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Barrouillet, Pierre Noël; Gavens, Nathalie; Vergauwe, Evie; Gaillard, Vinciane; Camos, Valérie

How to cite

BARROUILLET, Pierre Noël et al. Working Memory Span Development: A Time-Based Resource-Sharing Model Account. In: Developmental psychology, 2009, vol. 45, n° 2, p. 477–490. doi: 10.1037/a0014615

This publication URL: https://archive-ouverte.unige.ch/unige:88292

Publication DOI: 10.1037/a0014615

Developmental Psychology
2009, Vol. 45, No. 2, 477–490

0012-1649/09/$12.00 DOI: 10.1037/a0014615

Working Memory Span Development: A Time-Based Resource-Sharing Model Account

Pierre Barrouillet
Université de Genève

Nathalie Gavens
Université de Bourgogne

Evie Vergauwe and Vinciane Gaillard
Université de Genève

Valérie Camos
Université de Bourgogne and Institut Universitaire de France

The time-based resource-sharing model (P. Barrouillet, S. Bernardin, & V. Camos, 2004) assumes that during complex working memory span tasks, attention is frequently and surreptitiously switched from processing to reactivate decaying memory traces before their complete loss. Three experiments involving children from 5 to 14 years of age investigated the role of this reactivation process in developmental differences in working memory spans. Though preschoolers seem to adopt a serial control without any attempt to refresh stored items when engaged in processing, the reactivation process is efficient from age 7 onward and increases in efficiency until late adolescence, underpinning a sizable part of developmental differences.

Keywords: working memory, cognitive development, complex spans

Many theories of cognitive development consider working memory as a general causal construct in accounting for the age-related growth in processing complexity (Case, 1985; Halford, 1993; Pascual-Leone, 1970, 2000). Cognitive development would at least in part result from the development of working memory (Bjorklund, 2005). Accordingly, many studies have documented the age-related increase in working memory capacity using working memory span tasks in which children have to maintain information to be recalled while performing some intervening task (Case, Kurland, & Goldberg, 1982; Hitch, Towse, & Hutton, 2001). However, as pointed out by Towse, Hitch, and Horton (2007) in their recent survey of the literature, although an extensive body of research has been devoted to working memory in children, it is not easy to discern a developmental model of working memory. According to the authors, important developmental changes have been identified in working memory, but we are some way from understanding these in detail. The aim of the present study was to investigate developmental changes in a process that is central in the time-based resource-sharing (TBRS) model of working memory recently proposed by Barrouillet, Bernardin, and Camos (2004), namely, the reactivation of decaying memory traces by rapidly shifting attention between the different activities that are simultaneously run in working memory. As far as we know, this aspect of working memory functioning has never been studied in children.

Pierre Barrouillet, Evie Vergauwe, and Vinciane Gaillard, Department of Psychology, Université de Genève, Geneva, Switzerland; Nathalie Gavens, Department of Psychology, LEAD-CNRS, Université de Bourgogne, Dijon, France; Valérie Camos, Department of Psychology, LEAD-CNRS, Université de Bourgogne, and Institut Universitaire de France.

Part of this research was supported by Swiss National Science Foundation Grant 100014-118296/1. This article was written in part while Valérie Camos was supported by a Leverhulme Trust Fellowship at the University of Bristol, Bristol, England. We would like to thank Caroline Haller, Marion Bruschweiler, Diana Pereiro Pombo, and Céline Deffaugt for collecting data.

Correspondence concerning this article should be addressed to Pierre Barrouillet, Faculté de Psychologie et de Sciences de l'Education, Université de Genève, 40 boulevard du Pont d'Arve, 1205 Genève, Switzerland. E-mail: Pierre.Barrouillet@pse.unige.ch

Developmental Changes in Working Memory

One of the first factors of change that has been identified in working memory development is processing efficiency. Using a counting span task in which children at different ages were asked to count dots in series of arrays while remembering and then to recall the totals, Case et al. (1982) provided evidence that recall performance was a function of the maximum speed at which children were able to count the arrays. The authors assumed that a total processing space, which would remain constant across ages, is shared between an operating space devoted to processing (here counting) and a short-term storage space devoted to maintenance. They considered counting speed as an index of processing efficiency and reasoned that more efficient processing takes up fewer resources in working memory, thus freeing more available space for storage, hence the better recall in older children. However, Towse and Hitch (1995) proposed an alternative account for the relationship between counting speed and span. Discarding Case et al.'s hypothesis of resource sharing and trade-off between processing and storage, they proposed a task-switching hypothesis according to which children alternate their attention between processing and storage during working memory span tasks, with memory traces suffering from a time-related decay when children are engaged in the counting process. Better recall in older children would be due to their faster counting that results in shorter periods of retention of the items to be remembered.

Gavens and Barrouillet (2004) tested Case et al.'s and Towse and Hitch's proposals in a developmental study. They controlled both the duration of the retention period using computer-paced working memory span tasks and the processing efficiency by equating the difficulty of the intervening task across ages. Nonetheless, they observed a residual developmental effect indicating that the increase in processing efficiency is not the sole factor underpinning developmental changes in working memory. In line with this observation, Bayliss, Jarrold, Gunn, and Baddeley (2003) showed that, beyond processing efficiency, individual differences in storage ability contributed independent variance to the prediction of children's complex span performance. This storage ability was further specified by Bayliss, Jarrold, Baddeley, Gunn, and Leigh (2005), who investigated the constraints underlying developmental improvements in working memory spans. The authors did not deny that storage ability could reflect variations in the rate of forgetting of passively maintained information (Cowan, Nugent, Elliot, & Saults, 2000; Saults & Cowan, 1996; Towse & Hitch, 1995) or age-related changes in encoding and retrieval processes (Cowan et al., 1992, 1998, 2003). However, they suggested that this storage ability would mainly reflect differences in the process of refreshment of memory traces that we hypothesized in our TBRS model (Barrouillet et al., 2004). This model assumes that however demanding it is, a task rarely requires attention continuously, leaving the possibility to switch attention surreptitiously to other thoughts (Barrouillet & Camos, 2001). Thus, during complex span tasks, when individuals are not engaged in the processing activity, they would take advantage of these free pauses to reactivate or rehearse the memory items.

