms), $F(1, 23) = 89.06$, $p < .001$. List length did not influence latencies, $F < 1$. Finally, none of the interactions was significant;

Table 7
*Absolute and Relative Recall Performance of Experiment 3 as a Function of Preload and List Type*

| | Preload | | | | | | | | | | | | |
| | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | |
| Variable | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Absolute recall | | | | | | | | | | | | | |
| Low-switch list | .94 | .10 | .91 | .12 | .84 | .21 | .71 | .23 | .70 | .23 | .60 | .18 | .78 |
| High-switch list | .90 | .14 | .90 | .16 | .81 | .20 | .67 | .24 | .72 | .21 | .49 | .19 | .75 |
| Relative recall | | | | | | | | | | | | | |
| Low-switch list | .95 | .08 | .95 | .09 | .87 | .18 | .78 | .18 | .56 | .30 | .49 | .20 | .77 |
| High-switch list | .92 | .12 | .92 | .15 | .85 | .16 | .73 | .20 | .59 | .29 | .42 | .20 | .74 |

Table 8
*Response Times and Mean Errors (out of 8) of the Digit Processing in Experiment 3 as a Function of Preload*

| | Preload | | | | | | | | | | | | |
| | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | |
| Variable | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Response time | | | | | | | | | | | | | |
| Low-switch list | 5,738 | 697 | 5,805 | 924 | 5,673 | 758 | 5,833 | 695 | 5,862 | 725 | 5,899 | 672 | 5,802 |
| High-switch list | 6,157 | 753 | 6,069 | 915 | 6,165 | 814 | 6,243 | 789 | 6,095 | 700 | 6,226 | 660 | 6,159 |
| Errors | | | | | | | | | | | | | |
| Low-switch list | 1.30 | 0.74 | 1.33 | 0.80 | 1.19 | 0.75 | 1.32 | 0.68 | 1.58 | 0.89 | 1.25 | 0.63 | 1.33 |
| High-switch list | 1.67 | 0.96 | 1.67 | 1.08 | 1.94 | 0.93 | 1.99 | 1.15 | 1.66 | 0.93 | 1.91 | 1.03 | 1.80 |

the largest $F$ value was $F(1, 23) = 1.55$, $p = .22$. Thus, the switch cost did not change over list length (see Figure 3).

The error rates yielded a difference between low-switch and high-switch lists (.16 and .19, respectively), $F(1, 23) = 7.34$, $p < .05$, and fewer errors were made for task repetition compared with task switching (.13 and .22, respectively), $F(1, 23) = 40.36$, $p < .001$. The error rates did not increase as a function of list length, $F < 1$. No interactions were significant; the largest $F$ value was $F(5, 19) = 1.77$, $p = .17$.[4]

*Discussion*

Although a different procedure was used, the results of Experiment 3 mirrored the effects observed in Experiment 2. Recall performance on the high-switch lists was poorer than on the low-switch lists, and memory load did not affect the switch cost. These results offer a nice generalization of the relation between task switching and working memory maintenance that we observed in the previous experiment. In the present experiment, the delay between encoding and recall was less than 10 s, and only one series of digits had to be processed. As already mentioned, the concurrent load did not affect task switching performance. Even when the storage demands on working memory were increased to eight letters, the difference between task switching and task repetition remained unchanged. Contrary to the results of Experiment 2, there was no effect of list length on error rates. This rules out any possibility that an increase of the switch cost could be concealed by a speed–accuracy trade-off. Exactly as in Experiment 2, when sufficient time pressure is induced, the frequency of switches had a detrimental effect on the maintenance of consonants, but the concurrent load did not influence the processing of the digits.

In a series of three experiments taken together, we have demonstrated that task switching clearly impairs working memory maintenance. According to the time-based resource-sharing model, the effect on concurrent maintenance of a given activity is proportionate to the time during which this activity occupies attention (Barrouillet et al., 2007). Experiment 4 was designed to verify this assumption concerning the effect of task switching on working memory.

## Experiment 4

In this final experiment, the cause of the effects observed in previous experiments was further investigated. As mentioned in the introduction, the time-based resource-sharing model assumes that the impairment that task switching has on the maintenance of information in working memory is determined by the amount of time it occupies attention. In other words, this impairment is not inherent to task switching but rather follows from general time-consuming attentional demands. Experiment 4 tested this assumption. To this end, a variant of Experiment 3 was conducted in which not only the number of switches was manipulated but also the degradation of the stimuli to which the digit-processing tasks were applied. Stimulus degradation is known to put special demands on cognitive control, possibly through additional monitoring and adaptation mechanisms (e.g., Barch et al., 1997; Kok, 1986; Yeung & Cohen, 2006). Additionally, Rubinstein et al. (2001) demonstrated that stimulus degradation, which is especially of importance to stimulus identification processes, did not affect the size of the switch cost. If the main cause of the impairment of working memory maintenance due to task switching is the amount of time attention is occupied, then a stimulus degradation occupying attention for a similar amount of time should impair working memory maintenance to the same extent as task switching and lead to comparable recall performance.

*Method*

*Participants.* Twenty-five first-year psychology students at Ghent University participated for course requirements and credit. All participants met the same criteria as in the previous experiment.

*Material and procedure.* For each of the list lengths—four, six, and eight—three list types were created: (a) lists with normal digits and a few switches; (b) lists with normal digits and many switches; and (c) lists with a few switches but with degraded digits. This degradation was obtained by adding static visual noise on top of the presented digits (Holcomb, 1993). For each digit presentation, the digit was covered by a virtual square in which 70% of the pixels was randomly highlighted (see Figure 4). These pixels and the digits they covered were presented in blue or red depending on

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[4] Again an additional analysis was conducted in order to find out whether the observed preload effects were similar for the beginning and the end of the processing phase. However, the interaction between list lengths, trial type, and block failed to be significant for either the latencies, $F < 1$, or the error rates, $F(5, 19) = 1.14$, $p = .37$.

