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Time and Cognitive Load in Working Memory

Pierre Barrouillet
Université de Genève

Sophie Bernardin and Sophie Portrat
Université de Bourgogne

Evie Vergauwe
Université de Genève

Valérie Camos
Université de Bourgogne and
Institut Universitaire de France

According to the time-based resource-sharing model (P. Barrouillet, S. Bernardin, & V. Camos, 2004), the cognitive load a given task involves is a function of the proportion of time during which it captures attention, thus impeding other attention-demanding processes. Accordingly, the present study demonstrates that the disruptive effect on concurrent maintenance of memory retrievals and response selections increases with their duration. Moreover, the effect on recall performance of concurrent activities does not go beyond their duration insofar as the processes are attention demanding. Finally, these effects are not modality specific, as spatial processing was found to disrupt verbal maintenance. These results suggest a sequential and time-based function of working memory in which processing and storage rely on a single and general purpose attentional resource needed to run executive processes devoted to constructing, maintaining, and modifying ephemeral representations.

Keywords: working memory, cognitive load, time, executive processes, dual tasks

Working memory is one of the most heuristic and important concepts of cognitive psychology. Most of the theories that have followed the pioneering work of Baddeley and Hitch (1974) have suggested that working memory is a limited-capacity system in which some resource is shared between processing and storage, thus leading to a phenomenon of trade-off: Performance decreases when the concurrent memory load increases, and any increase in difficulty of processing results in a loss of information from short-term storage memory (Anderson, Reder, & Lebiere, 1996; Case, Kurland, & Goldberg, 1982; Conway & Engle, 1994; Daneman & Carpenter, 1980; Just & Carpenter, 1992). Within this theoretical framework, tasks differ in the cognitive load they place on working memory, that is, the amount of resources needed to carry them out. Though being intuitively appealing, the notions of resource and cognitive load have been the object of strong criticisms owing to their vagueness (Navon, 1984; Towse & Houston-Price, 2001). The aim of this article is to test the hypothesis that, far from being a vague metaphor, cognitive load is a function of the proportion of time during which a given activity captures attention, thus impeding other central processes.

The Resource-Sharing Hypothesis

The notion of cognitive load has not been universally accepted. For example, Towse and Hitch (1995; Hitch, Towse, & Hutton, 2001; Towse, Hitch, & Hutton, 1998) have argued that the idea of a limited resource-sharing capacity is superfluous to account for working memory phenomena. In complex working memory span tasks in which one must maintain memory items while performing a concurrent task, the loss of information would result not from the cognitive load of this intervening task but merely from its total duration. Longer processing times would result in longer delays of retention and, because memory traces suffer from a time-related decay, in poorer recall.

To test this assumption, our research group systematically explored the effect on recall of processing components that varied in either duration or cognitive demand in a series of studies using new working memory span tasks that were not self-paced but computer-paced (Barrouillet et al., 2004; Barrouillet & Camos, 2001; Gavens & Barrouillet, 2004; Lépine, Bernardin, & Barrouillet, 2005). It turned out that both factors had an effect on concurrent maintenance. First, in line with the resource-sharing hypothesis and contrary to Towse and Hitch's model, it appeared that even when duration of processing was controlled, great differences in spans still appeared as a function of the task. For example, solving arithmetic equations had a more detrimental effect on recall than a mere articulatory suppression (Barrouillet et al., 2004; Barrouillet & Camos, 2001; Gavens & Barrouillet, 2004). Second, and contrary to a widespread conception of cognitive load, even fairly simple tasks such as reading digits proved to have a highly detrimental effect on concurrent maintenance, provided that these tasks were performed under severe time constraints (Lépine, Barrouillet, & Camos, 2005; Lépine, Bernardin, & Barrouillet, 2005). To account for these phenomena, we proposed a new model of working memory, the *time-based resource-sharing model* (Bar-

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Pierre Barrouillet and Evie Vergauwe, Department of Psychology, Université de Genève, Geneva, Switzerland; Sophie Bernardin and Sophie Portrat, LEAD-CNRS, Université de Bourgogne, Dijon, France; Valérie Camous, LEAD-CNRS, Université de Bourgogne, and Institut Universitaire de France.

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Correspondence concerning this article should be addressed to Pierre Barrouillet, Université de Genève, 40 boulevard du Pont d'Arve, Geneva, Switzerland. E-mail: Pierre.Barrouillet@pse.unige.ch

rouillet et al., 2004), that leads to a new conception of cognitive load in which time plays a crucial role.

The Time-Based Resource-Sharing (TBRS) Model

The TBRS model is based on four main assumptions. First, the model assumes that in most of the working memory span tasks, both processing and maintenance of information rely on the same limited resource, that is, the attention involved in voluntarily controlled processes. This kind of attention has been referred to as controlled attention by Engle, Kane, and Tuholski (1999) and as attention directed by the central executive in Cowan (1999).

The second assumption is that many of the elementary cognitive steps involved in both processing and maintenance can take place only one at a time. We assume that this constraint can be described as an attentional or a central-processing limitation. In the former account, the focus of attention can select only one element of knowledge at a time as the object of the next cognitive operation (Garavan, 1998; Oberauer, 2002, 2005). In the latter, the central processes would be constrained by a central bottleneck applying to a variety of mental operations that are subject to voluntary control, such as response selection or memory retrieval (Pashler, 1998). Thus, we consider the two theoretical proposals as functionally equivalent, referring to the occupation of the central bottleneck and to the attentional capture as the same process. The main point is that when the focus of attention or the bottleneck is occupied by some processing episode, it is not available for the maintenance of memory items.

The third assumption is that memory items on which attention focuses receive activation, but as soon as attention is switched away, this activation suffers from a time-related decay (Cowan, 1995, 1999; Towse & Hitch, 1995). As a consequence, the memory traces of the items to be maintained fade away when attention is occupied by processing. The refreshment of these items before their complete disappearance necessitates their reactivation or reconstruction. This reactivation does not necessarily involve a rehearsal process, as Baddeley described in his model of the phonological loop (Baddeley, 1986; Baddeley & Logie, 1999). Rather, as demonstrated by Cowan (1992; Cowan et al., 1994), individuals can engage in a rapid and covert retrieval process through attentional focusing.

The fourth assumption is that, owing to the limitation of attention to only one element at a time and the time-related decay of memory traces outside the focus of attention, the sharing of attention is achieved through a rapid and incessant switching of attention from processing to maintenance. This rapid switching would occur during short pauses that would be made available while concurrent processing is running. We assume that a given task, however demanding it is, rarely induces a continuous capture of attention because attention can be frequently diverted, even for short periods of time, toward other thoughts and brought back to the current activity.

Time and Cognitive Load

What is *cognitive load* within the TBRS model? The answer to this question lies in the four assumptions stated above. Those tasks that tend to continuously occupy attention impede switching and involve a high cognitive load, whereas those tasks that permit frequent pauses and switches to other activities involve a low cognitive load and should be experienced as less demanding. This theory was tested by Barrouillet et al. (2004) using a working memory task known as the reading digit-span task, in which participants must maintain and recall series of letters of ascending length while reading digits. The stimuli are presented on successive screens displaying either a letter to be remembered or a digit to be read. After each letter to be remembered, some digits are presented in succession at a fixed pace. Barrouillet et al. assumed that when the processing component mainly involves retrievals, as in the reading digit-span task, the cognitive load (CL) would correspond to

$$\mathrm{CL} = aN/T, \tag{1}$$

where N corresponds to the number of retrievals (i.e., the number of digits to be read after each letter), a to a parameter that represents the time during which these retrievals capture attention, and T to the total time allowed to read the digits (i.e., the interletter interval). Thus, within the reading digit-span task, cognitive load can be assimilated to the number-of-retrievals/time ratio. Increasing the number of retrievals while keeping the total time unchanged should reduce the possibility to free up interdigit pauses to retrieve and update the decaying memory traces, thus resulting in poorer recall of letters. The same phenomenon should result from any reduction of the total time allowed to perform a constant number of retrievals. These predictions have been entirely confirmed: Barrouillet et al. (2004) observed that recall performance decreased linearly when the number-of-retrievals/time ratio increased. However, though in line with the TBRS model, the results reported by Barrouillet et al. do not constitute a comprehensive test of the model. Two main questions remain unanswered, both concerning the role of time in cognitive load and working memory functioning.