The TBRS Model

The TBRS model assumes that, within complex span tasks, both processing and maintenance of information rely on the same limited resource, which is attention. This is obviously the case for complex activities such as reading sentences and solving arithmetic equations (Conway, Kane, & Engle, 2003; Engle, Kane, & Tuholski, 1999; Kane & Engle, 2003), but also for simpler activities such as reading letters or digits, for which attention is needed to activate relevant declarative knowledge from long-term memory (Anderson, 1993; Anderson & Lebiere, 1998; Logan, 1988). The maintenance of information also requires attention because maintaining information active in primary memory necessitates attention (Cowan, 1995, 1999; Engle & Oransky, 1999; Lovett, Reder, & Lebière, 1999). Consequently, attention must be shared between processing and storage. However, there would be a processing limitation in cognition that constrains the elementary cognitive steps involved in both processing and maintenance to take place serially. According to Garavan (1998) and Oberauer (2002, 2005), the focus of attention can select only one element of knowledge at a time as the object of the next cognitive operation. In the same way, Pashler (1998) suggested that the central processes would be constrained by a central bottleneck applying to a variety of mental operations such as response selection and memory retrieval. Thus, when the focus of attention or the bottleneck that constrains central processes is occupied by some processing episode, it is not available for processes related to the maintenance of memory items. This constraint would have a direct consequence on performance in complex span tasks because we assume that as soon as attention is switched away from a memory item, its activation suffers from a time-related decay (Cowan, 1995, 1999; Towse & Hitch, 1995). Thus, the memory traces of the items to be maintained would fade away when attention is occupied by concurrent processing and might be reactivated before their complete disappearance. This reactivation does not necessarily involve a rehearsal process as Baddeley describes in his model of phonological loop (Baddeley, 1986; Baddeley & Logie, 1999) because individuals can engage in a rapid and covert retrieval process through attentional focusing (Cowan, 1992; Cowan et al., 1994; Raye, Johnson, Mitchell, Greene, & Johnson, 2007). As we noted above, this kind of refreshment can take place even during short pauses that might occur while concurrent processing is running. Thus, the sharing of attention between processing and storage is achieved through a rapid and incessant process of switching of the focus of attention. This switching differs from that hypothesized by Towse, Hitch, and Hutton (1998), who suggested a task switching reflecting the structure of the working memory span task, without any attempt to ensure the maintenance of memory items during processing. Rather, the rapid switching we hypothesize would occur during processing and is akin to the micro-task-switching process described by Towse et al. (2007).

As stressed by Barrouillet et al. (2004; see also Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007), this model leads to a new conception of cognitive load. Those tasks that almost continuously occupy attention, thus preventing switching and the refreshment of memory traces, would involve a high cognitive load and lead to poor recall when involved as processing component in working memory span tasks. By contrast, those activities that leave room for frequent attentional switches would involve a low cognitive load and would not greatly impair concurrent maintenance. More precisely, according to the TBRS model, the cognitive load that a given task involves is a function of the proportion of time during which this task occupies attention, thus preventing the refreshment of memory traces. Barrouillet et al. (2004) tested this hypothesis in their Experiment 7 in which adults performed a computer-paced working memory span task named the reading digit span task. In this task, participants are presented with series of letters to be remembered, with each letter being followed by a series of to-be-read digits successively displayed on-screen at a fixed pace. The authors varied this pace by manipulating both the number of digits (either 4, 8, or 12) and the interletter interval (i.e., the total time allowed to read them, either 6, 8, or 10 s). The authors reasoned that the proportion of time during which reading the digits occupies attention (i.e., the cognitive load) is proportionate to the number-of-digits-to-time ratio. In line with the TBRS model, they observed that working memory spans smoothly decreased as this critical ratio increased (see Figure 1). Thus, adult participants took advantage from the short pauses to reactivate the decaying memory traces, using the rapid-switching process. Indeed, increasing the number-of-digits-to-time ratio reduces the duration of these pauses and

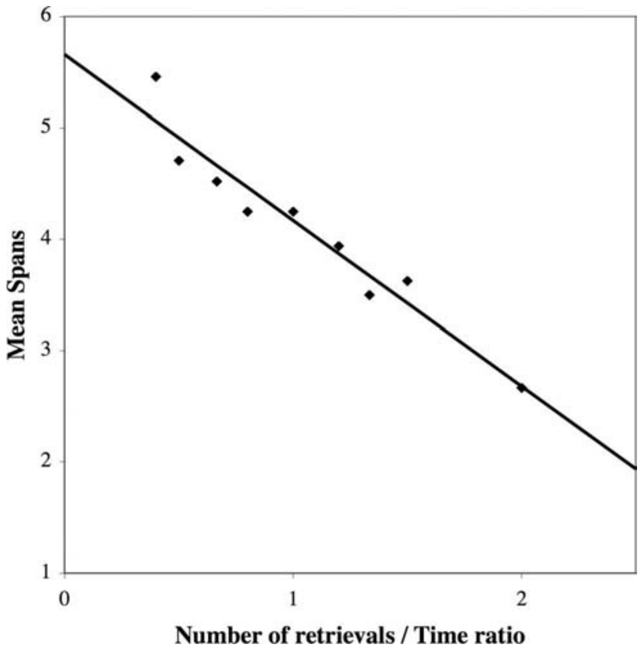

Figure 1. Mean spans as a function of the number-of-digits-to-time ratio in adults. Adapted from "Time constraints and resource-sharing in adults' working memory spans," by P. Barrouillet, S. Bernardin, and V. Camos, 2004, *Journal of Experimental Psychology: General*, *133*, p. 94. Copyright 2004 by the American Psychological Association.

hence impairs reactivation of memory traces, thus resulting in poorer recall.

The Present Study

Discussing the nature of working memory limitations within the TBRS model, Barrouillet et al. (2004) identified three main sources: the amount of available attention, the phenomenon of decay, and the efficiency of the mechanism of reactivation of memory traces through rapid attentional switching. We assume that these three factors are also main sources of the development of working memory. Among these factors, the impact of age-related changes in the amount of attention has already been documented by Gavens and Barrouillet (2004; see also Barrouillet & Camos, 2001), and Cowan and colleagues (Cowan et al., 2000; Saults & Cowan, 1996) devoted many studies to developmental changes in the rate of decay. By contrast, as far as we know, age-related changes in the capacity to refresh and reactivate memory items in working memory span tasks have never been investigated. The aim of this study was to investigate how working memory functioning is affected by the development of the process of reactivation through the rapid micro-task-switching mechanism hypothesized by the TBRS model.

