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Attention switching and working memory spans

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Barrouillet and Camos (2001) concluded from their developmental study on working memory that when performing complex span tasks, individuals maintain memory items by switching rapidly their attention from processing to storage while performing the concurrent task. Thus, a processing component that would require a continuous attentional focusing should have a highly detrimental effect on span. The present study verifies two predictions issuing from this hypothesis by comparing the classical self-paced reading and operation span tasks with new computer-paced tasks in adults. First, any increase in the pace at which the processing component of a working memory span task has to be performed impedes switching and then leads to lower spans. Second, when presented at a fast pace, even simple activities such as reading letters or adding and subtracting 1 to small numbers have an effect on spans as detrimental as complex activities like reading and understanding sentences or solving complex equations.

The concept of working memory (Atkinson & Shiffrin, 1968; Baddeley & Hitch, 1974) has been used to describe the cognitive architecture and processes that underlie the maintenance of relevant information during the completion of cognitive activities. As a consequence, the tasks designed to evaluate individual differences in working memory capacity are complex span tasks that involve both storage and processing of information. For example, the reading span task created by Daneman and Carpenter (1980) requires participants to read sentences while maintaining their last word in memory. Similarly, in Turner and Engle's (1989) operation span task, participants have to verify equations while maintaining words in memory. The counting span task (Case, 1985) requires participants to count dots on cards and remembering their totals. In all of these tasks, participants have to perform complex processing while concurrently maintaining items in short-term memory. These working memory spans proved to be lower than simple short-term memory spans such as the digit, letter, or word spans.

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Two hypotheses have been put forward to account for the difficulty of the complex span tasks, and more precisely how processing constrains storage and recall. As far as the cognitive space hypothesis (Case, 1985) is concerned, both processing and storage would share a common and limited pool of resources with a trade-off between the two components. Accordingly, Case, Kurland, and Goldberg (1982) demonstrated that a more demanding counting activity resulted in poorer recall performance and lower counting spans. However, Towse and Hitch (1995) proposed another explanation they called the memory decay hypothesis. The difficulty of complex span tasks would come from the fact that the memory traces of the to-be-remembered items suffer from a time-related decay while the concurrent task is being performed. In this account, more difficult concurrent tasks result in lower spans because they involve longer durations of processing and greater decay (Towse, Hitch, & Hutton, 1998).

In order to distinguish between time and cognitive load effects on working memory spans, Barrouillet and Camos (2001) designed a series of experiments for children aged from 6 to 11 years in which they manipulated the cognitive load induced by the concurrent task while maintaining its duration constant. They compared the spans obtained from two working memory tasks in which the processing component is demanding (i.e., the counting span and the operation span tasks) with a new measure of span that they called the baba span, in which the concurrent activity consisted in an allegedly free-load articulatory suppression, with participants just having to repeat the syllable ‘‘ba’’. The rationale of these experiments was to carefully control for the exact duration of counting or operation solving on the one hand and concurrent articulation on the other. The results were quite surprising.

As predicted by Towse and Hitch’s (1995) memory decay hypothesis, the authors failed to observe any significant difference between the baba span and the counting span. However, in line with the cognitive load hypothesis, the operation span was significantly lower than the baba span. The authors suggested to account for this pattern of results with an attentional hypothesis, which assumes that maintaining active the memory traces of the to-be-remembered items requires attentional focusing. However, activation decays as soon the attention is switched away from these items. Thus, complex span tasks that require processing plus storage result in lower spans than simple short-term memory span tasks because, in the former, attention is distracted from the items to be remembered by the concurrent task. Barrouillet and Camos (2001) suggested that the absence of difference between counting and baba spans could be due to the fact that counting is a highly automatised skill that does not require more attentional resources than saying ‘‘baba’’, even in young children (Camos, Barrouillet, & Fayol, 2001; Camos, Fayol, & Barrouillet, 1999; Towse & Hitch, 1997). Nonetheless, both types of processing prevent subjects from continuously maintaining the memory items in the focus of attention, hence the greater difficulty of counting and baba span tasks than a simple short-term memory task.