First, Barrouillet and colleagues (2004) manipulated the capture of attention induced by the processing component by varying the number of processing steps and the time allowed to perform them (parameters N and T in Equation 1). However, this procedure leads to a confounding of cognitive load with the rate at which the stimuli are processed. A more direct manipulation is needed. Furthermore, Barrouillet et al. exclusively used verbal processing components involving retrieval from long-term memory (i.e., reading digits or solving simple arithmetic problems). Within the TBRS model, the cognitive load a given task involves corresponds to the proportion of time during which this task captures attention, thus impeding concurrent activities that require central processes such as refreshing memory traces. Thus, even when both the number of stimuli to be processed and the total time allowed to process them remain unchanged (i.e., the N/T ratio), any increase in the duration of the attentional capture induced by each atomic processing step (parameter a in Equation 1) should lead to an increase in cognitive load and hence to lower recall performance. To test this hypothesis, we took advantage of the fact that the time needed to retrieve a given piece of information from long-term memory or to select a given response can vary with the physical characteristics of the stimuli. In the first experiment presented in this article, we used a reading digit-span task in which we varied the time needed to read the digits by manipulating their form (arabic digits, number words, or canonical dicelike patterns of dots). In a second experiment, the processing component consisted of a series of binary choices concerning the spatial location of a stimulus displayed on the screen (either up or down) that participants had to make while maintaining letters in memory. We varied the duration of these response selections by introducing a perceptual overlap between target stimuli, with high levels of perceptual overlap inducing slower responses (Nieuwenhuis, Yeung, & Cohen, 2004).

Second, according to the TBRS model, cognitive load varies as a function of the proportion of time during which attention is captured. Whatever the task to be performed as the processing component within a working memory span task, recall performance would depend only on the duration of the attentional capture it elicits. Thus, our third experiment tested the hypothesis that the differences in span induced by different demanding processing components (memory retrieval and response selection) should disappear when processing times are equated across tasks. However, our model predicts that cognitive load depends on the duration of the activity insofar as this activity is attention demanding; tasks involving a minimal attentional demand would not significantly occupy the central bottleneck, and their duration should thus not matter. To test this hypothesis, our fourth experiment compared the effect on recall of an attention-demanding task involving response selection with a simple reaction time (RT) task known to involve a negligible attentional demand. We predicted that in this case, even if the two processes are equated in duration, response selection should have a stronger disruptive effect on concurrent maintenance than a simple reaction.

Experiment 1

The aim of this first experiment was to test the hypothesis that, all other things being equal, increasing time during which an atomic processing step like memory retrieval captures attention results in a higher cognitive load and a more detrimental effect on concurrent maintenance. Though retrieving information from long-term memory may appear to be a basic process, many factors affect its duration. For example, it is well known that words are better and faster retrieved as their frequency increases (Monsell, 1991). The retrieval of number facts is faster when the problems involve small rather than large operands (Ashcraft & Battaglia, 1978; Siegler & Shrager, 1984; Zbrodoff & Logan, 2005). Goal-directed retrievals from long-term memory require controlled attention (Rosen & Engle, 1997), and we assume that differences in retrieval times reflect differences in the time during which the retrieval process captures attention and occupies the central bottleneck, exactly in the same way as Anderson et al. (1996) assumed that time and probability of retrieval reflect the amount of attention needed. Thus, we assume that the cognitive load involved by a given retrieval is a direct function of its duration: The slower this retrieval is, the higher is the cognitive load.

We tested this hypothesis by presenting adult participants with a reading digit-span task in which they had to remember letters while reading digits aloud. We varied the duration of the retrievals involved in reading digits by manipulating the form in which digits were displayed on the screen, either as words (e.g., *four*), arabic digits (*4*), or canonical dice patterns (::), assuming that each of these forms allows a direct access to stored representations in long-term memory (see Dehaene, 1992, and Dehaene & Cohen, 1995, for number words and arabic digits; see Mandler & Shebo, 1982, for canonical dicelike configurations of dots). As a pretest made clear, it takes longer to identify a given number when presented in its dicelike form as compared with its word or arabic form. Thus, assuming that these longer RTs reflect a longer capture of attention, we predicted that reading digit spans would be lower when the digits to be read were displayed as dicelike patterns of dots.

Method

Participants. Twenty-four undergraduate psychology students at the Université d'Aix-en-Provence (23 women, 1 man) received partial course credit for participating. Before being subjected to the three conditions of the reading digit-span task (arabic, words, and dots), the participants performed a preliminary test aimed at evaluating their reading times in these three forms.

Material and procedure. All of the experiments in this study were administered individually on the screen with PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993). During the preliminary test, participants were asked to read aloud two series of 24 items in each of the three forms (arabic, words, and dots), each number from 1 to 6 being presented four times in random order in each series. The order of completion of the three reading tasks was counterbalanced across participants. For each trial, a signal was centered on the screen for 750 ms, followed by the item to be identified after a delay of 350 ms. The reading times were measured using a voice key.

In a second phase, the participants performed the reading digit-span task, in which they had to memorize series of one to six consonants while reading numbers presented in three different formats (either as words, as arabic digits, or as patterns of dots) defining three experimental conditions. In this experiment and all of the following, all consonants in the alphabet were used except *W* (which is trisyllabic in French), with repetitions, acronyms, and alphabetically ordered strings avoided. There were two series of consonants of each length in each of these experimental conditions, resulting in three blocks of 12 series of letters to be remembered. Across participants, these blocks were assigned to the three experimental conditions following a Latin square design in such a way that each series of letters was studied in each experimental condition. Each series began with a signal (an asterisk) that was displayed on the screen for 750 ms and followed, after a delay of 500 ms, by the first letter. Each letter was displayed for 1,500 ms and followed by four numbers randomly selected from 1 to 6, which were successively displayed on the screen for 1,200 ms after a delay of 300 ms. This resulted in a pace of one number every 1,500 ms. These numbers were displayed as arabic digits (*1*, *2*, *3*, *4*, *5*, *6*), French number words from 1 to 6, or patterns of dots, and they appeared with the same frequency in each experimental condition. At the end of the series, the word *Recall* appeared on the screen, and the participants had to verbally recall the letters in the correct order. The 36 series were presented in a random order, the participants being informed about the length and the form of the numbers (arabic digits, words, or dots) of the forthcoming series.

The experimental session was preceded by a familiarization phase in which the participants read three series of four numbers in each of their three different forms and performed two trials of the span task for the one- and two-consonant lengths in each experimental condition.

Results and Discussion

The preliminary test confirmed that it takes longer to read digits presented as patterns of dots (507 ms) rather than in their word or arabic forms (425 ms and 424 ms, respectively), $F(2, 46) = 132.50$, $\eta_p^2 = .85$, $p < .001$, whereas these two latter RTs did not differ ($F < 1$; Table 1). Recall performance was assessed by computing both the rate of letters correctly recalled whatever the order and the rate of letters recalled in correct position within the series. As we predicted, the patterns of dots, which involved the longest reading times, elicited a lower rate of letters correctly recalled (87%) than both the arabic digits and the number words (90% in both conditions), $F(2, 46) = 3.43$, $\eta_p^2 = .13$, $p < .05$, a difference that was even clearer when recall order was taken into account (75% with dot patterns compared with 82% with both arabic digits and number words), $F(2, 46) = 5.48$, $\eta_p^2 = .19$, $p < .01$. This pattern of recall performance perfectly matched differences in reading times, with longer reading times resulting in poorer recall whereas equivalent reading times resulted in equivalent rates of correct recall. We replicated these findings in another experiment in which we used roman numerals instead of patterns of dots. In line with the present results, roman numerals, which induced longer reading times, involved poorer recall performance.[1]

Taken together, these facts lend strong support to the hypothesis put forward by Barrouillet et al. (2004) that the cognitive load induced by the processing component within the reading digit-span task depends not only on the number of retrievals to be performed and the total time allowed to perform them but also on the time during which these retrievals capture attention and block the central bottleneck. As the TBRS model postulates, parameter a in Equation 1 appears to play a major role in determining the cognitive load that a given task involves. However, our model predicts that not only retrievals from long-term memory but any attention-demanding process should have a detrimental effect on maintenance and that this effect should depend on the duration of this process. The following experiment explored this issue.

Experiment 2

The aim of this experiment was to assess the effect on concurrent maintenance of a secondary task involving not memory retrievals but rather a response selection process, the duration of which was manipulated. Several studies have demonstrated that response selection interferes with retrievals from long-term memory, suggesting that these two central processes compete for some common supply, which is probably executive control (e.g., Rohrer & Pashler, 2003; Szmalec, Vandierendonck, & Kemps, 2005), a hypothesis corroborated by imaging techniques (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000). According to the TBRS model, response selection should thus disrupt concurrent maintenance of information by impeding the refreshment of the decaying memory traces. Moreover, this effect should be more pronounced when response selection takes longer, something that we never investigated. The present experiment tested this hypothesis using a working memory span task with the same structure as the reading digit-span task: Participants had to maintain and recall series of letters, but the reading digit-task was replaced by a serial-choice RT task. Within each interletter interval, a black square appeared repeatedly on the screen at a fixed pace, centered in one of two possible locations (the upper or lower part of the screen), and participants were asked to judge this location by pressing one of two identified keys. We varied the duration of these response selections by manipulating the discriminability of the targets. In the distant condition, the two locations were clearly distinct, whereas in the close condition, the distance between the two locations was reduced to 5 mm. The resulting perceptual overlap between targets in the latter condition slowed down the selection of a response, as the measure of RTs during the task confirmed. We predicted that, all other things being equal, the close condition would have a more detrimental effect on maintenance and result in poorer recall.