As Bayliss et al. (2005) noted, the extent to which individuals will benefit from the short free pauses during processing depends on the rate at which they can reactivate or rehearse the memory items before the next processing episode. Following these authors, we assume that the rate at which children can reactivate items in memory becomes faster with age. Moreover, studies on the development of strategies in simple span tasks have demonstrated that children before the age of 7 do not attempt to rehearse verbal material (Gathercole, Adams, & Hitch, 1994; Hitch, Halliday, Dodd, & Littler, 1989). Though verbal rehearsal and reactivation by covert retrieval could be two distinct processes (Hudjetz & Oberauer, 2007), both may necessitate cognitive control and sufficiently developed executive functions. Thus, there might be an age at which children would be unable to refresh memory items while performing the processing component of the working memory span tasks.

The first two experiments of the present study tested the hypothesis that the rate of reactivation of the memory traces increases with age. For this purpose, Experiment 1 investigated the developmental differences in the effect of the pace at which the processing component is performed. If our hypothesis is correct, the effect of pace on working memory spans should be weaker in younger than in older children because the advantage that can be taken of any increase in the available reactivation time depends on the rate at which memory traces can be reactivated. Thus, and quite counterintuitively, working memory spans in young children should be less affected than in older children when the pace of the processing component increases, that is, when the duration of the available pauses decreases. However, the characteristics of our time-controlled working memory span paradigm imply that these developmental differences could partly result from the fact that older children are faster in performing each step of the processing component and thus actually benefit from longer pauses to reactivate memory traces. Experiment 2 aimed at controlling this potential confound by adapting the pace of the secondary task to children's processing speed. To keep constant across ages the proportion of time available for refreshing, that is, the cognitive load of the secondary task, we presented younger children with slower paces. As we see below, the control of developmental differences in processing speed should provide us with a clearer picture of the developmental increase in the rate of refreshing.

Experiment 3 investigated the reactivation process in young children by studying complex span task performance in preschoolers. If there is an age at which the reactivation process is not functional, children might adopt a serial control, as in the task-switching model (Towse et al., 1998), rather than the rapid micro–task switching hypothesized by the TBRS model. In this case, they could not take advantage from the pauses that can be freed during processing, and their recall performance should remain unaffected by changes in the pace at which the processing component has to be performed.

Experiment 1

The aim of this experiment was to test the hypothesis that the process of refreshment of memory traces through rapid switching is more efficient in older children. Within the TBRS model, this refreshment involves the covert retrieval process through attentional focusing described by Cowan et al. (1994). Accordingly, by analyzing the time course of output, these authors demonstrated that the rate of this process becomes faster with age. Thus, we aimed at demonstrating that older children are more able than younger children to reactivate memory traces while performing a concurrent task. For this purpose, we presented children from 8 to 14 years of age with the reading digit span task described above. Within this task, the digits were displayed at four paces selected from the nine used by Barrouillet et al. (2004) to maximize the effect of the number-of-digits-to-time ratio. Because recall performance depends on the cognitive load that the processing component involves, and because this load corresponds to the proportion of time during which attention is occupied, we expected an effect of the pace on working memory spans in each age group as Barrouillet et al. (2004) observed in adults. Slow paces should result in better recall because they leave more room for refreshment of the memory traces (Gavens & Barrouillet, 2004). However, as we argued above, the effect of pace depends on the rate at which memory traces can be reactivated. If this rate is faster in older children as Bayliss et al. (2005) and Cowan et al. (1994) suggested, increasing the time available for reactivation should lead to a greater improvement in working memory span with age, because the number of items that can successfully be reactivated and saved from complete disappearance in a given period of time increases with age. Thus, beyond the trivial effect of age and the effect of pace on spans, we predicted an interaction between pace and age. The pace effect should be more pronounced in older children, resulting in an increase in the size of developmental differences as the pace at which the processing component is performed is slower.

Method

Participants

Sixty-four children in each of four grades—third (30 boys, 34 girls; mean age = 8.5 years, *SD* = 3.3 months), fifth (31 boys, 33 girls; mean age = 10.6 years, *SD* = 3.7 months), seventh (37 boys, 27 girls; mean age = 12.6 years, *SD* = 4.7 months), and ninth (21 boys, 43 girls; mean age = 14.5 years, *SD* = 4.5 months)—participated as volunteers[1] and were randomly assigned to one of the four experimental conditions defined by the four paces.

Material and Procedure

All the participants were presented with the same series of one to eight consonants of ascending length, with three series in each length and repetitions, acronyms, and alphabetic-ordered strings being avoided. A signal (an asterisk) was displayed on-screen for 750 ms, followed after a delay of 500 ms by the first letter that was presented, as with all the letters, for 1,500 ms. Each letter was followed by series of numbers (1 to 12) successively displayed on-screen at a fixed and regular pace that varied according to the experimental condition. Four paces were selected from those used in Barrouillet et al. (2004, Experiment 7), namely, 2, 1.2, 0.8, and 0.4 digits per second resulting from the presentation of 12 digits within 6 s and 12, 8, and 4 digits within 10 s, respectively. The presentation time of each digit in each condition was divided in 25% of delay and 75% of display. For example, the digits were displayed on-screen for 375 ms after delays of 125 ms for a total of 500 ms in the 2-digits-per-second condition, whereas these values were of 1,875 ms and 625 ms for a total of 2,500 ms in the 0.4-digit-per-second condition. The word *recall* appeared on-screen at the end of each series.

The participants were asked to read aloud all the stimuli displayed on-screen and to maintain and recall the letters in correct order. Participants 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; Lépine, Bernardin, & Barrouillet, 2005; Smith & Scholey, 1992). For example, the correct recall of all the series of 1, 2, and 3 letters, two series of 4 letters, and one series of 5 letters resulted in a span of $(3 + 3 + 3 + 2 + 1) \times 1/3 = 4$. Before the experimental session, children were familiarized with the pace of the experimental condition in which they were involved by reading three series of numbers and by performing the reading digit span task with one series of 1 letter and one series of 2 letters.

Results

As expected, the difficulty of the reading digit task increased with the pace. In the two youngest groups in which the number of errors and omissions was recorded, 47%, 12%, 3.5%, and 1% of the series of digits were incorrectly read at the paces of 2, 1.2, 0.8, and 0.4 digits per second, respectively. Of interest is the fact that 71% of these incorrectly read series were followed by failures in recall, indicating that these reading errors were not due to a trade-off between processing and storage, with children favoring the memory task over the processing activity.