Table 9
*Reaction Times and Error Rates of the Task-Switching Performance During the Digit Processing of Experiment 3 as a Function of Preload, List Type, and Trial Type (Repetition or Switch)*

| | Preload | | | | | | | | | | | | |
| | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | |
| Variable | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Low-switch list | | | | | | | | | | | | | |
|   Repetition | 647 | 82 | 637 | 70 | 640 | 87 | 650 | 88 | 645 | 68 | 667 | 95 | 648 |
|   Switch | 712 | 72 | 714 | 98 | 718 | 96 | 720 | 93 | 720 | 83 | 739 | 102 | 721 |
|   Switch cost | 65 | | 77 | | 78 | | 69 | | 75 | | 72 | | 73 |
| High-switch list | | | | | | | | | | | | | |
|   Repetition | 687 | 122 | 649 | 87 | 636 | 95 | 660 | 89 | 674 | 111 | 683 | 98 | 665 |
|   Switch | 724 | 70 | 748 | 100 | 724 | 75 | 735 | 92 | 729 | 78 | 712 | 68 | 729 |
|   Switch cost | 37 | | 99 | | 88 | | 76 | | 55 | | 29 | | 64 |

the task to be performed, with red indicating the magnitude task and blue indicating the parity task. This way, only the identity of the digit was degraded but not the salience of the cue. The course of events for each list was the same as in Experiment 3. For each list type (low-switch lists with normal digits, high-switch list with normal digits, and low-switch lists with degraded digits) and length (four, six, or eight consonants), four lists were presented, resulting in the presentation of 36 lists. The experiment lasted about 40 min.

## Results

*Digit-processing times and recall performance.* Digit-processing times were obtained as in the previous experiments and subjected to a 3 (list type) by 3 (list length) MANOVA (see Table 10). Digit processing was significantly faster for low-switch lists with normal digits (5,840 ms) than for the other lists, $F(1, 24) = 56.81$, $p < .001$. More importantly, the high-switch lists with normal digits (6,164 ms) and the low-switch lists with degraded stimuli (6,234 ms) were processed equally fast, $F < 1$, thus creating appropriate conditions for the test of our hypothesis of an effect on recall performance related to the duration of attentional occupation. There was no significant effect of list length, $F < 1$, and no interaction between both effects, $F < 1$.
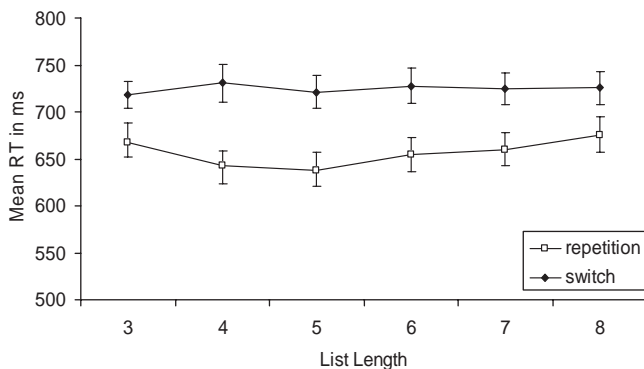
As we expected, the average recall score was larger in low-switch lists with normal digits (53.84 out of 72) than in high-switch lists with normal digits (49.24), $F(1, 24) = 5.77$, $p < .05$, and than in low-switch lists with degraded digits (49.22), $F(1, 24) = 5.29$, $p < .05$. In line with our time-based account of resource sharing, the latter conditions did not differ from each other, $F < 1$. The analyses of absolute and relative recall performance confirmed these results. Both scores were subjected to a 3 (list type) by 3 (list length) MANOVA (see Table 11). Absolute recall was larger for the low-switch lists with normal digits (.77) than for the remaining two lists, $F(1, 24) = 8.79$, $p < .01$, while the latter two lists yielded an equal recall score (.72 and .73, respectively), $F < 1$. Recall performance decreased with list length (.91, .73, and .57), $F(2, 23) = 68.91$, $p < .001$. The interaction between both effects was not significant, $F < 1$. Relative recall performance was also larger for the lists with low-switch and normal digits (.84) than for the other lists (.80 and .81, respectively), $F(1, 24) = 5.93$, $p < .05$, and the latter lists again yielded similar recall scores, $F(1, 24) = 1.31$, $p = .24$. Furthermore, the relative recall decreased as a function of list length (.93, .81, and .73), $F(2, 23) = 56.38$, $p < .001$. These effects did not interact, $F < 1$.

*Error rates in digit processing.* The mean number of errors was subjected to a similar analysis and mirrored the processing



*Figure 3.* Mean reaction times (and standard errors) as a function of the type of trial (either repetition or switch) and the length of the memory list in Experiment 3. RT = reaction time.
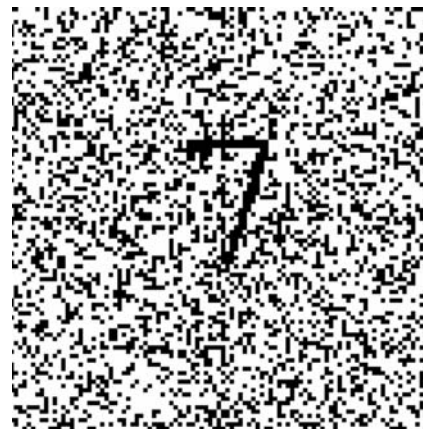


*Figure 4.* Example of the degraded stimuli presented in Experiment 4.