Table 1
Reading Times (ms) and Percentage of Correctly Recalled Letters As a Function of the Presentation Format of Numbers in Experiment 1

Condition	Reading times		Overall correct recall		Ordered correct recall	
	M	*SD*	*M*	*SD*	*M*	*SD*
Dots	507	46	87	8	75	12
Arabic	424	45	90	7	82	11
Word	425	45	90	6	82	13

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[1] This experiment replicated Experiment 1 by comparing the arabic and word conditions of the reading digit-span task with a condition in which digits were displayed in their roman form. We used a between- rather than a within-subject design and the same span task procedure with the same stop criterion as Barrouillet et al. (2004). One hundred two undergraduate psychology students at the Université de Bourgogne participated: 18 took part in the preliminary test and the remaining 84 (72 women, 12 men) were randomly assigned to one of the three experimental conditions of the reading digit-span task (either arabic, words, or roman). The preliminary test and the reading digit-span task were the same as in Experiment 1 except that (a) participants had to read numbers from 1 to 9 displayed either in their arabic, number word, or roman form, and (b) they were presented with only one form of numerals and with increasingly long series of letters from one to seven until they failed to recall the letters of all three series at a particular level. Testing was terminated at this point. Each correctly recalled series counted as one third; the total number of thirds was added up to provide a span score. The preliminary test confirmed that it takes longer to read numbers in their roman form (625 ms, $SD = 61$) than in their arabic (442 ms, $SD = 45$) or number word form (446 ms, $SD = 39$), $F(2, 34) = 204.05$, $\eta_p^2 = .92$, $p < .001$. In line with these observations and our predictions, the reading digit spans varied as a function of the form in which the numbers were presented, $F(2, 81) = 3.11$, $\eta_p^2 = .07$, $p < .05$. The roman numerals induced lower mean spans than the arabic digits (3.87, $SD = 1.20$, and 4.54, $SD = 1.15$, respectively), $F(1, 81) = 4.92$, $\eta_p^2 = .06$, $p < .05$, and the number words (4.50, $SD = 1.03$), $F(1, 81) = 4.40$, $\eta_p^2 = .05$, $p < .05$. The two latest forms, which did not differ in reading times, elicited very similar mean spans ($F < 1$). Thus, the mean spans observed perfectly reflected what could be expected from the reading times.

Method

Participants. Twenty-four undergraduate psychology students at the Université de Bourgogne (21 women, 3 men) received partial course credit for participating.

Material and procedure. Participants were seated about 60 cm from the computer screen and were presented with series of three to eight consonants to be remembered. Each consonant was followed by a series of eight stimuli successively displayed on the screen. These stimuli consisted of a black square (18 × 18 mm subtending 2° of visual angle) centered on one of two possible locations either in the upper or the lower part of the screen. In the distant condition, the two locations were 68 mm apart (6.5° of visual angle), whereas in the overlapping condition, this distance was reduced to 5 mm (0.5° of visual angle), thus creating a 13-mm overlap between the two target squares. For each length, three series of consonants were associated with each condition of discriminability in the serial-choice RT task, resulting in a total of 36 series of consonants to be remembered that were presented to each participant.

Each series began by a ready signal (an asterisk) centered on the screen for 750 ms, followed after a 500-ms delay by the first letter, presented for 1,500 ms. After a postletter delay of 500 ms, each of the eight stimuli of the serial-choice RT task appeared for 666 ms and was followed by a delay of 333 ms, for a total of 1 s per stimulus. The following consonant thus appeared for 1,500 ms, and so on. At the end of the series, the word *Recall* was displayed on the screen. The 36 series were randomly presented, the participant being informed about the length and level of discriminability of each series (e.g., "close stimuli/3 letters," "distant stimuli/7 letters"). In each condition and each series, the squares were randomly displayed in the upper and the lower locations with the same frequency. Participants were asked to read aloud each letter; to judge the location of each square as fast as possible without sacrificing accuracy by pressing either a left- or a right-hand key for the lower and the upper location, respectively; and then to write down the remembered letters in correct order by filling out frames containing the appropriate number of boxes when recall was required. Besides the letters recalled, RTs and accuracy during the serial-choice task were recorded.

A training phase familiarized participants with the serial-choice RT task (nine series of eight stimuli in each discriminability condition with an 80% correct criterion requested) and then with the working memory task with three series of letters and stimuli to be processed ("close stimuli/5 letters," "distant stimuli/8 letters," and "close stimuli/3 letters").

Results and Discussion

All of the participants reached the 80% correct criterion during their training phase and took part in the experimental session. Concerning the serial-choice RT task, the close condition was more difficult than the distant condition (87% and 97% correct responses, respectively), $t(23) = 11.87$, $p < .001$, and, as we anticipated, resulted in longer RTs (377 ms and 314 ms, respectively), $t(23) = 13.45$, $p < .001$. As we predicted, these longer processing times had a disruptive effect on memory. As in Experiment 1, recall performance was assessed by computing both the rate of letters correctly recalled whatever the order and the rate of letters recalled in correct position within the series. With both measures, the close condition resulted in poorer recalls than the distant condition (86%, *SD* = 14, and 92%, *SD* = 7, of letters correctly recalled, respectively; 75%, *SD* = 16, and 83%, *SD* = 10, when order was taken into account), $t(23) = 2.71$, $p < .02$, and $t(23) = 3.07$, $p < .01$, respectively. Thus, this experiment extended the facts previously observed with retrievals from long-term memory to the response selection process. Increasing the duration of successive response selections has a disruptive effect on concurrent maintenance exactly as we observed with memory retrievals.

General Discussion of Experiments 1 and 2

The aim of the first two experiments was to establish that the cognitive load a given task involves varies as a function of the proportion of time during which it captures attention, even when the number of stimuli to be processed and the total time allowed to process them remain unchanged. This was demonstrated with memory retrievals and response selections. In each case, increasing the duration of processing that remains unchanged in nature has a disruptive effect on concurrent maintenance. Even relatively small increases in the time during which attention is distracted have an effect on recall. The fact that this effect is not task or process specific and not restricted to memory retrievals but extends to response selection reinforces the hypothesis that the locus of the effect lies in the attentional capture induced by both processes. However, the TBRS model goes further by claiming that the time during which the central bottleneck is occupied is the sole determinant of cognitive load. In other words, mental activities involving cognitive processes that differ in nature should induce the same cognitive load if these processes occupy the central bottleneck for equivalent periods of time. This prediction was addressed in the two following experiments.

Experiment 3

The first part of this article demonstrated that both memory retrieval and response selection have a disruptive effect on maintenance commensurate with their duration. The present experiment compared the effect of these two processes when involved as processing components in working memory span tasks. The task we used had the same structure as a reading digit-span task. Participants were asked to remember series of letters while processing strings of digits successively displayed on the screen, but the digits appeared either above or below a line centered on the screen. Apart from varying the number of digits presented within constant interletter intervals, we manipulated the nature of the task to be performed on these digits by asking participants to perform either a parity or a location judgment, by responding *odd* or *even* in the former condition and *above* or *below* in the latter by pressing appropriate keys. It is known that information about the parity of small numbers is associated with their arabic representation and directly retrieved from long-term memory when needed (Dehaene, Bossini, & Giraux, 1993). Thus, the parity judgment task involves memory retrieval as well as the selection of the response induced by the retrieved information. By contrast, the location judgment task involves a response selection but no retrieval from long-term memory.

As already shown by Barrouillet et al. (2004), recall performance should decrease as the number of stimuli within the interletter intervals increases, but the predictions of interest were those related to the differences between tasks. First, because it requires an additional memory retrieval and prolonged capture of attention, the parity judgment task should induce lower spans than the location judgment task. Second, although the two tasks rely on different cognitive processes, their effect on maintenance should not go beyond the time during which they capture attention, and they should have the same effect on spans if they take the same time. As a consequence, any differences in recall performance should disappear when the duration of the two tasks is controlled.