An analysis of variance (ANOVA) was performed on the mean spans with age (8, 10, 12, and 14 years) and pace (2, 1.2, 0.8, and 0.4 digits per second) as between-subjects factors. This analysis revealed a trivial effect of age with mean spans increasing smoothly with age (2.14, 3.05, 3.72, and 4.76 in 8-, 10-, 12-, and 14-year-old children), $F(3, 240) = 107.28$, $p < .001$, $\eta_p^2 = .57$ (see Figure 2A). As already observed by Barrouillet et al. (2004) in adults, there was a main effect of pace with faster paces eliciting lower mean working memory spans (4.79, 3.77, 2.93, and 2.18 for 0.4, 0.8, 1.2, and 2 digits per second, respectively), $F(3, 240) = 110.92$, $p < .001$, $\eta_p^2 = .58$. More interesting is the fact that this effect was significant in each age considered separately, in 8-year-olds, $F(3, 60) = 9.08$, $p < .001$; 10-year-olds, $F(3, 60) = 33.93$, $p < .001$; 12-year-olds, $F(3, 60) = 26.16$, $p < .001$; and 14-year-olds, $F(3, 60) = 51.84$, $p < .001$. The linear trends accounted for 96%, 99%, 99%, and 100% of the experimental effects in 8-, 10-, 12-, and 14-year-old children, respectively, indicating that in each age, the increase in the number-of-digits-to-time ratio resulted in a smooth decrease in span as Barrouillet et al. (2004) observed in adults (see Figure 1). As we predicted, this effect of pace was more pronounced in older children, as testified by the significant interaction between age and pace, $F(9, 240) = 3.36$, $p < .001$, $\eta_p^2 = .11$. Whereas the youngest group exhibited an increase in span of 1.54 from the fastest to the slowest pace conditions (from 1.44 to 2.98), this increase was 3.60 in the oldest children (from 2.94 to 6.54).

However, it can also be observed that these increases in span in the extreme groups were approximately in the same ratio (3.60/1.54 = 2.33) as their mean spans across paces (4.57/2.14 = 2.23).

[1] Information regarding the socioeconomic background of the participants concerning occupation, income, and race or ethnicity were not communicated by schools and were thus unavailable for the experiments reported in this study.

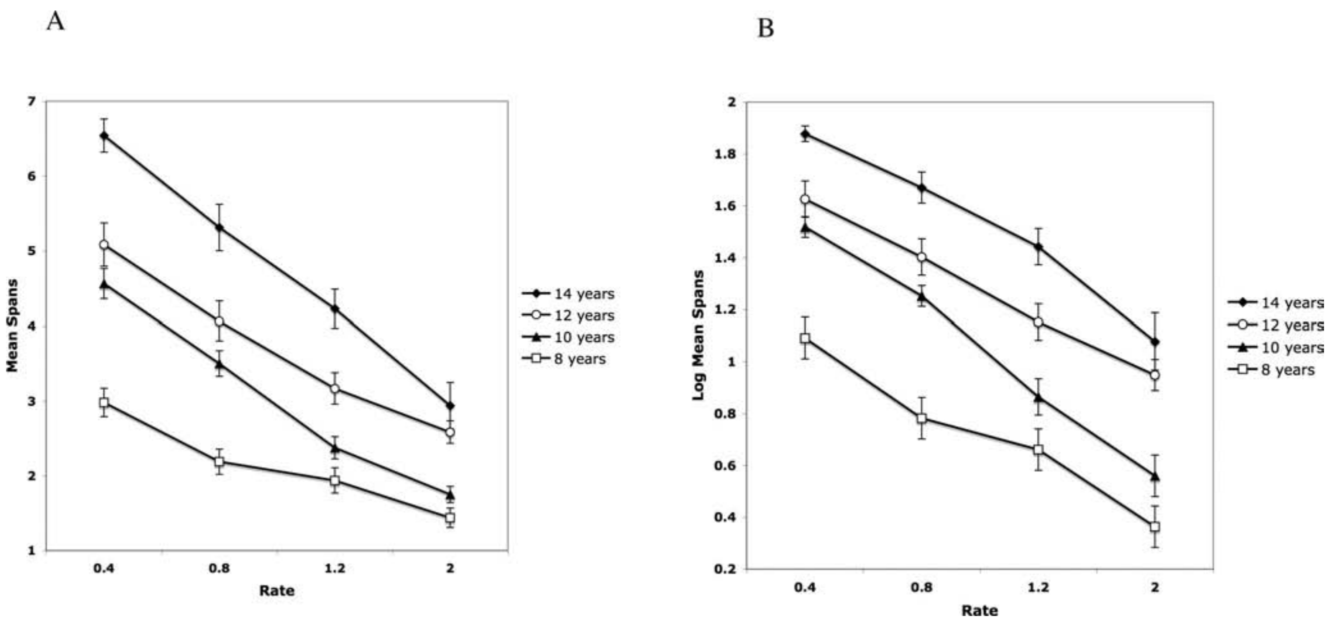

Figure 2. (A) Mean spans and (B) log values as a function of age and pace of the reading digit task in Experiment 1. Error bars are standard error.

This was reflected by the results of an ANOVA performed on working memory spans after their log transformation (see Figure 2B). Contrary to the effects of age, $F(3, 204) = 91.97$, $p < .001$, and pace, $F(3, 240) = 97.91$, $p < .001$, which were still significant, the interaction no longer reached significance, $F(9, 240) = 1.31$, $p > .20$, suggesting that the effect of pace was proportionate to the span levels.

Discussion

This experiment revealed three main findings. First, as observed in adults by Barrouillet et al. (2004), children's working memory spans are a function of the number-of-digits-to-time ratio in each of the ages under study, suggesting that for age 8 onward, recall performance varies with the pace of the processing component. This result lends strong support to the TBRS model by extending its main prediction to adolescence and childhood. This fact suggests in turn that the rapid switching process hypothesized by our model is functional in children. If they did not switch their attention from processing to storage during the reading digit task, their recall performance should conform to the predictions of the task-switching model (Towse et al., 1998) and should be a function of the raw duration of this reading activity (i.e., the duration of the interletter intervals). Thus, the three slowest paces that involved 10-s interletter intervals would have induced equivalent recall performance, and the fastest pace that was also the condition with the shorter delays of retention (intervals of 6 s) would have resulted in the highest spans. This was not the case. The simplest way to account for these results is to assume that even young children were able to divert their attention from the series of digits to refresh the memory traces surreptitiously, with this refreshment being more efficient as the reading task permits longer free pauses.