Table 10
*Absolute and Relative Recall Performance of Experiment 4 as a Function of Preload and List Type*

| Variable and type of list | Preload | | | | | | |
|---|---|---|---|---|---|---|---|
| | 4 | | 6 | | 8 | | |
| | M | SD | M | SD | M | SD | M |
| Absolute recall | | | | | | | |
| Low-switch list/normal stimuli | .93 | .10 | .75 | .21 | .62 | .20 | .77 |
| High-switch list/normal stimuli | .90 | .14 | .71 | .23 | .56 | .23 | .72 |
| Low-switch list/degraded stimuli | .91 | .16 | .73 | .26 | .54 | .21 | .73 |
| Relative recall | | | | | | | |
| Low-switch list/normal stimuli | .95 | .08 | .83 | .15 | .75 | .12 | .84 |
| High-switch list/normal stimuli | .91 | .14 | .79 | .16 | .71 | .17 | .80 |
| Low-switch list/degraded stimuli | .92 | .13 | .81 | .17 | .72 | .12 | .81 |

time data. Fewer errors were made for the low-switch lists with normal digits (1.61 errors out of 8 digits) than for either other list, $F(1, 24) = 14.67$, $p < .001$. The high-switch lists with normal digits (1.93) and the low-switch lists with degraded stimuli showed a similar number of errors (1.91), $F < 1$. The number of errors remained unaffected by list length, $F(2, 23) = 1.80$, $p = .19$, and no interaction was observed, $F(4, 21) = 2.19$, $p = .11$.

*Memory load by task switching.* The exclusion criteria of the previous experiments were used, and 19% of the trials were removed. A 3 (list type) by 3 (list length) by 2 (task repetition vs. task switching) MANOVA was performed (see Table 12). The latencies were shorter for the low-switch lists with normal digits (685 ms) than for the high-switch list with normal stimuli (706 ms), $F(1, 24) = 6.15$, $p = .05$, and the latencies on this latter list were shorter than on the low-switch list with degraded stimuli (750 ms), $F(1, 24) = 36.49$, $p < .001$. List length did not affect the latencies, $F(2, 23) = 1.03$, $p = .37$, and task repetition was faster than task switching (676 ms and 751 ms, respectively, with a switch cost of 75 ms), $F(1, 24) = 202.92$, $p < .001$. The interaction between list type and task switching, and the interaction between list length and task switching, were not significant, $Fs < 1$ (see Figure 5). The error rates indicated that low-switch lists with normal digits were associated with fewer errors (.18) than with the other lists, $F(1, 24) = 6.38$, $p < .001$, while the other lists did not differ significantly (.20 and .22, respectively), $F(1, 24) = 2.27$, $p = .14$. The error rates did not increase as a function of list length, $F(2, 23) = 1.33$, $p = .28$, and fewer errors were made on repetition trials (.17) than on switch trials (.24), $F(1, 24) = 31.58$, $p < .001$. Finally, the switch cost was not affected by list type or by list length, $Fs < 1$.[5]

## Discussion

In line with the time-based resource-sharing model, the degree of recall impairment was of a similar size for both low-switch lists with degraded stimuli and high-switch lists with normal stimuli, as was the extent to which the processing time was increased. These results confirm the prediction that the key factor underlying the impairment of working memory maintenance by a cognitive activity is the amount of time this cognitive activity occupies attention (Barrouillet et al., 2004, 2007).

This interpretation could be challenged in the light of many studies using the psychological refractory period (PRP) paradigm in which participants are asked to respond to two successive targets at varying stimulus onset asynchronies. In this paradigm, it seems that stimulus degradation affects processing stages prior to attention, the early processing steps that are slowed down by degradation being carried out in parallel with other resource-demanding processes such as response selection. Indeed, it has been shown that increasing the difficulty of processing of the second target by stimulus degradation results in an underadditive interaction between the manipulated factor and the stimulus-onset asynchrony (SOA) as SOA is decreased. This underadditive interaction suggests that the early stages of processing of the second target have been carried out in parallel with central-attention-demanding stages of the first task (Pashler, 1984; Pashler & Badgio, 1985). As a consequence, stimulus degradation in our experiment could not be considered as involving attention-demanding processes that could impair the concurrent refreshment of memory traces.

However, it is worth noting that these phenomena seem to be confined to the PRP paradigm. Interestingly, the underadditivity of the interaction disappears when stimulus degradation is used in a task-switching paradigm. Oriet and Jolicoeur (2003), using an alternating runs paradigm in which participants judged digits for parity and magnitude as in our experiments, observed that the effect of stimulus degradation did not differ as a function of whether participants switched or repeated tasks. From the additive effects of task switching and degradation, the authors concluded that task switching may impose a hard bottleneck even for early stimulus processing. Now, it is important to note that in our continuous span procedure, participants must not only switch back and forth between parity and magnitude judgments but also from maintenance activities to digit processing at stimulus onset. What is demonstrated by Oriet and Jolicoeur (2003) is that early processing of digits waits until task set reconfiguration or whatever operation responsible for the task switch cost is completed. Thus, it can be assumed that stimulus degradation within our paradigm induced a prolonged occupation of attention that resulted in the predicted impairment of maintenance and recall.