Method

Participants. Ninety-seven undergraduate psychology students at the Université de Bourgogne (84 women, 13 men) received partial course credit for participating and were randomly assigned to one of the six experimental groups defined by the factorial design 2 (task: parity vs. location judgment) × 3 (number of stimuli within the interletter intervals: 4, 6, or 8).

Material and procedure. Participants in each of the six experimental groups were presented with the same series of consonants of ascending length (from one to seven), with three series of each length. The 21 resulting series contained a total of 84 letters, each followed by strings of either 4, 6, or 8 stimuli consisting of a number from 1 to 10 displayed in its arabic form either above or below a horizontal line centered on the screen. In each condition (i.e., 4, 6, or 8 stimuli), the stimuli appeared in a fixed random order, with as many even as odd numbers equally distributed between the two possible locations. Thus, in both task conditions (parity and location), participants saw exactly the same strings of stimuli.

First, the participants were asked to focus for 750 ms on a signal (an asterisk) centered on the screen, which was replaced, after a delay of 500 ms, by the first letter to be remembered. The letters were displayed on the screen for 1,500 ms and followed by a delay of 500 ms before a string of stimuli to be processed appeared. Within these strings, each stimulus was displayed on the screen for either 1,067 ms, 711 ms, or 533 ms and followed by a delay of either 533 ms, 356 ms, or 267 ms for the 4-, 6-, and 8-stimulus conditions, respectively. Thus, the time available to process a stimulus was 1,600 ms, 1,067 ms, and 800 ms for the 4-, 6-, and 8-stimulus conditions, respectively, resulting in a constant interletter interval of 6,400 ms. At the end of the string of stimuli, either the word *Recall* or a second letter appeared, and so on.

The participants were asked to read aloud and to remember the letters. According to the condition they were assigned to, they had to judge, for each stimulus, either the parity of the number or its location by pressing one of two keys on the keyboard: one on the right for the *even* and *above* responses or one on the left for the *odd* and *below* responses. The computer recorded the nature of the responses as well as RTs. When the word *Recall* appeared, the participants had to recall aloud the series of letters in the correct order. They were presented with increasingly long series of letters until they failed to recall the letters of all three series at a particular level. Testing was terminated at this point. Each correctly recalled series counted as one third; the total number of thirds was added up to provide a span score (Barrouillet et al., 2004; Conlin, Gathercole, & Adams, 2005). For example, the correct recall of all of the series of one, two, and three letters, of two series of four letters, and of one series of five letters resulted in a span of $(3 + 3 + 3 + 2 + 1) \times 1/3 = 4$.

Before the experimental session, participants completed a training phase in which they performed, at the same pace as in the forthcoming experiment, either the parity or the location judgment task on 96 items (i.e., either 24, 16, or 12 strings of 4, 6, and 8 stimuli, respectively, at the paces described above). They received feedback for errors and had to obtain at least 80% correct responses to continue; if they did not, they were asked again to train with the same block of items. Then, three one-letter and three two-letter training series of the working memory span task were presented.

Results

One participant who did not achieve the criterion of 80% correct responses on the parity task was discarded from the analyses. The remaining 96 participants reached high rates of correct responses (91% and 97% for the parity and locations tasks, respectively), and all of the recalls were taken into account. We first report the data concerning working memory spans and then move to the results and analyses concerning processing times.

Working memory span analyses. We performed an analysis of variance (ANOVA) on the working memory spans with type of task (parity or location) and number of stimuli (4, 6, or 8) as between-subjects factors. In line with our predictions, the parity judgment task induced a lower mean span than the location judgment task (4.48 and 5.23, respectively), $F(1, 90) = 19.64$, $\eta_p^2 = .18$, $p < .001$ (Table 2), and the mean spans decreased as the number of items to be processed within the interletter intervals increased (5.36, 5.05, and 4.15 for 4, 6, and 8 stimuli, respectively), $F(2, 90) = 18.67$, $\eta_p^2 = .29$, $p < .001$. There was no significant interaction, $F(2, 90) = 1.10$, $\eta_p^2 = .02$, $p = .34$. Thus, the difference in spans produced by the parity and the location judgment tasks conformed to our expectations. However, our main prediction was that this effect is due only to differences in duration.

RT analyses. Two kinds of RT measures were of interest. The first was the mean RT reflecting the time needed to process a stimulus in a given experimental condition. Mean RT can be considered as an index of the difficulty of a task. For this purpose, we calculated individual mean RTs from the total amount of stimuli for which a given participant gave a response (i.e., excluding nonresponses but taking incorrect responses into account). The second was the mean total processing time, which corresponds to the total time devoted to processing the stimuli within the interletter intervals (i.e., the total of the RTs per string of stimuli). This last measure can be considered as reflecting the product aN in Equation 1, but it did not simply correspond to the mean RT multiplied by the number of stimuli per string, owing to rare but existing nonresponses that we considered, for sake of simplicity, to have involved no processing at all.

We performed an ANOVA on the individual mean RTs with the same factors as for the mean spans (Table 2). As we expected, parity judgments elicited longer RTs than location judgments (554 ms and 411 ms, respectively), $F(1, 90) = 120.09$, $\eta_p^2 = .57$, $p < .001$. Of interest, these RTs decreased when the number of stimuli

Table 2

Means and Standard Deviations for Reaction Time (RT) per Stimulus, Total Processing Time (TPT) per Interletter Interval, and Spans As a Function of Task Type and Number of Stimuli to Be Processed in Interletter Intervals in Experiment 3

	Type of judgment task											
	Parity						Location					
	RT		TPT		Span		RT		TPT		Span	
Number of stimuli	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
4	628	117	2,467	400	5.16	0.78	484	61	1,928	233	5.56	0.75
6	551	53	3,251	316	4.58	1.23	387	41	2,297	239	5.52	0.62
8	483	32	3,724	218	3.69	0.63	361	39	2,827	266	4.60	0.82
M	554		3,147		4.48		411		2,351		5.23	

Note. RT and TPT values are in milliseconds; spans reflect maximum number of letters recalled.

to process increased (556 ms, 469 ms, and 422 ms for 4, 6, and 8 stimuli, respectively), $F(2, 90) = 36.12$, $\eta_p^2 = .44$, $p < .001$, a phenomenon that was observed in both tasks without significant interaction ($F < 1$). This suggests that participants cope with the secondary task through some speed–accuracy trade-off. When the number of stimuli and thus time pressure increased, participants gave faster but, as we reported above, less accurate responses.

Of course, these differences in RTs resulted in differences in total processing times, which were longer for the parity than for the location task (3,147 ms and 2,351 ms, respectively), $F(1, 90) = 186.47$, $\eta_p^2 = .67$, $p < .001$, and obviously increased in both conditions with the number of stimuli to process (Table 2). The question of interest was whether the differences in spans observed between the parity and the location conditions would persist if both tasks involved similar processing times. We thus introduced individual total processing times as a covariate in the ANOVA on mean spans described above. The total processing times had a strong effect on spans, $F(1, 89) = 47.70$, $\eta_p^2 = .35$, $p < .001$. The F value associated with the effect of the number of stimuli was reduced from 18.67 to 4.75 but remained significant ($p < .05$, $\eta_p^2 = .05$). This remaining effect suggests that the impact of the number of stimuli to be processed while maintaining memory traces goes beyond the effect of the total duration of processing. The higher number of attentional switches between processing and maintenance resulting from an increasing number of items to be processed could account for this phenomenon, because switching is a demanding process the cognitive cost of which is not taken into account by measuring total processing time (Liefooghe, Barrouillet, Vandierendonck, & Camos, 2006). By contrast, and as we predicted, the F value associated with the effect of task dropped from 19.64 to 0.10, an effect that was no longer significant ($p = .75$, $\eta_p^2 = .001$), demonstrating that the effect of task was almost entirely underpinned by processing time differences.

A way to illustrate this phenomenon is to compare the equations resulting from the linear regressions of the mean spans on the mean total processing times per group for both tasks. More precisely, span scores were regressed on the total-processing-time/total-time-allowed ratio, the total time allowed corresponding to the duration of the interletter interval (here 6,400 ms + 500 ms of postletter delay = 6,900 ms) (Figure 1). In line with what is predicted by the TBRS model, the two slopes (–7.82 and –7.68 for the parity and the location tasks, respectively) were very close ($t < 1$), as were the two intercepts (8.04 and 7.84, respectively), suggesting that recall performance was determined almost entirely by the time allocated to the processing component rather than by its nature. Another way to illustrate this phenomenon is to calculate the extrapolated mean spans for the location judgment task as if it had taken the same total processing time as the parity judgment task, using the parameters of the regression line indicated above (slope = –7.68; intercept = 7.84). The extrapolated means were 5.10, 4.23, and 3.70 for 4, 6, and 8 stimuli, respectively, which can be compared with the observed mean spans for the parity judgment task, 5.16, 4.58, and 3.69, respectively. There was no significant difference between the two series of values (ps > .25).