The second fact revealed by this study is that the effect of pace is less pronounced in young children, who seem less able than their older peers to take advantage of the pauses freed by the slow pace conditions. This phenomenon is consistent with Bayliss et al.'s (2005) idea that young children have a slower rate of reactivation than older children. In line with Cowan et al.'s (1994) observations, young children seem to be able to refresh only a limited number of digits per unit of time. Of course, other factors could be involved. For example, it is possible that young children have not only a lower rate of reactivation when concentrating on the memory items but also a lower capacity to control their activity to switch their attention easily from processing to storage. Hitch (2006) has suggested that there might be a developmental shift from an early bias in favor of task switching and serial control to a greater degree of resource sharing and parallel processing, a shift underpinned by the development of executive processes and a greater capacity to control attention. Young children could exhibit a smaller pace effect owing to their lower capacity to disengage attention from processing as the current digit has been read. However, these hypotheses are compatible with the TBRS model and suggest that the reactivation process that allows children to maintain memory traces while performing concurrent activities is one of the main factors underpinning working memory development. As Figure 2A makes clear, developmental differences in working memory spans strongly vary with the cognitive load that the processing component involves, with less pronounced differences when the processing component occupies attention almost continuously.

Third, it appeared that the increase in span related to variations in cognitive load was proportionate to the span levels, as testified by analyses conducted on log-transformed scores. This suggests that the efficiency of the reactivation process is related to other factors that underpin working memory span performance. For example, the reactivation rate across ages might be related to those factors that determine performance in the most time-constrained condition (i.e., pace of two digits per second) in which it is probable that even the oldest children were not able to save time to refresh memory traces during processing. In this case, performance would depend both on the rate at which passively maintained information decays and on the activation this information received at encoding, with slower rate of decay and higher activation yielding longer memory persistence and better recall. Within the TBRS model, levels of activation depend on the amount of available attention. The present results are thus in line with our model, which assumes that both the refreshing and the encoding process rely on the same mechanism of activation through attentional focusing that allows to create and restore transient representations within working memory (Barrouillet et al., 2007). Of course, this does not mean that the reactivation process that Bayliss et al. (2005) described as storage ability cannot contribute unique variance in working memory spans when compared with other factors such as processing efficiency or more general speed in correlational studies. This is because these factors can interact with other cognitive processes in determining recall performance and are assessed by specific tasks (e.g., simple span tasks for storage ability in Bayliss et al.) that necessarily lead to compound rather than pure measures. The present results suggest that the efficiency of the refreshing mechanism is in some way related to some general cognitive resource, probably attention, that determines working memory performance, as the TBRS model suggests along with other models of working memory (Cowan, 2005; Lovett et al., 1999).

However, part of the developmental differences observed in the present experiment could result from the fact that older children are probably faster in reading the digits, thus benefiting from longer free pauses to refresh memory traces. As a consequence, the cognitive load involved by the secondary task, that is, the proportion of the interletter interval during which reading digits occupies attention, was probably weaker in older children. Thus, we designed a second experiment in which the effects of age-related differences in processing speed were controlled.

Experiment 2

According to the TBRS model, the cognitive load involved by a reading digit task as we used in Experiment 1 corresponds to $CL = a\ N/T$, where CL is cognitive load, T is the time available to read the digits (i.e., the interletter interval), N is the number of digits to be read, and a is a parameter that represents the time during which reading a digit totally captures attention. Thus, although the different age groups were presented with the same paces (i.e., N/T) in Experiment 1, cognitive load probably varied from one age group to the other because of the well-documented developmental increase in processing speed that directly affects parameter a (Kail, 2001). Because older children are faster in reading the digits, they probably had more time available to refresh memory traces than younger children. As a consequence, both the effect of age and the interaction between age and pace observed in the previous experiment could have been blurred by these variations in cognitive load between ages.[2]

The aim of the present experiment was to evaluate developmental differences in the reactivation process while controlling age-related differences in processing speed. For this purpose, we used the same reading digit span task as in Experiment 1, but the time available to read each digit was tailored to the mean time needed to read digits in each age, as assessed in a pretest. For the sake of simplicity and for us to obtain a clear data pattern about a potential interaction between age and cognitive load, the present experiment concentrated on the two extreme age groups of Experiment 1 (i.e., 8- and 14-year-old children). Three levels of cognitive load were created by presenting each digit in the reading digit span task for a duration equivalent to either one, two, or four mean reading times (e.g., for a reading time of 622 ms in the pretest, each digit was presented during 622 ms, 1,244 ms, or 2,488 ms for the high, medium, and low level of cognitive load, respectively). It is important to note that in Experiment 2, and contrary to Experiment 1, the pace (i.e., the number of digits per second) varied between ages because the time available to read the same number of digits was longer in younger than in older children. By contrast, the reading digit task involved the same cognitive load between groups because the reading activity occupied the same proportion of the interletter intervals in both ages (i.e., 100%, 50%, and 25% for the high, medium, and low levels of cognitive load, respectively).

The TBRS model permits two main predictions. First, although the cognitive load of the secondary task was the same in both age groups, we still predicted higher spans in older children. Gavens and Barrouillet (2004) already observed that even when the difficulty of the processing component of a working memory span task was equated across ages, older children still outperformed younger children. The authors accounted for this phenomenon by assuming an age-related increase in cognitive resources leading to a higher level of activation of the to-be-remembered items at encoding and a slower time-related decay of memory traces. As a consequence, we expected better recall performance in older children, even in the high cognitive load condition in which each digit was presented for a duration that did not exceed the time needed to read it, thus probably strongly impeding the reactivation of memory traces during processing. Second, an effect of cognitive load was expected, with higher load resulting in lower recall performance in both age groups. However, our hypothesis of an age-related improvement in the reactivation process could lead to two patterns of results. On the one hand, it could be assumed that the development of this process does not go beyond the general increase in processing speed and efficiency that affects most of the cognitive processes such as memory search, mental rotation, name retrieval, and visual search as observed by Kail (2001). In this case, the effect of cognitive load should be the same in both age groups because the effects of differences in processing speed were controlled in this experiment. On the other hand, we could suppose that the development of the refreshing process goes beyond a general increase in processing speed. For example, it could be assumed that the reactivation rate is higher in older children not only because they process information faster but also because they have greater capacity to control their attention and are more able to switch their attention back and forth from processing to storage. In this case, even when controlling for age-related differences in processing speed, our paradigm should reveal a weaker effect of

[2] We would like to thank an anonymous reviewer for this thoughtful suggestion.

cognitive load in younger children, who are less able to take advantage of the free pauses resulting from a low cognitive load.

Method

Participants

Fifty-four children in the third grade (26 boys, 28 girls; mean age = 8.5 years, *SD* = 3 months) and 69 children in the ninth grade (35 boys, 34 girls; mean age = 14.3 years, *SD* = 6 months) participated. All participants volunteered and were randomly assigned to one of the three experimental conditions defined by the three cognitive loads (18 and 23 participants per group for the third and ninth graders, respectively).