## General Discussion

Although a close relationship between task switching and working memory has often been postulated (e.g., Baddeley et al., 2001; Emerson & Miyake, 2003; Mayr & Kliegl, 2000, 2003; Rubinstein et al., 2001), there was a lack of direct evidence supporting this relationship (e.g., Friedman et al., 2006; Miyake et al., 2000) and a lack of evidence indicating that task switching places additional demands on working memory (e.g., Kane et al., 2007; Logan, 2004; see also Hogan, Kelly, & Craik, 2006). The present study was designed to clarify this issue by investigating the impairment of working memory functioning due to task switching within

[5] As in the previous experiments, the additional analysis was conducted to test whether the observed load effects were similar for the beginning and the end of the processing phase. The interaction between list lengths, trial type, and block, however, failed to be significant for either the latencies, $F < 1$, or the error rates, $F < 1$.

Table 11
*Response Times and Mean Errors (out of 8) of the Digit Processing in Experiment 4 as a Function of Preload*

| | Preload | | | | | | |
|---|---|---|---|---|---|---|---|
| | 4 | | 6 | | 8 | | |
| Variable | M | SD | M | SD | M | SD | M |
| Response time | | | | | | | |
| Low-switch list/normal stimuli | 5,861 | 628 | 5,825 | 635 | 5,834 | 580 | 5,840 |
| High-switch list/normal stimuli | 6,174 | 607 | 6,133 | 577 | 6,187 | 473 | 6,165 |
| Low-switch list/degraded stimuli | 6,137 | 613 | 6,254 | 563 | 6,312 | 624 | 6,234 |
| Errors | | | | | | | |
| Low-switch list/normal stimuli | 1.64 | 0.96 | 1.52 | 0.60 | 1.69 | 0.88 | 1.62 |
| High-switch list/normal stimuli | 2.09 | 1.09 | 1.62 | 0.84 | 2.10 | 1.23 | 1.94 |
| Low-switch list/degraded stimuli | 1.81 | 0.93 | 1.97 | 0.94 | 1.95 | 1.13 | 1.91 |

computer-paced continuous span tasks issuing from the time-based resource-sharing model (Barrouillet et al., 2004). All four experiments indicated that task switching impaired working memory maintenance, whereas the size of the switch cost remained unaffected by the number of consonants to be maintained. In the following sections, we first address the implications of the relationship between task switching and working memory maintenance for different accounts of task switching. Next, we discuss how different accounts of task switching and different conceptions of working memory architecture and resource sharing can account for the absence of an influence of working memory load on the size of the switch cost.

### Task Switching and Working Memory Maintenance

The present results suggest that task switching calls upon working memory functioning to a strong enough extent to impair the concurrent maintenance of items in working memory. Furthermore, the impairment observed is a function of the additional amount of time task switching occupies attention compared with task repetition. As a consequence, the amount of time that attention could be devoted to the refreshment of decaying memory traces was shorter during task switching than during task repetition. This resulted in more deterioration of working memory maintenance when the number of task switches increased.

On the one hand, the present findings can be connected in a straightforward way to the research assuming that switch costs are elicited by additional task set reconfiguration processes mediated by working memory (Baddeley et al., 2001; Emerson & Miyake, 2003; Mayr & Kliegl, 2000, 2003). In this perspective, our results are consistent with the hypothesis that when the number of switches increases, the total time involved in task set reconfiguration also increases. Because each change occupies attention for some time through processes of task set reconfiguration such as long-term retrieval (Mayr & Kliegl, 2000, 2003) or task set inhibition (Mayr & Kliegl, 2000), the amount of time left to refresh the decaying memory traces is reduced when the number of switches is increased. In turn, this results in the impairment of working memory maintenance. On the other hand, our findings can be linked equally well to accounts that do not assume task set reconfiguration. For instance, on the assumption that switch costs follow from the interaction between task set priming and executive control (e.g., Gilbert & Shallice, 2002; Yeung & Monsell, 2003), our

Table 12
*Reaction Times of the Task-Switching Performance During the Digit Processing of Experiment 4 as a Function of Preload, List Type, and Trial Type (Repetition or Switch)*

| | Preload | | | | | | |
|---|---|---|---|---|---|---|---|
| | 4 | | 6 | | 8 | | |
| Variable | M | SD | M | SD | M | SD | M |
| Low-switch list/normal stimuli | | | | | | | |
| Repetition | 653 | 69 | 637 | 64 | 654 | 79 | 648 |
| Switch | 724 | 116 | 731 | 107 | 711 | 73 | 722 |
| Switch cost | 71 | | 96 | | 57 | | 75 |
| High-switch list/normal stimuli | | | | | | | |
| Repetition | 664 | 87 | 690 | 89 | 662 | 125 | 672 |
| Switch | 740 | 76 | 741 | 72 | 736 | 100 | 739 |
| Switch cost | 76 | | 51 | | 74 | | |
| Low-switch list/degraded stimuli | | | | | | | |
| Repetition | 700 | 72 | 720 | 68 | 702 | 49 | 707 |
| Switch | 778 | 89 | 804 | 70 | 797 | 84 | 793 |
| Switch cost | 78 | | 84 | | 95 | | |
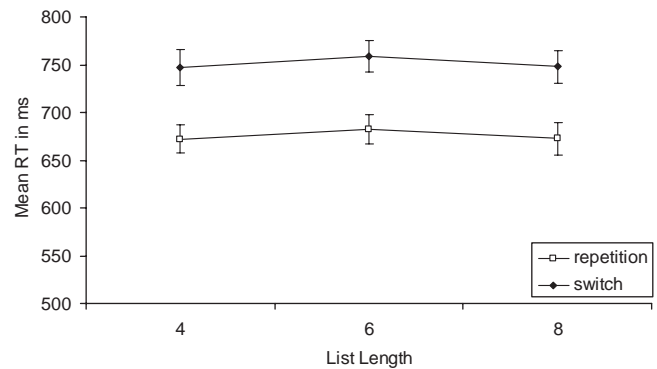


*Figure 5.* Mean reaction times (and standard errors) as a function of the type of trial (either repetition or switch) and the length of the memory list in Experiment 4. RT = reaction time.

results would then indicate that biasing top-down control in view of task set priming impairs working memory maintenance.