In contrast, the authors suggested that the solution of multi-operand arithmetic problems involves many retrievals from memory at the same time as the calculation and maintenance of intermediate results, all processes that need attentional resources and sustained focusing. As a consequence, the operation spans were lower than the baba spans. However, Barrouillet and Camos (2001) noted that the difference between the two spans was not as large as it could be expected. They suggested that children, while solving the operations, are able to switch their attention from the task in hand to the memory items, for example when they reach some intermediate result. Such a rapid switching could permit to reactivate memory traces without any covert rehearsal process: an item retrieved by a simple mental search could briefly enter the focus of attention and become reactivated (Cowan, 1992; Cowan, Keller, Hulme, Roodenrys, McDougall, & Rack, 1994). The authors assumed that, if their hypothesis is correct, a task that would require an uninterrupted attentional focusing on algorithmic computation should have a highly detrimental effect on span.

The aim of the following experiments was to test two predictions issuing from this hypothesis in adults. First, if the maintenance of the memory items relies on a frequent and rapid switching of attention from processing to storage, the more continuously the processing captures attention, the rarer the opportunities to switch attention, and the stronger the decay of memory traces would be. In other words, increasing the pace at which a given processing component is performed should reduce the possibilities to switch attention and should result in lower spans. Second, even a quite simple activity could disrupt maintenance and have a highly detrimental effect on spans if it has to be performed at a pace that prevents participants from switching attention from processing to maintenance. To test these predictions makes it necessary to constrain the participants to continuously focus their attention on the processing component of the task. As Towse, Hitch, and Hutton (2002) have stressed, the self-paced presentation of stimuli in traditional working memory span tasks is problematic because it allows participants to use a switching strategy that undermines the rationale of these tasks (see also McNamara & Scott, 2001, for a similar idea). For example, in the operation span task (Turner & Engle, 1989), participants can momentarily interrupt the verification of the operations to refresh the memory traces, then go back to the processing of operations, and so on. To avoid this shortcoming, a computer-paced procedure was needed in which the information to be processed is progressively displayed on screen, participants being asked to perform the successive processing steps in due time. In Experiment 1, we compared the effects on span of the self-paced verification of complex equations as in the operation span task (Turner & Engle, 1989) with a simpler but computer-paced activity like a browse in the numerical chain by adding or subtracting one. In Experiment 2, the comparison involved the complex activity of reading and understanding sentences and the simple activity of reading a series of letters. The use of computer-paced tasks allowed us to manipulate the pace at which they were performed.

EXPERIMENT 1

In this experiment, the traditional operation span task[1] was compared with a new task we called the ‘‘continuous operation span task’’. In the former, the processing component was self-paced and consisted of verifying complex equations (8 + 6 + 9 = 24?), each of them being preceded by a letter to be remembered. In the latter, instead of solving equations, the concurrent activity consisted of a computer-paced elementary algorithmic processing task. Between the letters to be remembered, adults were asked to perform a running operation by simply adding or subtracting 1 to a small number. After the presentation of this small number we called the root, a series of sign-operand pairs (either +1 or -1) were displayed on screen. For example, 4 / +1 / +1 / -1 / +1 were successively presented at a predetermined pace and adults were asked to read and solve the operations aloud, saying ‘‘four, plus one five, plus one six, minus one five, plus one six’’.

According to our hypothesis, such a simple activity should have a highly detrimental effect on span provided that it continuously captures attention and prevents switching from processing to storage. As a consequence, the effect of the continuous operations should be all the more detrimental if they prevent more efficiently such a switching. In order to test this prediction, we manipulated the rhythm of presentation of the stimuli used in the continuous operations. Pretests indicated that about 700 ms are needed to initiate a vocal answer to simple one-digit operand additions or subtractions. Because, in the continuous operation span task, participants have to read aloud the operands and to utter the answer in due time before the next sign–operand pair appears, we considered that presenting a sign–operand pair each second should induce a sustained focusing of attention. In this fast condition, the attentional hypothesis then predicts that the continuous operations, though being simple, should have an effect on span at least as detrimental as solving complex equations in the classical self-paced operation span task. By contrast, a slower pace (e.g., 2 s for each sign–operand pair) should be more comfortable and should allow participants to rapidly switch their attention and refresh the decaying memory traces of the letters to be remembered. This slow condition should result in higher spans than both the classical operation span and the fast continuous operations span tasks. In summary, we predicted higher working memory spans from the slow than the fast continuous operation span tasks, the latter task resulting in no better recall performance than the self-paced operation span task.