Material and Procedure

Mean reading digit times were assessed in a pretest involving 20 additional participants in each age level who were asked to read aloud as fast as possible digits presented on-screen, with eight trials per digit. We recorded reading times using a voice key that stopped the computer clock. As we surmised, 14-year-old children were faster in reading digits, with a mean reading time of 489 ms (*SD* = 74 ms), compared with 622 ms (*SD* = 234 ms) in 8-year-old children, $t(38) = 8.96$, $p < .001$. These values were used to determine in each age group the time available to read each digit in the reading digit span task.

The design of this task was essentially the same as in the previous experiment. The participants were presented with the same series of one to eight consonants of ascending length with three series in each length. A signal (an asterisk) was displayed on-screen for 750 ms, followed after a delay of 250 ms by the first letter that was presented, as with all the letters, for 1,000 ms. Each letter was followed by series of digits successively displayed on-screen. The time available to read each digit was equivalent to either one, two, or four mean reading times as assessed in the pretest, resulting in three levels of cognitive load in each age group. Thus, for the high, medium, and low cognitive load conditions, the time available to read each digit was 622 ms, 1,244 ms, and 2,488 ms, respectively, in 8-year-old children and 489 ms, 978 ms, and 1,956 ms, respectively, in 14-year-old children. As in Experiment 1, these presentation times were divided in 75% of display and 25% of delay. For us to keep the interletter intervals constant across conditions, the number of digits presented in each interletter interval for the high, medium, and low cognitive load conditions was 12, 6, and 3, respectively (see Table 1). All other methodological aspects were similar to Experiment 1.

Results

As in the previous experiment, we performed an ANOVA on the mean spans, with age (8 and 14 years) and cognitive load (high, medium, and low) as between-subjects factors. As previously observed, the mean spans were higher in 14- than in 8-year-old children (2.88 and 1.81, respectively), $F(1, 117) = 43.09$, $p < .001$, $\eta_p^2 = .27$. The cognitive load had a significant effect in spans, $F(2, 117) = 20.33$, $p < .001$, $\eta_p^2 = .26$, an effect that was observed in 8-year-old children (1.39, 1.70, and 2.35 for high, medium, and low cognitive load, respectively), $F(2, 51) = 8.52$, $p = .001$, $\eta_p^2 = .25$, as well as in 14-year-old children (2.17, 2.75, and 3.71, respectively), $F(2, 66) = 13.60$, $p < .001$, $\eta_p^2 = .29$. Though the effect of age steadily increased as the cognitive load decreased (differences of 0.78, 1.05, and 1.36 for the high, medium, and low cognitive load, respectively), the Age × Cognitive Load interaction was not significant, $F(2, 117) = 1.05$, $p = .35$, $\eta_p^2 = .02$ (see Figure 3). This suggests that a substantial part of the Age × Pace interaction observed in Experiment 1 resulted from age-related differences in reading digit speed. This would mean in turn that, as we noted above, the development of the reactivation processes does not go beyond the general age-related increase in processing speed. However, as we observed in Experiment 1, variations in cognitive load had an effect proportionate to recall performance in both groups. The variations in cognitive load induced in younger children a gain in span of 0.96 from a span of 1.39 in the most difficult condition, resulting in a ratio of 0.69, which was very close to the ratio observed in the 14-year-old children (increase of 1.54 from a span of 2.17; ratio of 0.70). The fact that 14-year-old children exhibited a greater increase in span than 8-year-old children, whereas they benefited from shorter periods of refreshment tailored to their reading times, suggests that the development of the reactivation mechanism could go beyond the general increase in processing speed, as the following analysis shows.

Analyses concerning the efficiency of this refreshing mechanism were made possible by the design used in this experiment. Indeed, it was possible to estimate in each condition and age group the time available to refresh memory traces. If we assume that the time needed to read each digit was 489 ms in the older children and 622 ms in the younger, the time available for refreshing was equivalent to 0 ms in each age group for the high cognitive load

Table 1
Summary of the Number of Digits and the Temporal Parameters (in Milliseconds) for Their Presentation in Experiment 2

Cognitive load	Time available per digit	Display	Delay	Interletter interval	Number of digits
Age 8					
High	622	466	156	7,464	12
Medium	1,244	933	311	7,464	6
Low	2,488	1,866	622	7,464	3
Age 14					
High	489	367	122	5,868	12
Medium	978	733	245	5,868	6
Low	1,956	1,467	489	5,868	3

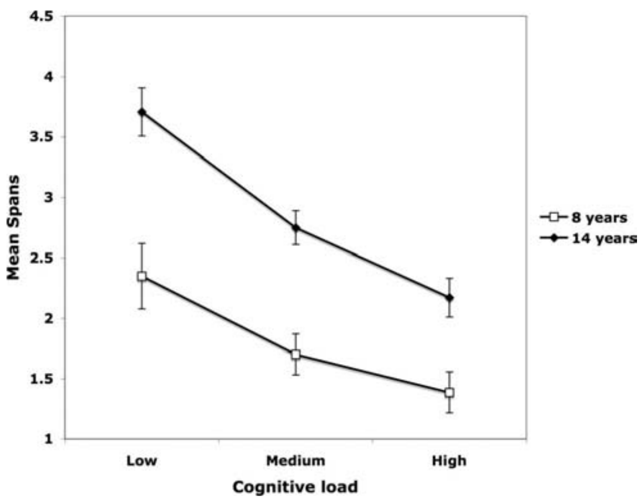

Figure 3. Mean spans as a function of age and cognitive load of the reading digit task in Experiment 2. Error bars are standard error.

condition; to 489 ms and 622 ms in 14- and 8-year-old children, respectively, for the medium cognitive load condition; and to 1,467 ms and 1,866 ms, respectively, for the low cognitive load condition. Linear regressions of the spans on these available times revealed a quasi-perfect linear function in each age group (see Figure 4), with a steeper slope in older than in younger children. Whereas 14-year-old children increased their recall performance by approximately one item for each additional second of time available after reading a digit (slope of 1.037), the same amount of time yielded only half this increase in 8-year-old children (slope of 0.516). These two slopes differed significantly, $t(119) = 2.97$, $p < .005$, confirming that older children were more efficient in refreshing memory traces.