In a similar vein, it has been proposed that switch costs may result from facilitative priming of instructional task cues. In the task-cueing procedure, the same procedure we used in Experiments 2–4, switch costs are to a large extent accounted for by cue switches rather than by actual task switches (e.g., Logan & Bundesen, 2003, 2004; Mayr & Kliegl, 2003). D. W. Schneider and Logan (2005) proposed that in the task-cueing procedure, the perceptual representation of the cue must be compared with the transient representation of the possible cues in short-term memory. Although the activation of these representations decays in the interval between trials, there is some residual activation from the previous trial. Switch costs thus result from differences in residual activations that prime cue encoding. While such account discards task set reconfiguration, encoding cues and comparing their perceptual representation with transient representations in short-term memory remain processes that require attention. Accordingly, we assume that the difference between task-repetition and task-switch trials is that the former trials occupy attention for shorter periods of time because cue encoding and comparison are faster. As a consequence, even when endorsing the cue-encoding account, task switching will disrupt concurrent maintenance because it involves an attentional demand for a longer period of time.

In sum, our results show that processing differences related to task switching involve attention-demanding control processes. Additionally, the results of Experiment 4 even demonstrate that working memory impairment due to task switching is mediated by processes that are in fact not specific to the task-switching performance. Task switching interferes with the maintenance of items in working memory because, on task-switch trials, attention is occupied for a certain amount of time without opportunity for compensatory activities within the strictly controlled environment we used. This is in line with previous findings indicating that any task that occupies attention disrupts concurrent maintenance because it impedes, at least for short periods of time, the refreshment of the decaying memory traces (Barrouillet et al., 2004, 2007).

### Working Memory Load and Switch Costs

An important finding of the present study is that switch costs remained unaffected by working memory load. In Experiments 2–4, increasing the number of items to be maintained concurrently during task switching did not increase the size of the switch cost. On the one hand, this finding challenges the proposal that task sets are maintained by working memory itself (e.g., Logan & Gordon, 2001; Mayr & Kliegl, 2000, 2003) and is consistent with the idea that some task elements, such as response codes, are represented in the activated part of long-term memory (e.g., Kiesel et al., 2007; Meiran & Kessler, 2008; Rubin & Meiran, 2005). It is important to note that this conclusion does not contradict our central finding that task switching taxes the maintenance of information in working memory. According to time-based resource sharing, the crucial element is the amount of time attention is occupied by task switching and not the amount of information to be maintained actively during task switching. The finding that stimulus degradation also impaired the maintenance of consonants offers a nice test of this claim, as such manipulation does require additional processing but not the maintenance of additional information. Taken

together, the asymmetry we observed (i.e., task-switching impairing information maintenance, while concurrent load not affecting task switching) seems to suggest that task switching is related to working memory through simple attention-demanding processes but not through the active maintenance of task-related information.

Although the focus of the present article is mainly on the relation between task switching and working memory, the absence of an effect of a concurrent load on task switching must also be considered in relation to working memory theories. For instance, on the basis of the task span procedure, Logan (2004) concluded that task switching and information maintenance in working memory call on different resources and do not compete for the same limited supply. In other words, task switching and working memory would be supported by different resources within a multiresource working memory framework.

Trade-offs between the processing and the maintenance of information in working memory have been considered as a strong indication of a single-resource working memory system (e.g., Daneman & Carpenter, 1980; Just & Carpenter, 1992; Lovett, Reder, & Lebière, 1999), while the absence of such trade-offs has been interpreted as evidence favoring a working memory architecture consisting of multiple resources, with separate resources for the processing and for the maintenance of information (e.g., Kieras, Meyer, Mueller, & Seymour, 1999; W. Schneider & Detweiler, 1987). All the experiments in the present study revealed an impact of task switching on maintenance of information, lending strong support to the time-based resource-sharing model, which assumes that both the processing and the maintenance of information within working memory require attention, which is a single limited resource that must be shared.

It should be noted that, according to the classic view of the trade-off, performance on one component is inversely proportional to performance on the other component (e.g., Navon & Gopher, 1979; Sperling & Melchner, 1978). In the present study, it was observed that the number of switches had a negative impact on the maintenance of the consonants but, conversely, that the number of consonants to be maintained had no influence on task switching, a result converging with recent findings by Logan (2007; Experiment 4) suggesting that load per se does not affect switch costs. In other words, our findings do not conform to working memory theories that assume continuous sharing of a single resource between processing and storage. Indeed, these theories would expect that an increase in the number of items to be maintained would lead to a decrease in resources available for processing. Thus, they would predict slower performance under memory load (e.g., Anderson, Reder, & Lebière, 1996; Just & Carpenter, 1992). As a consequence, an increased memory load would have some impact on task repetitions and a much larger impact on task switches, resulting in a higher switch cost (panels B and B′ in Figure 6). In line with this expectation, Baddeley et al. (2001) observed an effect of a concurrent verbal load on the size of the switch cost.