Discussion

Two main facts arose from this experiment. As we expected, the parity judgment task, which involves both memory retrieval and response selection, has a more detrimental effect on concurrent maintenance than the location judgment task, which involves only response selection. An additional attention-demanding cognitive step, such as memory retrieval, extends the time during which the task blocks the central bottleneck, resulting in a higher cognitive load and an amplified memory loss. However, is this effect really a matter of time, as we predicted? This would suggest that memory retrieval and response selection do not differ in their effect on concurrent maintenance beyond the amount of time for which they capture attention. The present experiment demonstrated that both processes have actually the same effect. Indeed, when processing time was controlled, activities that differ in nature were found to have effects on recall performance that could no longer be distinguished. However, it could hastily be concluded from the previous experiments that the cognitive load a given activity involves is a direct function of its raw duration. The aim of the following experiment was to establish that cognitive load is commensurate with the duration of the task insofar as this task entails a sizable attentional demand.

Experiment 4

Up to now, we have studied the effect on concurrent maintenance of tasks involving attention-demanding activities such as retrieval or selection of response. Because this effect depends on

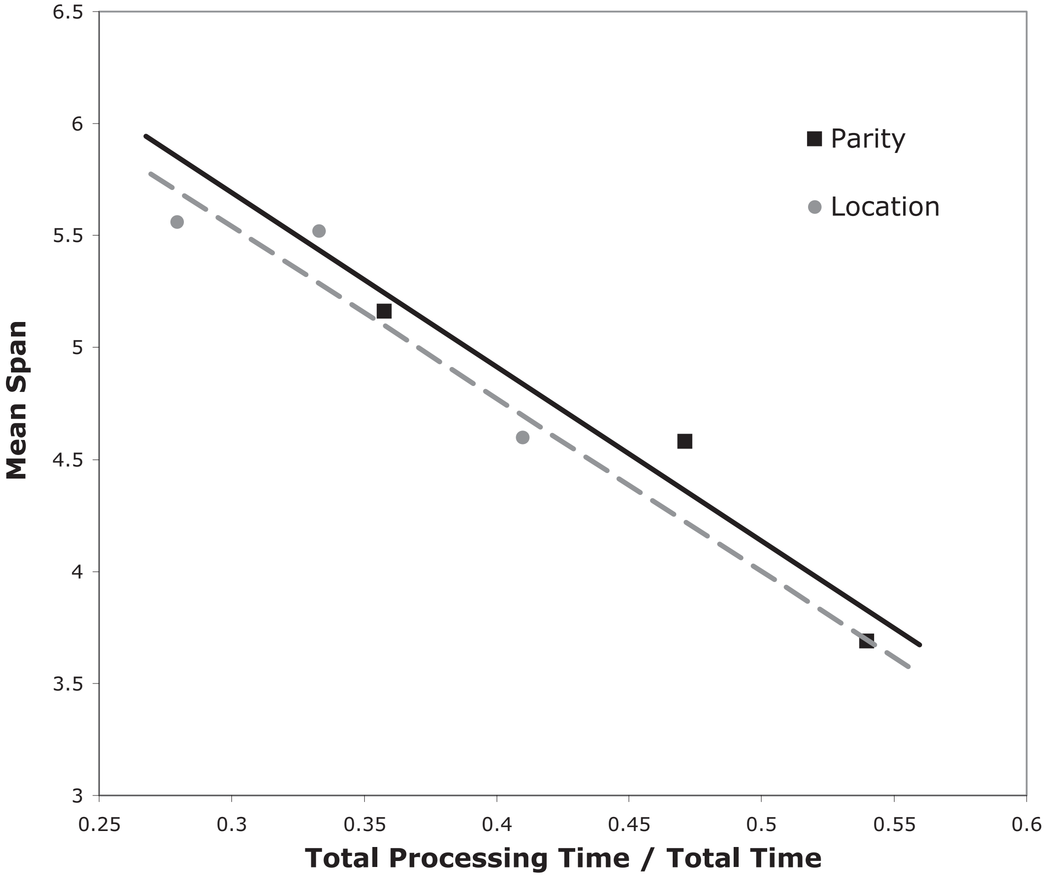

Figure 1. Mean spans in each experimental condition of Experiment 3 as a function of the proportion of time devoted to perform either the parity or the location task on the 4, 6, or 8 stimuli presented in each interletter interval (from left to right), along with linear regression line for each task.

the proportion of time during which these tasks capture attention, their duration mattered. By contrast, this last experiment tested the hypothesis that activities that place a negligible demand on executive processes should have, if any, moderate effects on spans, whatever their raw duration. For this purpose, we compared choice RT and simple RT tasks as processing components within working memory span tasks. Several authors have claimed that the choice RT task involves a series of processes requiring executive control that do not come into play in the simple RT task, such as stimulus discrimination (Cavina-Pratesi et al., 2006; Di Russo, Taddei, Apnile, & Spinelli, 2006; Neubauer & Knorr, 1997; Schluter, Krams, Rushworth, & Passingham, 2001), stimulus–response mapping (Gilbert, Simons, Frith, & Burgess, 2006; Stuss, Binns, Murphy, & Alexander, 2002), and response selection (Cavina-Pratesi et al., 2006; Donders, 1868; Frith & Done, 1986; Schluter et al., 2001; Schubert, 1999; Stuss et al., 2002). This difference in executive control implication has been corroborated by Szmalec, Verbruggen, De Baene, and Vandierendonck (2006) using imaging techniques. Accordingly, it has been demonstrated that choice RT tasks interfere with serial recall whereas simple RT tasks do not (Szmalec et al., 2005; Vandierendonck, De Vooght, & Van der Goten, 1998). Of course, the simple RT task at the least involves input monitoring, and as Deschuyteneer and Vandierendonck (2005) noted, it is implausible to assume that this process does not entail any executive control. However, the facts reported above suggest that a simple reaction consecutive to stimulus detection does not engage executive control and attention to the same extent as response selection does.

Thus, we assumed that by comparing the effect on maintenance of a choice and a simple RT task, we were comparing two processing components that strongly differ in the amount of executive control and attention they involve. The design of the present experiment was basically the same as in Experiment 3, except that it was not a digit but a dot that appeared either above or below the horizontal line. In the choice RT condition, participants were asked to judge the location of this dot, whereas in the simple RT condition, they were asked only to press a key as quickly as possible every time the dot appeared on the screen, whatever its location. If the cognitive load of the processing component and its impact on recall depend on the duration of the attentional capture it involves rather than on its raw duration, two main hypotheses can be drawn. The first, which is not specific to the TBRS model, predicts that the choice RT condition will result in lower spans than the simple RT condition, as already observed by Szmalec et al. (2005). The second hypothesis, derived from the TBRS model, predicts that increasing the number of stimuli while keeping unchanged the total time available to process them should induce a strong decrease in working memory spans in the choice RT condition but a negligible effect in the simple RT condition. As a consequence, and contrary to what we observed in Experiment 3, when equated in duration, the two tasks should still differ in the working memory spans they elicit.

Method

Participants. One hundred fourteen undergraduate psychology students at the Université de Bourgogne (107 women, 7 men) participated for partial fulfillment of a course requirement. One additional participant also took part but could not complete the experimental session owing to technical problems. Sixty-four participants were assigned to the simple RT condition; the remaining 50 participants were placed in the choice RT condition. Within these conditions, participants were randomly assigned to one of the subconditions defined by the number of stimuli in the interletter interval (5, 7, or 9 stimuli in the choice RT condition; 5, 7, 9, or 11 stimuli in the simple RT condition).

Material and procedure. All participants, irrespective of the task and the condition they were assigned to, were asked to read out loud and memorize the same series of consonants of ascending length (from three to eight letters) with three series of each length, resulting in 18 series (i.e., a total of 99 letters). Each series of letters was preceded by an asterisk that was centrally displayed on the screen for 750 ms and then replaced by the first letter after a delay of 500 ms. In the choice RT condition, each letter was presented for 1,500 ms, followed by either 5, 7, or 9 successively displayed dots situated randomly above or below a horizontal line.