Discussion

The results observed in Experiment 1 could have been due to developmental differences in reading speed: Because the older participants are faster in reading each digit, as the pretest of the present experiment confirmed, they benefited from longer free pauses during which they could refresh memory traces and achieve better recall performance. Thus, here the time available to read each digit was tailored to the time young and older children need to read these digits. Two phenomena are of interest. First, though younger children were given more time to perform the task and were subjected to the same cognitive loads as older children, they still had lower spans. This shows that the developmental differences observed in Experiment 1 can not simply be explained by older children's greater processing efficiency. Even when the proportion of time during which the reading activity occupies attention is kept constant across ages, older children still outperform younger children in recall performance. The fact that developmental differences were observed even though cognitive load was kept constant, and even in the high cognitive load condition in which the time available to refresh memory traces was virtually nil, confirms Gavens and Barrouillet's (2004) findings that we previously described and the hypothesis of a developmental increase in cognitive resources (Halford, 1993; Pascual-Leone, 1970).

The second finding of interest in this experiment concerns the developmental differences in the efficiency of the refreshing mechanism. The Age × Condition interaction observed in Experiment 1 was strongly reduced and no longer significant. This suggests that part of the differences observed in Experiment 1 is due to developmental differences in processing speed. However, the fact that the effect of variations in cognitive load in the present experiment was at least as large in older as in younger children even though the former benefited from shorter periods of refreshing clearly indicates that the rate of reactivation is faster in older children. An important question is whether this developmental increase in reactivation rate goes beyond the general increase in processing speed. Our paradigm allows the estimation of the time available for refreshing in each experimental condition and each age. Regression analyses revealed that the rate of refreshing is twice as high for 14- than for 8-year-old children (1.037 vs. 0.516 items per second)—a ratio that goes beyond what could be expected from the increase in processing speed reflected by the reading times (489 ms vs. 622 ms) or from the increase in capacity reflected by mean spans in the high cognitive load condition that prevented refreshing activities (2.17 vs. 1.39; ratio of 1.56). Thus, it seems that there is an increase in efficiency of the refreshing mechanism between the ages of 8 and 14 that cannot be totally accounted for by age-related increases in resources and processing speed. As we suggested above, it is possible that older children have greater capacity to control their attention and maintain task goals in active memory. Thus, older children would be more prone to take advantage of the pauses between processing episodes and to switch their attention back and forth from processing to storage, whereas younger children would be more passive.

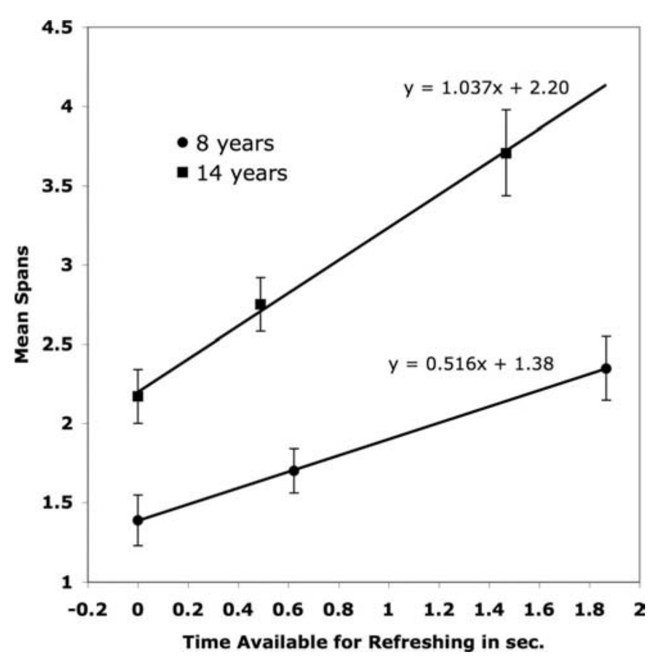

Figure 4. Mean spans as a function of age and free time available to refresh memory traces in Experiment 2. Error bars are standard error.

These results and analyses raise an important question. If the process by which attention is switched to reactivate decaying memory traces is less and less efficient in younger children, is there an age at which children do not use this mechanism at all? This question was addressed in the following experiment.

Experiment 3

Experiment 1 made clear that the slope of the function relating working memory spans to the pace at which the intervening task is performed becomes flatter as children involved in the study are younger, and Experiment 2 confirmed that the refreshing mechanisms are less efficient in young children. This developmental change suggests, as Hitch (2006) surmised, that there might be an age at which children do not switch their attention from processing to storage during the processing component of the task, adopting a serial control. What kind of recall performance pattern would result from such a working memory functioning? Suppose children who would not switch their attention during processing. Their attention would thus remain continuously occupied by, and stuck on, the processing part of the task except when items to be remembered are displayed. Such a functioning would correspond to the task switching described by Towse and Hitch (1995; Towse et al., 1998) in which the cognition is driven by the structure of working memory span tasks, that is, by external events. In this case, memory traces should suffer from a continuous decay during processing without any attempt to refresh them. As a consequence, working memory spans should remain unaffected by the variation in cognitive load of the intervening task, and any effect of pace should disappear because recall performance would depend only on the duration of this task. This is not to say that this intervening activity would not have any effect on maintenance and recall performance. Because attention is focused and remains stuck on the intervening task, the memory items leave primary memory and suffer from a time-related decay, resulting in more difficult retrieval at recall (Unsworth & Engle, 2007). By contrast, when there is no intervening activity, the attention can remain focused on the to-be-remembered items that benefit from higher levels of activation and are thus easier to retrieve. Thus, even if younger children's working memory span should remain unaffected by the variation in cognitive load of the intervening task because they do not switch their attention from processing to storage, their recall performance should nonetheless be poorer when an intervening task is to be performed.

We tested this hypothesis in two groups of 5- and 7-year-old children who performed a working memory span task in which they were presented with animals (drawings appearing on-screen) to be remembered while naming the color of characters' head drawings successively displayed on-screen. We called this task the naming color span task. The duration of the intervals between two successive memory items was constant, whereas we varied the number of colors to be identified in each interval (either zero, two, or four colors). The ages were chosen according to many studies demonstrating that before 7 years of age, children do not spontaneously use strategies to maintain memory items in short-term memory span tasks (Gathercole et al., 1994; Gathercole & Hitch, 1993; Hitch, Halliday, Dodd, & Littler, 1989). Because of the necessity to perform an intervening task, the naming color span task is more complex than a simple span task, and it is highly probable that 5-year-old children will not attempt to maintain memory items actively while performing the naming color task. They should thus present a pattern of recall performance reflecting the task-switching process described by Towse and Hitch (1995), with attention being continuously occupied during the processing phases. Thus, in the younger children, the presence of an intervening task (i.e., two or four colors to be named) should disrupt recall performance compared with the zero-color condition because the resulting occupation of attention should remove the memory items from primary memory (Unsworth & Engle, 2007). However, the two- and four-color conditions should elicit the same spans because the youngest children would not benefit from the pauses to refresh memory traces. By contrast, the micro-task-switching mechanism described by the TBRS model might be efficient in 7-year-old children, leading to a smooth decrease in span as the cognitive load involved by the naming color task increases, as we observed in Experiment 1.