Hence, though the time-based resource-sharing model predicts that task switching impairs concurrent maintenance, this theory predicts no effect of memory load on task switching. Of course, at a macro level of analysis, the theory is consistent with a continuous resource sharing between competing parallel activities. Yet, at a micro level of analysis, it does not hypothesize such a continuous sharing. Indeed, a basic assumption of the time-based resource-sharing model is that the attention to be shared between processing
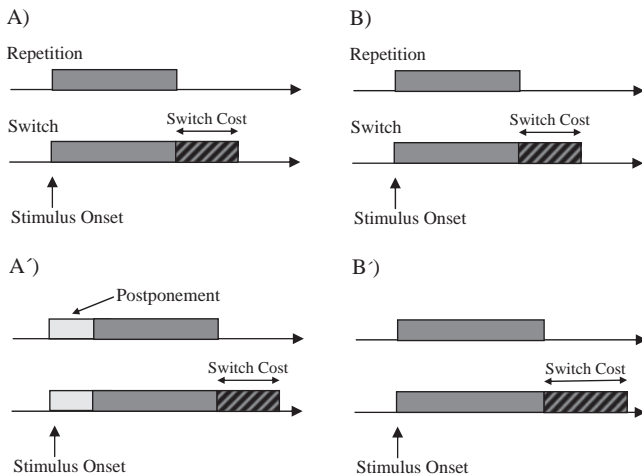
*Figure 6.* Hypothesized effect of a concurrent memory load on the time course of processing for repetition and switch trials according to either the time-based resource-sharing model (panels A and A′) or theories assuming a continuous sharing between competing processes (panels B and B′). Panels A′ and B′ represent hypothesized time courses when a concurrent memory load is added.

and maintenance is rapidly shifted between both activities. This implies that when several things are going on at once, activities can be postponed but their duration remains unchanged because, when they are performed, they benefit from all the available attention that is not divided between concurrent activities. For example, in our experiments, participants could postpone the concurrent task in order to give priority to the refreshment of the memory traces of the letters. This postponement probably becomes longer when the number of letters to be refreshed is larger. However, when the tasks are computer-paced, such as our continuous span tasks, then postponement could in some cases become impossible, and some letters would be lost. Even in these extreme cases, however, memory load affects only the duration of the postponement but not the duration of the processing steps themselves. Indeed, the number of memory traces waiting for refreshment does not matter when attention is devoted to a given processing step. As a consequence, the duration of processing steps should remain unchanged for both repetition and switch trials, and the switch cost will remain unaffected (see panels A and A′ in Figure 6).

Our results were precisely in line with these latter predictions. The reaction times of the pure lists in Experiment 1 increased when the number of consonants to be maintained increased, which is in agreement with the postponement idea, but in the subsequent experiments, the performance on the mixed lists in general remained unaffected when the number of consonants increased. More importantly, the size of the switch cost remained unaffected. Additionally, the reaction times displayed in Tables 3, 6, 9, and 12 for repetitions and switches were quite fast considering the fact that these repetitions and switches were performed in a dual-task situation. On average the reaction time when processing a digit while maintaining eight consonants was 701 ms for Experiment 3 and 720 ms for Experiment 4. In comparison, Verbruggen, Liefooghe, Vandierendonck, and Demanet (2007) used the same tasks in similar conditions (i.e., indicated by meaningless cues and supplying only a restricted amount of preparation time) but

without an additional working memory load. The average speed of processing a digit under those circumstances varied from 781 ms to 825 ms. Those differences illustrate that when processing mixed lists, participants preferred to give immediate and fast responses. So, depending on the list to be performed (pure or mixed), the processing of the digits was either postponed or immediately executed. This is consistent with proposals issuing from the domain of multitasking research assuming that when individuals have to perform tasks at virtually the same time (i.e., in the context of heavy time constraints), they adopt scheduling strategies (Meyer & Kieras, 1997a, 1997b). It is even possible that the adoption of different prioritization schemes in either blocked or alternating lists led to the apparent increase in switch cost observed by Baddeley et al. (2001). However, the strict control of time parameters we adopted in the present study reveals that whatever the strategy participants use, either postponing or immediately performing the secondary task, in neither case the findings are in agreement with the view that memory load increases switch cost as predicted by the theories assuming a continuously shared resource. Thus, our results challenge the traditional single-resource conceptions of working memory but support the hypothesis of a serial attention switching as proposed by the time-based resource-sharing model.

## Conclusion

In line with the time-based resource-sharing model, the present experiments offer neat evidence that task switching impairs the maintenance of items in working memory, offering the empirical confirmation of the widespread assumption that task switching involves working memory and consequently puts a cost on working memory functioning. Moreover, we did not observe that increasing the load on working memory modified the size of the switch cost, something accounted for by the conception of resource sharing developed within the time-based resource-sharing model. Additionally, the present study indicated that the effect of task switching on concurrent maintenance of information in working memory did not necessarily rely upon specific task set reconfiguration processes or task switching in general, but resulted from the combination of simple and more fundamental attention-demanding processes.

## References

Allport, D. A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 421–452). Cambridge, MA: MIT Press.

Allport, D. A., & Wylie, G. (1999). Task-switching: Positive and negative priming of task-set. In G. W. Humphreys, J. Duncan, & A. M. Treisman (Eds.), *Attention, space and action: Studies in cognitive neuroscience* (pp. 273–296). Oxford, England: Oxford University Press.

Allport, D. A., & Wylie, G. (2000). Task switching, stimulus response bindings, and negative priming. In S. Monsell & J. S. Driver (Eds.), *Attention and performance XVIII: Control of cognitive processes* (pp. 35–70). Cambridge, MA: MIT Press.

Anderson, J. R., Reder, L. M., & Lebière, C. (1996). Working memory: Activation limitations on retrieval. *Cognitive Psychology, 30*(3), 221–256.

Arrington, C. M., & Logan, G. D. (2004). Episodic and semantic components of the compound-stimulus strategy in the explicit-task cuing procedure. *Memory & Cognition, 32,* 965–976.