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[1] Though, technically, the operation span and the reading span tasks we used in Experiments 1 and 2 respectively are not the seminal versions of Daneman and Carpenter’s (1980) and Turner and Engle’s (1989) tasks, we refer to these tasks as the ‘‘traditional working memory span tasks’’ because they share with these previous versions two main characteristics. Like these seminal versions, and most of the working memory span tasks used in the literature, they are self-paced and involve a complex processing component.

Method

Participants. Sixty-six undergraduate students at the University of Bourgogne (59 females and 7 males, mean age: 20;6 years, *SD*: 4;6 years, range: 17–45 years) received course credit to participate. They were randomly assigned to the three experimental groups of 22 participants each (slow continuous operation span, fast continuous operation span, classical operation span tasks).

Materials and procedure. All the tasks were administered individually using Psyscope software (Cohen, MacWhinney, Flatt, & Provost, 1993). In the three groups, participants had to read out loud and to memorise the same series of consonants of ascending length (from 1 to 7) with three series of each length. All the consonants except W (which is trisyllabic in French) were used. Each series began by a signal (an asterisk) that was displayed on screen for 1 s and followed, after a delay of 500 ms, by the first letter. Each letter was displayed on screen for 1500 ms. For all the tasks, when the word ‘‘recall’’ was displayed on screen, participants were instructed to recall the letters of the series in their order of appearance. The experimental conditions differed by the intervening task that was presented after each letter to be remembered.

Concerning the continuous operation span tasks, each letter was followed, after a delay of 500 ms, by a root (a number from 1 to 9) that remained on screen for 1500 ms. This root was then followed by a series of either 2, 3, or 4 sign–operand pairs (either +1 or -1). We varied the length of the series of sign–operand pairs in order to avoid an absolutely constant and predictable rhythm of presentation of the letters. These series of sign–operand pairs were constructed at random, but those series that led to an intermediate or final result lower than 1 or higher than 9 were discarded (e.g., 3 / -1 / -1 / -1, or 8 / +1 / +1). In the fast condition, the pace was of one sign–operand pair per second, each pair being displayed on screen for 750 ms after a delay of 250 ms, whereas in the slow condition the pace was twice slower, with 1500 ms of presentation and 500 ms of delay. A delay of 500 ms preceded the presentation of the following letter at the end of each continuous operation. Participants were asked to read aloud the letters as well as the roots, the signs and the operands and to give all the answers aloud. For example, when presented with 4 / +1 / +1 / -1 / +1, participants were asked to say ‘‘four, plus one five, plus one six, minus one five, plus one six’’.

The operation span task was adapted from Turner and Engle (1989). Eighty-four three-operand additions were constructed (e.g., ‘‘ 6 + 7 + 2 = 13?’’). The proposed answer was true for half of the problems and false for the other. After each letter, and following a delay of 500 ms, an equation was displayed on screen and remained until the participant gave his response by pressing the ‘‘Q’’ key if the proposed answer was true and the ‘‘M’’ key if it was false. The participants were asked to read the equation aloud before responding. There was no time limit to answer. Pressing the key removed the operation from the screen and the next letter was presented after 500 ms for 1500 ms.

In each condition, two one-letter and two two-letter training series preceded the experimental session. For all the tasks, participants were presented with increasingly longer 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 (Kemps, de Rammelaere, & Desmet, 2000; Smith & Scholey, 1992). For example, the correct recall of all the series of 1, 2, and 3 letters, of two series of 4 letters and one series of 5 letters resulted in a span of $(3 + 3 + 3 + 2 + 1) \times 1/3 = 4$.