In the simple RT condition, letters were also presented for 1,500 ms, but they were followed by either 5, 7, 9, or 11 such dots. The 11-stimulus condition was added to obtain a processing time in the simple RT task comparable to the one in the 9-stimulus condition in the choice RT task. Regardless of the number of stimuli involved in the intervening task (5, 7, 9, or 11), the duration of the interletter intervals was kept constant at 6,750 ms. Within this interval, each dot was presented for 250 ms on the screen, accounting for 1,250 ms, 1,750 ms, 2,250 ms, and 2,750 ms for 5, 7, 9, and 11 stimuli, respectively, with the remaining time divided in 6, 8, 10, and 12 different durations of delays, respectively. The different delays ranged from 580 ms to 1,230 ms for 5 stimuli; from 353 ms to 899 ms for 7 stimuli; from 250 ms to 650 ms for 9 stimuli; and from 250 ms to 420 ms for 11 stimuli. For each interletter interval, these delays were randomly inserted as either the postletter delay (i.e., the delay that followed the letter) or one of the postdot delays (i.e., the delay that followed one of the dots). In this way, the duration of the interletter interval was kept constant while the duration of the interstimulus intervals was randomized. Thus, the dots appeared at an unpredictable rhythm, preventing completion of the simple RT task by learning and reproducing a steady rhythm.

Participants were instructed either to judge the location of the dot (above or below the horizontal line) in the choice RT task, by pressing the same keys as in Experiment 3, or to react as quickly as possible every time a dot appeared on the screen in the simple RT task, by pressing the right-hand key. When the word *Recall* appeared on the screen at the end of the series, participants were instructed to recall the letters in their order of appearance. After registering the oral recall, the experimenter started the next series.

For each task, a training session preceded the experimental series. First, according to the condition they were assigned to, participants were presented with approximately 120 stimuli (i.e., 24 series of 5 dots, 17 series of 7 dots, 13 series of 9 dots, or 11 series of 11 dots), in order to train the fast and accurate execution of the secondary task. Every time participants committed an error or did not respond fast enough (i.e., within 500 ms), they heard a beep. To continue the training session, participants had to attain a level of 80% correct responses (the correct response in the simple RT task was pressing the key before the next dot or letter appeared). If they did not, they were presented with the same training stimuli once again. When participants failed to attain 80% after three such attempts, the experiment was terminated. When this first part was completed, the training session was continued with two three-letter and two four-letter series in which participants had to maintain the letters while carrying out the secondary task. The same stop rule as in the previous experiments was used, as well as the same method for calculating span scores, except that we added 2 to the total because this experiment used series of ascending length starting from three letters instead of one.

Results

Though the choice RT task was more difficult than the simple RT task (91% compared with 94% correct responses), all of the participants except 2 in the training session of the choice RT condition reached the criterion of 80% correct responses in both the training and the experimental sessions, resulting in 16 participants in each subcondition.

RT analyses. As in Experiment 3, we analyzed the mean RT as well as the total processing times (Table 3). In both the choice RT and the simple RT conditions, the effect of the number of stimuli on mean RT (5, 7, and 9 stimuli in the former and 5, 7, 9, and 11 stimuli in the latter condition) was not significant, $F(2, 45) = 1.10$, $\eta_p^2 = .05$, $p = .34$, and $F < 1$, respectively. The fact that the mean RT did not vary with the number of stimuli, contrary to what was observed in Experiment 3, suggests that the unpredictable rhythm prevented any planning in processing stimuli. Not surprisingly, ANOVAs on the total processing times in both the choice RT condition and the simple RT condition revealed a main effect of number of stimuli, $F(2, 45) = 137.29$, $\eta_p^2 = .86$, $p < .001$, and $F(3, 60) = 93.08$, $\eta_p^2 = .82$, $p < .001$, respectively.

Working memory span analyses. We performed an ANOVA on the working memory spans in the choice RT condition with number of stimuli per interletter interval (5, 7, or 9) as a between-subjects factor (Table 3). In line with our predictions, the increase in the number of stimuli to process led to a decrease in span when participants had to perform the choice RT task (mean spans of 5.50, 5.10, and 4.14 for 5, 7, and 9 stimuli, respectively), $F(2, 45) = 8.70$, $\eta_p^2 = .28$, $p < .001$. Conversely, an ANOVA on the working memory spans in the simple RT condition with number of stimuli per interletter interval (5, 7, 9, or 11) as a between-subjects factor showed that the number of stimuli did not have any significant effect on spans (mean spans of 5.31, 5.25, 5.13, and 5.33 for 5, 7, 9, and 11 stimuli, respectively; $F < 1$).

As in Experiment 3, span scores were regressed on the total-processing-time/total-time-allowed ratio, with total time allowed

Table 3
Means and Standard Deviations for Reaction Time (RT) per Stimulus, Total Processing Time (TPT) per Interletter Interval, and Spans As a Function of Task Type and Number of Stimuli to Be Processed in Interletter Intervals in Experiment 4

Number of stimuli	Simple RT *M*	Simple RT *SD*	Simple TPT *M*	Simple TPT *SD*	Simple Span *M*	Simple Span *SD*	Choice RT *M*	Choice RT *SD*	Choice TPT *M*	Choice TPT *SD*	Choice Span *M*	Choice Span *SD*
5	296	32	1,420	158	5.31	1.04	352	39	1,710	191	5.50	0.85
7	279	31	1,820	213	5.25	0.68	339	27	2,254	184	5.10	1.03
9	290	30	2,390	225	5.13	0.82	337	27	2,831	199	4.14	0.94
11	285	37	2,910	430	5.33	0.83						
M	287		2,135		5.26		343		2,265		4.92	

Note. RT and TPT values are in milliseconds; spans reflect maximum number of letters recalled.

corresponding to the duration of the interletter interval (here 6,750 ms) for the seven groups involved in Experiment 4. Two main facts arose. First, the variations on spans produced by varying the number of stimuli in the choice RT task resulted in a slope slightly steeper than those observed in Experiment 3 for the parity and location judgment tasks (−8.19 compared with −7.82 and −7.68, respectively), with an intercept slightly lower (7.66 compared with 8.04 and 7.84; Figure 2). These small differences could be due to the irregular pace at which the stimuli appeared in Experiment 4, whereas the pace was regular in both conditions of Experiment 3, which probably resulted in a more attention-demanding task. Second, the slope associated with the simple RT task was, as we predicted, practically nil (−0.05) and significantly different from the slope associated with the choice RT task, $t(108) = 18.40$. These last analyses made clear that a succession of simple reactions in response to stimuli does not impede concurrent maintenance of information in short-term memory, whereas performing binary spatial choices on the same stimuli has a strong impact on recall performance. Accordingly, though the 11-stimulus condition of the simple RT task involved approximately the same mean total processing time as the 9-stimulus condition of the choice RT task (2,910 ms and 2,831 ms, respectively), it elicited a higher working memory span (5.33 compared with 4.14), $t(30) = 3.78$, $p < .001$.

Discussion

As we expected, this experiment demonstrated that not all cognitive activities have an effect on concurrent maintenance commensurate with their duration: Those activities that do not solicit central processes for a sizable portion of time have no measurable impact on span. The implications of this fact are of importance. It makes clear that the effect on spans of the simple activities we use in our computer-paced working memory span tasks is not merely due to some distraction induced by events that burst into participants' field of vision while they are trying to remember items. If this were the case, increasing the number of events would worsen recall performance, contrary to what we observed. Moreover, this fact demonstrates that cognitive load is not a simple matter of time. Although the total processing time increased with more items to be processed, the spans were not significantly affected when participants were asked just to detect these items instead of analyzing them to select the appropriate answer. As the TBRS model predicted, what matters is not the raw duration of an activity but the proportion of time during which attention is captured and central processes are occupied. Taken together, the sets of results gathered in the two parts of this article delineate a conception of working memory and cognitive load that we confront, along with other conceptions and theories, in the following General Discussion.

General Discussion

The present study tested and confirmed the predictions issuing from the TBRS model concerning the relationships between time and cognitive load. Our findings have implications for three main questions related to working memory structure and functioning: the role of time in working memory, the relationships between processing and storage, and the nature of the mechanisms that underpin the loss of information from working memory. We address these three points in turn.