Baddeley, A. D., Chincotta, D., & Adlam, A. (2001). Working memory and the control of action: Evidence from task switching. *Journal of Experimental Psychology: General, 130,* 641–657.

Barch, D. M., Braver, T. S., Nystrom, L. E., Forman, S. D., Noll, D. C., & Cohen, J. D. (1997). Dissociating working memory from task difficulty in human prefrontal cortex. *Neuropsychologia, 35,* 1373–1380.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General, 133,* 83–100.

Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 570–585.

Berg, E. A. (1948). A simple objective technique for measuring flexibility in thinking. *Journal of General Psychology, 39,* 15–22.

Bryck, R. L., & Mayr, U. (2005). Does executive task management require verbalization? *Memory & Cognition, 33,* 11–23.

Camos, V., & Barrouillet, P. (2004). Adult counting is resource demanding. *British Journal of Psychology, 95,* 1–12.

Collette, F., & Van der Linden, M. (2002). Brain imaging of the central executive component of working memory. *Neuroscience and Biobehavioral Reviews, 26,* 105–125.

Cowan, N. (1995). *Attention and memory: An integrated framework.* New York: Oxford University Press.

Cowan, N. (2005). *Working memory capacity.* Hove, East Sussex, United Kingdom: Psychology Press.

Cowan, N., Keller, T. A., Hulme, C., Roodenrys, S., McDougall, S., & Rack, J. (1994). Verbal memory span in children: Speech timing clues to the mechanisms underlying age and word length effects. *Journal of Memory and Language, 33,* 234–250.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19,* 450–466.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and numerical magnitude. *Journal of Experimental Psychology: General, 122,* 371–396.

Emerson, M. J., & Miyake, A. (2003). The role of inner speech in task switching: A dual-task investigation. *Journal of Memory and Language, 48,* 148–168.

Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control.* London: Cambridge Press.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology: General, 128,* 309–331.

Friedman, N. P., & Miyake, A. (2005). Comparison of four scoring methods for the reading span test. *Behavior Research Methods, 37,* 581–590.

Friedman, N. P., Miyake, A., Corley, R. P., Young, S. E., DeFries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological Science, 17,* 172–179.

Garavan, H. (1998). Serial attention within working memory. *Memory & Cognition, 26*(2), 263–276.

Gavens, N., & Barrouillet, P. (2004). Delays of retention, processing efficiency, and attentional resources in working memory span development. *Journal of Memory and Language, 51,* 644–657.

Gilbert, S. J., & Shallice, T. (2002). Task switching: A PDP model. *Cognitive Psychology, 44,* 297–337.

Hogan, M. J., Kelly, C., & Craik, F. (2006). The interactive effects of attention switching and type of encoding on recognition memory in younger and older adults. *Experimental Aging Research, 32,* 153–185.

Holcomb, P. J. (1993). Semantic priming and stimulus degradation: Implications for the role of the N400 in language processing. *Psychophysiology, 30,* 47–61.

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology, 89,* 1–81.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99,* 122–149.

Kane, M. J., Conway, A. R. A., Hambrick, D. Z., & Engle, R. W. (2007). Variation in working memory capacity as variation in executive attention and control. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, and J. N. Towse (Eds.), *Variation in working memory* (pp. 21–48). New York: Oxford University Press.

Kieras, D. E., Meyer, D. E., Mueller, S., & Seymour, T. (1999). Insights into working memory from the perspective of the EPIC architecture for modeling skilled perceptual-motor performance. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control,* Cambridge, MA: Cambridge University Press.

Kiesel, A., Wendt, M., & Peters, A. (2007). Task switching: On the origins of response congruency effects. *Psychological Research, 71,* 117–125.

Koch, I., & Philipp, A. M. (2005). Effects of response selection on the task-repetition benefit in task switching. *Memory & Cognition, 33,* 624–634.

Kok, A. (1986). Effects of degradation of visual stimuli on components of the event-related potential (ERP) in go/no-go reaction tasks. *Biological Psychology, 23,* 21–38.

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging, 15,* 126–147.

Lépine, R., Bernardin, S., & Barrouillet, P. (2005). Attention switching and working memory spans. *European Journal of Cognitive Psychology, 17,* 329–346.

Lehto, J. (1996). Are executive function tests dependent on working memory capacity. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 49*(A), 29–50.

Liefooghe, B., Vandierendonck, A., Muyllaert, I., Verbruggen, F., & Vanneste, S. (2005). The phonological loop in task alternation and task repetition. *Memory, 13,* 650–660.

Logan, G. D. (2004). Working memory, task switching, and executive control in the task span procedure. *Journal of Experimental Psychology: General, 133,* 218–236.

Logan, G. D. (2006). Out with the old, in with the new: More valid measures of switch cost and retrieval time in the task span procedure. *Psychonomic Bulletin & Review, 13,* 139–144.

Logan, G. D. (2007). What it costs to implement a plan: Plan-level and task-level contributions to switch costs. *Memory & Cognition, 35,* 591–602.

Logan, G. D., & Bundesen, C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task cuing procedure? *Journal of Experimental Psychology: Human Perception and Performance, 29,* 575–599.

Logan, G. D., & Bundesen, C. (2004). Very clever homunculus: Compound stimulus strategies for the explicit task-cuing procedure. *Psychonomic Bulletin & Review, 11,* 832–840.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108,* 393–434.

Lovett, M. C., Reder, L. M., & Lebière, C. (1999). Modeling working memory in a unified architecture: An ACT-R perspective. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 135–182). Cambridge, MA: Cambridge University Press.

Mayr, U. (2001). Age differences in the selection of mental sets: The role of inhibition, stimulus ambiguity, and response-set overlap. *Psychology and Aging, 16,* 96–109.

Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 1124–1140.

Mayr, U., & Kliegl, R. (2003). Differential effects of cue changes and task

changes on task-set selection costs. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 362–372.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 1423–1442.

Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology, 41,* 211–253.

Meiran, N., & Kessler, Y. (2008). The task rule congruency effect in task switching reflects activated long term memory. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 137–157.

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review, 104,* 3–65.

Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review, 104,* 749–791.

Miyake, A., Emerson, M. J., Padilla, F., & Ahn, J. (2004). Inner speech as a retrieval aid for task goals: The effects of cue type and articulatory suppression in the random task cuing paradigm. *Acta Psychologica, 115,* 123–142.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49–100.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7,* 134–140.

Navon, D., & Gopher, D. (1979). On the economy of the human processing system. *Psychological Review, 86,* 214–255.

Nuerk, H. C., Iversen, W., & Willmes, K. (2004). Notational modulation of the SNARC and the MARC (linguistic markedness of response codes) effect. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 57*(A), 835–863.

Oberauer, K. (2003). Selective attention to elements in working memory. *Experimental Psychology, 50*(4), 257–269.

Oriet, C., & Jolicoeur, P. (2003). Absence of perceptual processing during reconfiguration of task-set. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 1036–1049.

Pashler, H. (1984). Evidence against late selection: Stimulus quality effects in previewed displays. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 429–448.

Pashler, H. (1998). *The psychology of attention.* Cambridge, MA: MIT Press.

Pashler, H., & Badgio, P. (1985). Visual attention and stimulus identification. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 105–121.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124,* 207–231.

Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task switching paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31,* 1477–1491.

Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 763–797.

Saeki, E., & Saito, S. (2004a). Effect of articulatory suppression on task switching performance: Implications for models of working memory. *Memory, 12,* 257–271.

Saeki, E., & Saito, S. (2004b). The role of the phonological loop in task switching performance: The effect of articulatory suppression in the alternating runs paradigm. *Psychologia, 47,* 35–43.

Saito, S., & Miyake, A. (2004). On the nature of forgetting and the processing-storage relationship in reading span performance. *Journal of Memory and Language, 50,* 425–443.

Schneider, D. W., & Logan, G. D. (2005). Modelling task switching without switching tasks: A short-term priming account of explicitly cued performance. *Journal of Experimental Psychology: General, 134,* 343–367.

Schneider, D. W., & Logan, G. D. (2006). Hierarchical control of cognitive processes: Switching tasks in sequences. *Journal of Experimental Psychology: General, 135,* 623–640.

Schneider, W., & Detweiler, M. (1987). A connectionist/control architecture for working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 21, pp. 54–119). New York: Academic Press.

Schuch, S., & Koch, I. (2003). The role of response selection for inhibition of task-sets in task shifting. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 92–105.

Sperling, G., & Melchner, M. J. (1978, October 20). The attention operating characteristic: Some examples from visual search. *Science, 202,* 315–318.

Sternberg, S. (1967). Retrieval of contextual information from memory. *Psychonomic Science, 8,* 55–56.

Stevens, M., Lammertyn, J., Verbruggen, F., & Vandierendonck, A. (2006). Tscope: A C library for programming cognitive experiments on the MS Windows platform. *Behavior Research Methods, 38*(2), 280–286.

Szmalec, A., Vandierendonck, A., & Kemps, E. (2005). Response selection involves executive control: Evidence from the selective interference paradigm. *Memory & Cognition, 33,* 531–541.

Turner, M. L., & Engle, R. W. (1989). Working memory capacity: An individual differences approach. *Journal of Memory and Language, 28,* 127–154.

Vandierendonck, A., De Vooght, G., & Van der Goten, K. (1998). Interfering with the central executive by means of a random interval repetition task. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 51*(A), 197–218.

Vandierendonck, A., Kemps, E., Fastame, M. C., & Szmalec, A. (2004). Working memory components involved in the Corsi block test. *British Journal of Psychology, 95,* 57–79.

Verbruggen, F., Liefooghe, B., Szmalec, A., & Vandierendonck, A. (2005). Inhibiting responses when switching: Does it matter? *Experimental Psychology, 52,* 125–130.

Verbruggen, F., Liefooghe, B., & Vandierendonck, A. (2006). Selective stopping in task switching: The role of response selection and response execution. *Experimental Psychology, 53*(1), 48–57.

Verbruggen, F., Liefooghe, B., Vandierendonck, A., & Demanet, J. (2007). Short cue presentations encourage advance task preparation: A recipe to diminish the residual switch cost. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33,* 342–356.

Waszak, F., Hommel, B., & Allport, A. (2003). Task switching and long-term priming: Role of episodic S-R bindings in task-shift costs. *Cognitive Psychology, 46,* 361–413.

Waszak, F., Hommel, B., & Allport, A. (2004). Semantic generalizations of stimulus-task bindings. *Psychonomic Bulletin & Review, 11,* 1027–1033.

Waszak, F., Hommel, B., & Allport, A. (2005). Interaction of task readiness and automatic retrieval in task switching: Negative priming and competitor priming. *Memory & Cognition, 33,* 595–610.

Wylie, G. R., & Allport, A. D. (2000). Task switching and the measurement of "switch costs." *Psychological Research, 63,* 212–233.

Yeung, N., & Cohen, J. D. (2006). The impact of cognitive deficits on conflict monitoring: Predictable dissociations between the error-related negativity and N2. *Psychological Science, 17,* 164–171.

Yeung, N., & Monsell, S. (2003). Switching between tasks of unequal familiarity: The role of stimulus-attribute and response-set selection. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 455–469.