Results

As far as the performance on the secondary tasks was concerned, the verification of the equations in the operation span task elicited 91% of correct responses with a mean verification time of 5524 ms. For sake of comparison, the duration of the interletter intervals for the two-, three-, and four-operand continuous operations was 6500 ms, 8500 ms, and 10500 ms, respectively in the slow condition, and 4500 ms, 5500 ms, and 6500 ms in the fast condition. In these latter tasks, the rate of correct responses was 99% for both slow and fact continuous operations.

An analysis of variance (ANOVA) was performed on the spans with the type of task (slow continuous operation span task, fast continuous operation span task, operation span task) as a between-subject factor. This analysis revealed that the mean continuous operation span was significantly higher in the slow than in the fast condition (3.65 and 2.30, respectively), $F(1, 63) = 28.90$, $MSe = 0.693$, $p < .01$. As we expected, increasing the rhythm of presentation of the operands impaired switching strategies and resulted in a significant decrease in spans (Table 1). Moreover, as we anticipated, this fast presentation resulted in a mean span that did not differ from the mean span from the classical Turner and Engle's (1989) operation span task, which is known for its difficulty (2.30 for both tasks), $F < 1$.

Discussion

The results of Experiment 1 clearly demonstrated that the effect of a given activity on working memory span depends mainly on the extent to which this task captures attention and prevents participants from switching their attention to the items to be recalled in order to refresh their decaying memory traces. As the cognitive load hypothesis would predict, a demanding task such as verifying complex arithmetic equations has a more detrimental effect on spans than adding or subtracting 1 to small numbers at a slow and comfortable pace. Many studies in cognitive arithmetic have established that solving this kind of simple problem just involves direct retrievals of the answer from memory, retrievals

TABLE 1
Mean spans (and standard deviations) as a function of the nature of the processing component involved in the working memory span tasks for Experiments 1, 2, and 3

	Nature of the processing component		
	Simple computer-paced tasks		*Complex self-paced tasks*
	Slow	*Fast*	
Operation solving (Experiment 1)	3.65 (0.92)	2.30 (0.78)	2.30 (0.81)
Reading (Experiment 2)	4.17 (1.00)	3.11 (0.93)	3.38 (0.78)
Parity judgement (Experiment 3)	5.10 (1.16)	3.81 (1.03)	—

that have been described as automatic (Aschcraft & Battaglia, 1978; Barrouillet & Fayol, 1998; Campbell, 1994; LeFevre, Bisanz, & Mrkonjic, 1988; Zbrodoff & Logan, 1986). It is thus not surprising that the operation span task is more difficult than the continuous operation span task. However, this is true only when the latter task is presented at a comfortable pace. When the same task has to be performed at a high pace that just allows participants to give the current answer before receiving the next operand, the resulting span drops to the level of the operation span.

This pattern of results suggests two main conclusions. First, as we predicted, what is needed to disrupt maintenance and recall is just a task that captures attention. This fact lends strong support to the theories that assume that the activation and maintenance of items of knowledge in working memory is achieved through a process of attentional focusing (Cowan, 1995, 1999; Lovett, Reder, & Lebière, 1999). As soon as these items leave the focus of attention, their activation decays. Second, time pressure seems to play a major role in what is considered as the cognitive demand. The slow and fast versions of the continuous operation tasks involved exactly the same processes but resulted in very different recall performance. Considering that the spans reflect the cognitive demand of the processing component involved in the working memory span task, we must conclude that the cognitive demand that a given task involves depends on the rate at which this task is performed. This phenomenon shed light on the reasons why complex cognitive activities such as problem solving, reasoning, or text comprehension are demanding. As Kahneman (1973) has already stressed, many of the tasks usually considered as demanding are tasks in which time pressure is inherent to their structure. For example, mental arithmetic necessitates keeping track of the problem to be solved, of subgoals, and of intermediary results, the memory traces of which suffer from decay and interference in short-term memory. Any interruption or even slowing down calculation can lead to irremediable loss of information and failure. Our results suggest that a time pressure induced by the experimental design has the same effects as the time pressure inherent to the structure of complex activities.