Time and Working Memory

The two first experiments demonstrated that the cognitive load induced by a task involving executive processes (memory retrievals or response selection) depends not only on the amount of information to be processed and the rate of processing but also on the duration of the atomic processing steps. Experiment 3 showed that the effect on concurrent maintenance of activities differing in the nature of the central processes they involve is commensurate with, and does not go beyond, their duration. These two facts suggest that the detrimental effect of processing activities on the concurrent maintenance of memory items depends on the time during which some resource or supply, which is recruited by memory retrievals but also by response selections, is occupied. The simplest way to account for this fact is to assume (a) that some central system is in charge of the mental operations needed to perform both the secondary task and the maintenance of memory items, (b) that this system is characterized by a sequential functioning, and (c) that memory traces suffer from a time-related degradation while this system is occupied by secondary task processes. Moreover, it seems from Experiment 4 that not all activities occupy this system to the same extent, suggesting that it is mainly

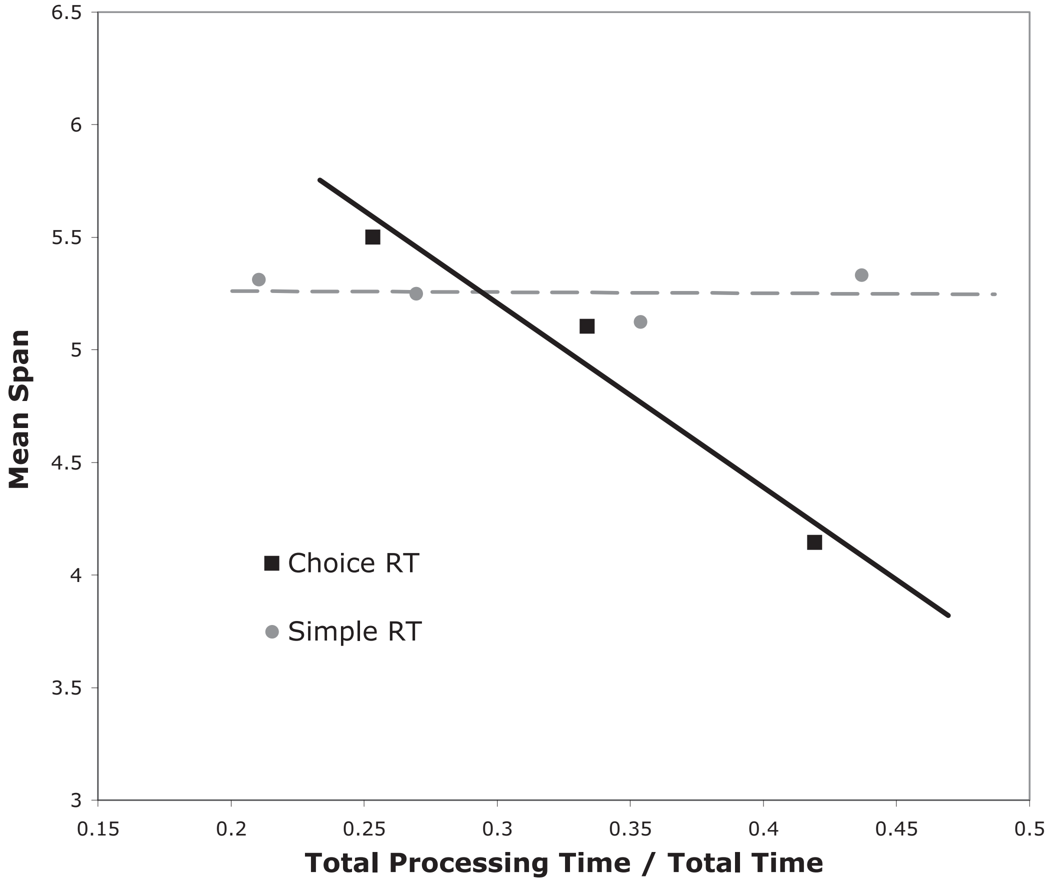

Figure 2. Mean spans in each experimental condition of Experiment 4 as a function of the proportion of time devoted to perform either the simple or the choice reaction time (RT) task on the 5, 7, or 9 stimuli presented in each interletter interval (from left to right), along with linear regression line for each task. The rightmost point in the simple RT condition refers to the control group with 11 stimuli.

involved in central processes known as *executive functions*. This system, which can be evenly described as a central bottleneck (Pashler, 1998) or as the focus of attention (Cowan, 1999, 2005; Oberauer, 2005), corresponds to the central executive in most of the working memory theories (Baddeley, 1986; Cowan, 1999; Engle et al., 1999). However, our results suggest some elaboration of the notion of central executive.

We assume that the role of the central executive is to form, maintain, and transform temporary representations held in working memory. These representations could integrate information from a variety of sources, similar to the representations stored in Baddeley's (2000) episodic buffer. According to Cowan (1999, 2005), this integration could take the form of binding activated features of memory within the focus of attention. Such an integrative and constructive process is thus attention demanding (Baddeley, 2000). What are known as executive functions (i.e., attention shifting and focusing, memory retrieval, information updating and monitoring, inhibition, response selection) are processes that select and combine the features that form working memory representations. We assume that this system is constrained in three ways. The first constraint is beyond the scope of this article and concerns the maximum number of features that can be focused and bound to form a representation (Cowan, 2001, 2005; Oberauer, 2002). Second, two operations transforming the current working memory representation (i.e., two executive processes) could not be performed at the same time, leading to a sequential functioning of working memory. Third, the temporary nature of the representations constructed in working memory implies that as soon as a representation leaves the focus of attention, a time-related degradation occurs, weakening the activation level of its constitutive features as well as the bonds between them.

Thus, the disruptive effect on concurrent maintenance of any activity—that is, its cognitive load—is a function of the time during which this activity occupies the central executive by involving executive functions that are temporarily unavailable to refresh and reconstruct precise representations of the memory items. Because recall performance depends on the integrity of the representations of these items, different processes can have the same effect on recall provided that they occupy the central bottleneck for equivalent periods of time, as we observed in Experiment 3. However, those activities that place a minimal demand on executive processes can have a slight and possibly negligible impact on concurrent maintenance. For example, a task could involve executive processes for periods of time that are so short that they are not sufficient to significantly corrupt representations of memory items. In Cowan's (1999) model, it could be assumed that in the simple RT task, the stimuli grasp attention automatically when they appear but do not require deep encoding because there is only one type of response to produce (there is no need to construct a representation of the target to produce the response). As a consequence, the simple RT task does not require the involvement of the central executive. This is probably why the simple RT task did not significantly affect recall performance in Experiment 4.

The Relationships Between Processing and Storage

Many theories favor a multicomponent approach of working memory in which processing and storage rely on different systems (Baddeley, 1996, 2000; Baddeley & Logie, 1999; Kieras, Meyer, Mueller, & Seymour, 1999; Schneider & Detweiler, 1987). Accordingly, many studies have reported that two demanding tasks could be simultaneously performed without dual-task interference (Duff & Logie, 2001; see Baddeley & Logie, 1999, for a review), leading Cocchini, Logie, Della Sala, MacPherson, and Baddeley (2002) to recently conclude that "the dual-task findings are more readily explained by a multiple-resource model, with each resource functioning more or less independently and with demands on one resource having little impact on the efficiency of other resources" (p. 1093). All of our results are at odds with this conclusion. Varying the demand of a silent parity judgment task or even a spatial task had a strong effect on verbal memory and recall. These results considerably extend the impact of the TBRS model. In all of our previous studies, the disruptive effect on maintenance of verbal material (either letters or digits) was produced by secondary tasks involving some verbal component such as reading digits or letters, solving arithmetic problems, or browsing the numerical chain (Barrouillet et al., 2004; Gavens & Barrouillet, 2004; Lépine, Bernardin, & Barrouillet, 2005). By contrast, in Experiments 3 and 4, not only were the processing activities silent, but it can be assumed that the location tasks did not involve a verbal component. The straightforward conclusion for these phenomena is that visuospatial processing disrupts verbal memory.

As Morey and Cowan (2005) noted, the possibility of interferences between similar verbal stimuli could not be discarded in accounting for the trade-off observed by Barrouillet et al. (2004) between processing (reading numbers aloud) and storage (maintaining consonants). However, such interferences could hardly account for the phenomena observed in Experiments 2, 3, and 4 of the present study. It is difficult to imagine how and why the spatial task we used could involve some verbal recoding. At most, it could be argued that selecting a response, even in a spatial task, does involve some inner speech. However, even such an extreme hypothesis cannot account for the fact that increasing the duration of the spatial task in Experiment 2 had a detrimental effect on verbal memory whereas the number of stimuli, and thus the number of responses to be produced, remained unchanged. Thus, it seems improbable that the effects we observed are due to similarity-based interference. Rather, they suggest that, contrary to Cocchini et al. (2002), processing and storage rely on a single and general-purpose attentional resource. The discrepancy in results between Cocchini et al. and our study probably stems from methodological differences. It should be noted that our paradigm involves a strict control of time.[2] It is only under time constraints that tasks as simple as judging spatial locations can disrupt concurrent maintenance of verbal information. When participants are allowed to perform the secondary task at their own pace, as in Cocchini et al., or at a moderate rate, as in the easiest conditions of Experiment 7 in Barrouillet et al. (2004), recall performance remains practically unaffected by concurrent processing, something predicted by the TBRS model. Because time is the critical factor, the interactions between processing and storage can be properly estimated only under time control.