However, does any activity impair maintenance and recall provided that it is presented at a sufficiently high pace? Experiment 1 does not allow us to answer this question. Indeed, the cognitive processes involved in the continuous operation span task are akin to those involved in the solution of complex arithmetic problems. We designed the former to mimic the algorithmic solution of arithmetic problems in which a current result is continuously updated by further computational steps until the final answer is reached (for example, solving $8 + 6 + 9 = 24$ by $8 + 6 = 14$, $14 + 6 = 20$, $20 + 3 = 23$). Thus, it could be argued that both activities involve the same elementary processes, and that our computer-paced design just created the time pressure inherent to complex arithmetic problem solving, hence the comparable cognitive demand of both activities. Experiment 2 was designed to evaluate this possibility by comparing the effects on span of two activities that deeply differ in the cognitive processes they involve.

EXPERIMENT 2

Daneman and Carpenter's (1980, 1983) reading span was the first and remains one of the most frequently used measures of working memory span. Actually, the reading span task is paradigmatic of the complex span tasks with a highly complex and demanding processing component such as reading and understanding sentences. As Siegel (1994) pointed out, working memory is assumed to play an important role in reading because the executive component is involved in triggering grapheme–phoneme conversion rules, retrieving information about word meanings, and processing syntax while subsidiary systems retain for brief periods the words, propositions and sentences that have been already processed in order that longer units of text can be comprehended. The fact that the reading span is predictive of text comprehension abilities, whereas simple short-term memory spans are not, has largely confirmed this analysis (Daneman & Carpenter, 1980, 1983; Daneman & Hannon, 2001). However, according to Barrouillet and Camos' (2001) hypothesis, the difficulty of the reading span task does not result from the complexity of its processing component but merely from the fact that reading and processing sentences capture attention that is therefore not available to refresh decaying memory traces. We tested this hypothesis by comparing the reading span task with a computer-paced reading letter span task, the processing component of which comprised reading series of letters. It should be noted that this comparison differs from the previous we conducted between operation and continuous operation span tasks. In the latter case, both tasks could be considered as involving the same cognitive processes. In the present comparison, identifying letters is of course one of the elementary components of reading, but reading series of letters, even under time pressure, can not be considered as mimicking the activity of reading sentences in order to comprehend them. Nonetheless, as in the previous experiment, we predicted that a simple activity of reading series of letters could have the same detrimental effect on spans as processing sentences provided that it is presented at a pace that prevents attentional switching. Thus, we predicted that a fast reading letter span task should have the same effect on recall performance as a classical reading span task, whereas a reading letter span task presented at a slower pace should result in better recall performance.

Method

Participants. Sixty-six undergraduate students at the University of Bourgogne (60 females and 6 males, mean age: 21;1 years, *SD*: 5;1 years, range: 18–45 years) were randomly assigned to three groups of 22 participants defined by the three experimental conditions (slow reading letter span task, fast reading letter span task, classical reading span task). None of them participated in the previous experiment.

Materials and procedure. In the three groups, participants were asked to read out loud and to memorise series of numbers of ascending length (from 1 to 7) with three series of each length. All the numbers from 1 to 16 were used (except 14, which is a bisyllabic word in French). As in Experiment 1, each series began by a signal (an asterisk) that was displayed on screen for 1 s and followed, after a delay of 500 ms, by the first number. Each number was displayed on screen for 1500 ms in its Arabic form.

As far as the reading letter span tasks were concerned, participants were asked to read aloud series of 4–6 letters that were successively presented after each number. In these series, each letter was displayed on screen for either 500 ms or 1000 ms with a delay of either 175 ms or 300 ms in the fast and slow conditions respectively. The reading span task was inspired from Daneman and Carpenter (1980). After each number to be remembered, participants were asked to read aloud and to evaluate the plausibility of a sentence displayed on screen. The 84 experimental sentences contained 4–11 words (mean 6.9). Half of them were true and the others false (e.g., ‘‘A cow lays eggs’’). The sentence remained on screen until the participant pressed one of the two keys identified as ‘‘true’’ and ‘‘false’’ on the keyboard. There was no time limit.

In the three tasks, participants were asked to recall the series of numbers in their correct order when the word ‘‘recall’’ appeared on screen. The stop rule and the procedure to evaluate spans were the same as in Experiment 1.

Results and discussion

As far as the secondary tasks were concerned, more than 98% of the sentence judgements in the reading span task were correct, while the reading of letters was virtually perfect in both the slow and the fast conditions. The mean time to judge the sentences was 2803 ms, which was shorter than the mean internumber intervals in both the fast and the slow reading letter spans tasks (3375 and 6750 ms).

An analysis of variance (ANOVA) was performed on the spans with the type of span task (slow reading letter span task, fast reading letter span task, reading span task) as a between-subject factor. As we predicted and in line with the results of Experiment 1, the slow reading letter span was significantly higher than the fast reading letter span (4.17 and 3.11, respectively), $F(1, 63) = 14.94$, $MSe = 0.827$, $p < .01$. The traditional reading span (3.38) was lower than the slow reading letter span, $F(1, 63) = 8.22$, $MSe = 0.827$, $p < .01$, but did not significantly differ from, and was even slightly higher than, the fast reading letter span, $F < 1$ (Table 1).

In summary, this experiment replicated the results of Experiment 1. For both types of concurrent task, either verbal or arithmetic, increasing the pace at which simple processing components have to be performed resulted in a significant span decrease, in such a way that the spans in the fastest condition did not differ from the classical self-paced reading or operation spans. A global ANOVA on the results of the two experiments with the type of processing component (arithmetic in Experiment 1 vs. verbal in Experiment 2) and the type of span task (slow paced, fast paced, and classical) as between-subject factors did not reveal any significant interaction, $F < 1$.

Thus, the surprising difficulty of the continuous operation span task, at least in its fast version, is not due to the algorithmic nature of the processes involved or to the need to keep track of the current result of the continuous operation. An activity that does not require any memory load or algorithmic process but only the retrieval of overlearned information from memory such as reading letters is sufficient to disrupt the concurrent maintenance of information in short-term memory. This fact confirms our prediction that a task that continuously captures attention would have a highly detrimental effect on span. However, before discussing the theoretical implications of this result, a possible alternative explanation must be discarded. It could be argued that the effect of solving continuous operations or reading letters on the concurrent maintenance in short-term memory is not due to the capture of attention but merely to the articulatory suppression these activities involve. Indeed, the articulatory suppression hypothesis would account for the fact that faster pace results in poorer recalls. Reading aloud the same letters or solving aloud the same operations in a reduced period of time involves a higher level of articulatory suppression, thus resulting in a greater difficulty to refresh decaying memory traces and at the end in poorer recall. The aim of our third experiment was to discard this hypothesis by demonstrating that, even when the intervening task does not involve any articulatory suppression, the pace at which it has to be performed has a direct impact on spans.

EXPERIMENT 3

In this experiment, participants were presented with a computer-paced working memory span task in which they were asked to maintain letters while evaluating the parity of one-digit numbers presented successively on screen in the inter-letter intervals. The participants gave their response by pressing appropriate keys on the keyboard, thus avoiding articulatory suppression. According to our theory, the more continuously the processing component captures attention, the stronger the decay of memory traces and the poorer the recall would be. Thus, we contrasted two experimental groups that differed only by the time allowed to judge the parity of each number presented, that was either 800 ms or 1500 ms. We predicted that reducing the available time and thus increasing the pace at which the participants had to judge the parity of the numbers would result in lower spans.

Method

Participants. Thirty-two undergraduate students at the University of Bourgogne (29 females and 3 males, mean age: 20;5 years, *SD*: 3;5 years, range: 17–37 years) received course credit to participate and were randomly assigned to the two experimental conditions (slow or fast parity judgement span task). None of them participated in the previous experiments.