Moreover, and in line with Morey and Cowan's (2005) observations, our results tend to contradict the idea that verbal and spatial processing and memories are underpinned by modality-specific attentional capacities. Increasing the rate of the spatial location task in Experiment 3 resulted in a sharp decrease in verbal recall, suggesting that a shared attentional resource is involved rather than independent modality-specific attentional capacities. This does not mean that there are no code-specific storage devices, such as the phonological loop (Baddeley & Logie, 1999), or that some form of passive storage and attention-free maintenance is impossible. Many studies have demonstrated that some passive storage can be surprisingly efficient without any attentional involvement (Keller, Cowan, & Saults, 1995; Naveh-Benjamin & Jonides, 1984; Saults & Cowan, 1996). Such a passive storage could account for some results considered as strongly contradicting any resource-sharing model. For example, Duff and Logie (2001) compared the word spans obtained through immediate verbal serial recall of lists with those obtained through a reading span procedure in which maintenance of words was combined with the reading of sentences under severe time constraints. The authors observed a significant reduction of memory span under the combined-tasks condition (from 4.75 to 3, approximately), but

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[2] It could be argued that presenting the memory items for 1,500 ms or the stimuli to be processed for 1 s or more, as we did here, does not allow one to consider that time was controlled. It is true that items to be recalled are usually presented for 1,000 ms (Conlin & Gathercole, 2006; Kahana & Jacobs, 2000; Oberauer et al., 2004; Rosen & Engle, 1997; Shah & Miyake, 1996), but it should be remembered that this duration is generally used for convenience and out of habit rather than being theoretically grounded. Longer presentations are not rare (1,250 ms in Hale, Myerson, Rhee, Weiss, & Abrams, 1996; 1,500 ms in Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; 2,000 ms in Duff & Logie, 2001). The computer-paced nature of our tasks makes them particularly demanding, with participants often reporting that they feel bombarded with letters and digits by a computer that they cannot stop or even slow down. We chose these durations of presentation to prevent, as far as possible, such a feeling and to ascertain a comfortable completion of the tasks. Moreover, it should be noted that our aim in controlling time was not to prevent the participants from refreshing memory traces by impeding any attentional switching but to constrain these refreshing activities in strictly controlled temporal boundaries. Such a control is the only way to grasp the subtle effects on memory maintenance of small variations in processing activities that would go unnoticed if participants had the opportunity to organize their activity without restraint. Finally, these long presentation durations could only run counter to our hypotheses. The fact that differences of about 100 ms in processing components result in significant differences in recall performance even though participants could probably rehearse the memory items can be seen as additional evidence for the impact of time on working memory.

they argued that if both processing and storage demands are stretching working memory to its capacity limits, then combining the task demands should result in a greater drop than observed.

Is this argument compelling, and would the TBRS model predict a drop so great that all memory traces would be lost? Of course not. The shift of attention from some period of time, even without any possibility of distraction, would not necessarily result in a dramatic memory erasing. Considering that the reading period lasted exactly 10 s in Duff and Logie (2001) and that word encoding was distributed over this period as in a traditional Daneman and Carpenter (1980) reading span procedure, it is not so surprising that adults were able to recall three words, even if their attention was totally captured by reading and was focused on memory material only for short encoding episodes. What this result indicates is that without any probable refreshment, adults can retrieve up to three words from working memory after a delay of 10 s. However, it does not provide information about the existence (or nonexistence) of resource sharing between processing and storage. Despite the fact that a moderate amount of information can be passively maintained for some period of time in short-term memory, mundane experiences of thought, as well as our results, show that information stored in working memory often suffers from the slightest distraction of attention. Thus, we turn now to one of the main problems of working memory: the loss of information.

The Loss of Information From Working Memory

The results of the present study suggest that information within working memory suffers from a time-related decay as soon as attention is switched away and captured by concurrent activities. However, many authors have argued against the idea that memory traces decay with time in short-term memory. For example, Nairne (2002) claimed that it is relatively easy to falsify the decay theories that assume a progressive fanning of memory traces through time by demonstrating, as many studies did, that longer periods of retention can result in no memory loss or even improved recall performance (Greene, 1996; Turvey, Brick, & Osborn, 1970). Other models have suggested that time affects memory not by degrading memory traces but by modifying the temporal distinctiveness between items, their distinctiveness decreasing as the time between input and recall increases (e.g., the SIMPLE model; Brown & Chater, 2001; Brown, Neath, & Chater, 2002). However, predictions from this model have also been ruled out by demonstrating that memory performance does not decline as the delay between study and recall of an item increases (Lewandowsky, Duncan, & Brown, 2004).

Though they seem compelling, we claim that these findings do not contradict our theory. First, the TBRS model does not predict that memory performance declines when the delay between encoding and recall increases. On the contrary, Barrouillet et al. (2004) predicted and observed all of the possible combinations between duration of retention and memory performance, including better recall through longer retention periods. This is not at all surprising, because what matters is not the delay between input and output but the proportion of time during which attention is captured over this delay. In the same way, the TBRS model easily accounts for the findings of Lewandowsky et al. (2004), who observed that immediate serial recall performance was not disrupted when participants had to repeat a suppressor word (“super”) either one, two, or three times between recalls, thus increasing the delay between study and output. As Barrouillet et al. demonstrated, the critical factor is not the delay but the rate at which the intervening activity is performed. It is possible that the “super” manipulation did not have any effect because in all of the conditions, the suppressor was uttered at the same rate, thus leaving unchanged the cognitive load induced by this secondary task. Lewandowsky et al. concluded that time-based theoreticians have either to show that a time-based theory can handle their results or to provide new empirical evidence. We claim that the TBRS model meets both parts of the challenge and that a time-related decay is the simplest hypothesis to account for the findings reported here.

However, this cognitive-load-related degradation of memory traces cannot in any way account for all of the phenomena of forgetting within working memory. For example, when studying working memory span tasks, Lustig, May, and Hasher (2001) demonstrated the specific effect on recall performance of interference produced by items from antecedent test trials. More recently, Conlin et al. (2005) convincingly suggested that complete accounts of working memory need to include mechanisms that mediate similarity-based decrements in addition to attentional constraints and time-based forgetting described by the TBRS model. The notion of similarity-based interference has been developed by Nairne (1990) within his feature model of immediate memory and recently extended to the domain of working memory by Saito and Miyake (2004) and Oberauer and colleagues (Lange & Oberauer, 2005; Oberauer, Lange, & Engle, 2004). Within this theoretical framework, similarity-based interference, or representation-based interference, occurs when representations generated during the processing episodes share the same features or attributes as the representations generated from the encoding of the to-be-remembered items. The greater the overlap is, the greater the degree of interference and the lower the probability of correct recall will be. Saito and Miyake stressed that this account differs from time-based interference because the degree of representational overlap and not the duration of interference determines later recall performance. Accordingly, many studies have shown that recall performance is better when the representations constructed for the processing and storage requirements are dissimilar (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Conlin & Gathercole, 2006; Conlin et al., 2005; Shah & Miyake, 1996). However, we have already noted that this kind of interference could not account for the results presented here. Moreover, the TBRS model can account for both time- and similarity-based forgetting.

As we suggested above, working memory representations are temporary and thus are progressively broken down into their component features when leaving the focus of attention. It can be assumed that the process of reconstruction or *redintegration* (Hulme et al., 1997) by which memory traces are refreshed will be more difficult when the features pertaining to the relevant representations cannot be easily distinguished from other features recently activated. This is the case when the representations used during processing share many features with those of the memory items. The resulting overwriting process described by Nairne (1990) and Cowan (2005) would then lead to the construction of new and inappropriate links, leading to incorrect retrievals and recalls. It is even possible that the sheer passage of time increases the probability of this similarity-based interference if the features and the bonds between them are weaker and weaker with time, as Posner and Konick (1966) proposed in the acid-bath theory.[3] As a consequence, although time-related decay and interference constitute two distinct causes of short-term forgetting that are frequently contrasted, they do not necessarily call for different theoretical accounts and models. The extensions we introduced above to the TBRS model account for both forms of forgetting within a unified theoretical framework. One form of forgetting is related to cognitive load through the occupation by concurrent activities of the executive processes needed for maintenance, the other to similarity-based interference and failures in the reconstructive process when relevant and irrelevant representations share features and overlap. Whether one form of forgetting is more important than the other remains an open question that necessitates further studies.

Nonetheless, the present series of experiments makes clear that time is one of the main determinants of cognitive load and mental effort. Apart from the fact that our theory substantiates folk conceptions of mind and daily experience in which time is a main and inescapable constraint, it replaces rather vague and metaphorical conceptions with a simple metric to understand and evaluate cognitive load. After all, it is not so surprising that this metric includes time as the main factor, relating the mechanics of cognition to the physical laws of work and power.

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[3] We would like to thank Klaus Oberauer for suggesting this reference.

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