Materials and procedure. The two span tasks were administered individually using PsyScope. Participants were asked to read and memorise the same series of letters as in Experiment 1. Three series of each length, from 1 to 7 letters, were presented. As in the previous experiments, each series began by a signal that was displayed on screen for 1 s and followed, after a delay of 500 ms, by the first letter displayed on screen for 1500 ms. Participants were asked to recall the series of letters in their order of presentation when the word ‘‘recall’’ appeared. The stop rule and the procedure to evaluate spans were the same as in Experiments 1 and 2.

As far as the secondary task was concerned, participants were asked to evaluate the parity of one-digit numbers and to give their response by pressing one of two keys identified as ‘‘odd’’ and ‘‘even’’ on the keyboard. Each letter was followed by a series of between four and eight numbers (from 1 to 9) presented in their Arabic form. There were 18 series of each length (4–8) resulting in a total of 90 series of digits (i.e., 84 experimental and 6 practice series). The numbers in each series were randomly drawn from the set of one-digit numbers, so that in the entire task half of the numbers were odd and the others even. All the participants in both experimental conditions were presented with the same series of numbers. In the fast condition, each number was displayed on screen for 600 ms and the delay between two numbers was 200 ms, whereas in the slow condition, the numbers were presented during 1125 ms with a delay of 375 ms. Thus, the time allowed for the parity judgement was 800 ms and 1500 ms per digit in the fast and slow conditions respectively.

In order to familiarise participants with the pace of presentation of numbers and the response keys, a training task was presented before the span task. Participants were asked to perform the parity judgement task on five series of eight numbers each, presented at the same pace as in the subsequent span task (1500 ms or 800 ms per number). When the participant failed to give the correct answer as well as when he or she did not answer in assigned time, a beep sounded. At the end of the training task, each participant was given his or her percentage of correct responses. An extra training session was given when the rate of correct responses was lower than 80% (six participants in the fast condition). Feedback was restricted to the training session. Following this training and before the experimental task, participants were presented with four practice trials for the working memory span tasks, with two series of one letter and two series of two letters.

Results and discussion

As far as the secondary task was concerned (parity judgement), the mean correct response rate was 88%. The participants were less accurate in the fast than in the slow condition (83% and 94%, respectively), $t(30) = 5.04$, $p < .01$. Although this difference could suggest that participants in the fast condition paid less attention to the secondary task, they also exhibited, as we predicted, lower spans than those involved in the slow condition (3.81 and 5.10, respectively), $F(1, 30) = 11.01$, $MSe = 1.21$, $p < .01$ (Table 1). Thus, this control experiment clearly indicated that the effects observed in the previous experiments can not simply be accounted for by the well-known effect of articulatory suppression in short-term memory maintenance and reinforced our hypothesis that the main factor is the capture of attention.

GENERAL DISCUSSION

Reasoning about the moderate differences in working memory spans that resulted from the comparison between processing components that would greatly differ in cognitive demand, Barrouillet and Camos (2001) suggested that individuals achieve rapid switching from processing to storage that permits them to maintain memory items. Thus, the authors predicted that a task that would prevent such a switching by inducing a continuous attentional focusing should have a highly detrimental effect on spans. Our two experiments confirmed this hypothesis by demonstrating that even simple activities disrupt maintenance and recall when they are performed under time pressure. In line with this hypothesis, working memory spans depend on the pace at which these activities are completed. The higher this pace, the shorter the periods during which attention can be diverted from processing to refresh decaying memory traces. Accordingly, even a mere reading of letters can have an effect on spans as detrimental as reading and understanding sentences, provided that the letters are presented in such a way that their identification captures attention almost continuously. This fact suggests that activities such as reading and problem solving have such a detrimental effect on concurrent maintenance of memory items probably because time pressure is inherent to their structure. It is even possible that the complexity of the tasks usually used as processing components in working memory span tasks (reading, problem solving, reasoning) is a nonessential characteristic needed merely to induce the required time pressure that impels continuous attentional focusing. When working memory span tasks are computer-paced, complex processing components are no longer needed.

This fact echoes working memory models that consider attentional resources as a kind of mental energy that produces activation and determines which information enters working memory (Kintsch, Healy, Hegarty, Pennington, & Salthouse, 1999). For example, in their application of ACT-R model (Anderson, 1993; Anderson & Lebiere, 1998) to working memory functioning, Lovett et al. (1999) assume that attentional energy is needed to produce the activation and retrieval of items of knowledge from long-term memory. Those items activated above threshold would enter working memory and are available for processing. However, the total amount of available attentional resource would be limited, and any simultaneous activations would require to divide up this limited amount, thus resulting in lower activations, slower retrievals, and an increased probability of failure. This kind of model can account for our results. Frequent retrievals from working memory, for example when reading series of letters, could capture a substantial amount of the attentional resource which is no longer available to concurrently refresh and maintain memory traces that suffer from a time-related decay. Our results can then be accounted for by the Time-Based Resource Sharing model (Barrouillet, Bernardin, & Camos, 2004), according to which working memory span tasks would involve a time-constrained resource-sharing process between processing and storage. Because memory traces of the items to be remembered decay as soon as attention is switched away, their maintenance depends on the amount of time attention is captured by the intervening treatment.

However, it is worth noting that our results are not at odds with other working memory theories that consider cognitive resources as a capacity for controlled attention (Engle, Kane, & Tuholski, 1999) or the capacity of some central executive (Baddeley, 1996; Cowan, 1995). Indeed, performing simple activities under time pressure while maintaining memory items requires focused and sustained attention as well as rapid and efficient switching from one part of the task to the other, all activities that necessitate some central executive to control attention and monitor processes. In contrast, some of our results could be considered as contradictory to Towse, Hitch, and Hutton's (1998) task switching model. Indeed, the authors assume that working memory spans depend mainly on the retention interval, that is the duration of the processing component. Longer delays would result in stronger memory decay and lower spans. At the opposite, we predicted and observed in both experiments that a faster completion of the processing component, and then shorter delays of retention, resulted in lower spans. Our results would contradict the task switching model if one considers that participants do not attempt to maintain memory items during processing, but switch between phases of activity devoted to either processing or retention in a way that reflects the structure of working memory task, something that Towse and Hitch have sometimes argued (Hitch, Towse, & Hutton, 2001; Towse et al., 2002).

Although our results can be accommodated with the main models of working memory, it could be considered as surprising that simple activities such as elementary additions or reading letters have so great an effect on concurrent maintenance and recall. Indeed, these activities have often been described as automatic and non-demanding. For example, it has been argued that the answer of simple operations as we used in the continuous operation span task is automatically activated by the presentation of the operands (LeFevre et al., 1988; Winkelman & Schmidt, 1974; Zbrodoff & Logan, 1986). In the same way, the identification of letters by adults has been considered as automatic and used to produce interference and Stroop effects (Navon, 1977; Regan, 1981). These simple activities, relying on direct and automatic retrievals from long-term memory, are often considered as leaving the pool of resources intact (Rosen & Engle, 1997). However, this conception of cognitive demand does not fit easily with available observations. For example, Kahneman (1973) reported that when measuring mental effort by arousal and pupillary dilations, tasks that could be considered as ''easy'' (such as recall of thoroughly overlearned information or retaining five digits for immediate recall) induced larger pupillary dilations than apparently more complex tasks. Thus, he concluded, ''the intuitive notion of task difficulty is not sufficient to determine the amount of effort that a task demands'' (p. 25). Moreover, Kahneman noted that the amount of effort that is required to perform a task could not merely depend on intrinsic characteristics of this task because it is also obviously determined by the rate at which this task is completed. Our results totally confirm this point of view. When performed at a moderate pace, solving continuous operations and reading letters are not particularly demanding activities as testified by the high spans we observed. When performed at a high pace, they proved to have a highly detrimental effect on concurrent maintenance. This suggests that simple activities can involve a large amount of effort but during short periods of time. Their reiteration under time pressure becomes highly demanding because it requires continuous attentional focusing.

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