Method

Participants

Fifty-seven preschoolers (31 boys, 26 girls; mean age = 4.9 years, minimum = 4.3 years, maximum = 5.7 years, *SD* = 4 months) and 57 first graders (23 boys, 34 girls; mean age = 6.9 years, minimum = 6.2 years, maximum = 7.8 years, *SD* = 4 months) participated and were randomly assigned to the three experimental conditions defined by the number of colors to be named during the processing episodes.

Material and Procedure

Children were presented with series of one to four animal drawings (one to five for the 7-year-old group) to be remembered, with four series in each length. A total of 60 animals were used to avoid strong between-lists interferences. Each animal was presented for 2 s and followed by a period of 8,500 ms before the appearance of the next animal or a question mark on-screen. This period either remained empty with a white screen or was filled with two or four characters' heads colored either in yellow, blue, or red that appeared successively on-screen. In both conditions, the first head appeared after a delay of 500 ms. In the two-color condition, each head was displayed on-screen for 2,667 ms and followed by a delay of 1,333 ms for a total of 4 s. In the four-color condition, these values were 1,333 ms and 667 ms, respectively, for a total of 2 s. Children were asked to repeat the name of each animal after the experimenter and to name the color of each head presented. They were instructed to recall in the correct order the name of the animals they had seen when the recall signal appeared on-screen. As in the previous experiment, children were presented with increasingly long series of animals until they failed to recall all four series at a particular level. Testing was terminated at this point. Each correctly recalled series counted as one fourth; the total number of fourths was added up to provide a span score.

The experimental session was preceded by a training phase. First, children involved in the two- and four-color conditions were familiarized with the color task by naming the color of 12 heads displayed on-screen at a pace corresponding to upcoming experimental condition. Then they were shown in a booklet how the different screens will follow one another, and they were trained to repeat the name of each animal and to name the color of the character's head if needed. Finally, they performed two series of one animal and two series of two animals of the naming color span task on the computer.

Results

For the naming color task, the rate of correct responses was particularly high, with 98% and 96% in 5-year-old children and 99% and 98% in 7-year-old children for the two- and four-color conditions, respectively. The difference between the two conditions was significant in the younger children only, $t(36) = 2.08$, $p < .05$.

We performed an ANOVA on the mean spans with age (5 and 7 years) and number of colors (either zero, two, or four) as between-subjects factors. This analysis revealed that the mean span was higher in older than in younger children (2.48 and 1.45, respectively), $F(1, 108) = 93.82$, $p < .001$, $\eta_p^2 = .47$ (see Figure 5). There was also a main effect of experimental conditions with a decrease in mean span as the number of colors to be named increased (2.72, 1.74, and 1.43 for zero, two, and four colors, respectively), $F(2, 108) = 52.71$, $p < .001$, $\eta_p^2 = .49$. These two factors interacted, $F(2, 108) = 6.81$, $p < .01$, $\eta_p^2 = .11$. Separate analysis indicated that, as it was observed in Experiment 1 with 8-year-old children and as we predicted, the increase in the number of colors elicited a progressive decline in working memory span in 7-year-old children. The difference between the zero- and two-color conditions was significant, $F(1, 108) = 23.17$, $p < .001$, as was the difference between two- and four-color conditions, $F(1, 108) = 17.44$, $p < .001$, with the linear trend accounting for 99.8% of the effect of the number of colors. By contrast, in 5-year-old children, the two- and four-color conditions elicited lower spans than the zero-color condition, $F(1, 108) = 32.07$, $p < .001$, and $F(2, 108) = 24.55$, $p < .001$, respectively, but they did not differ from each other ($F < 1$). It can be assumed that this leveling was not due to a floor effect for two reasons. First, only one child in the four-color condition obtained the minimum score, which was zero because memory items were presented before and not after the processing episodes, making possible to forget the targets even in the shortest lists of one animal. Second, there was no reduction of the standard deviations as it would occur if there was a floor effect ($SD = 0.54$, 0.60, and 0.53 for the zero-, two-, and four-color conditions, respectively). Thus, the effect of pace differed from one age group to the other, as the significant interaction between pace (two vs. four colors) and age testified, $F(1, 108) = 11.93$, $p < .01$.

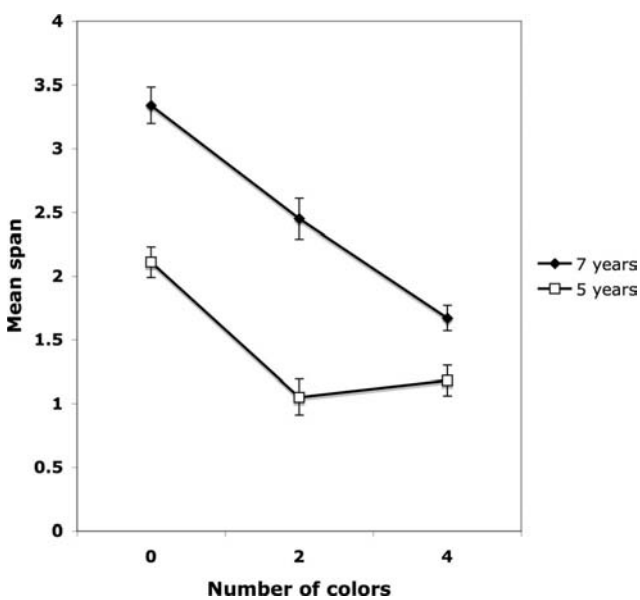

Figure 5. Mean spans as a function of age and number of colors to be named in Experiment 3. Error bars are standard error.

Discussion

This experiment revealed that before 7 years of age, the maintenance of items in working memory is impaired by an intervening task but that the cognitive load induced by this task has no impact in recall performance. Indeed, whereas the working memory spans decreased smoothly in 7-year-old children as the number of colors to be named increased, recall performance in 5-year-old children remained unaffected when the number of colors varied. This suggests that, contrary to older children, 5-year-olds did not attempt, or were unable, to divert their attention from the processing component of the task. As soon as the first character's head appeared, they probably switched their attention to this part of the task and waited for the successive stimuli without any attempt to refresh memory until the next animal was displayed on-screen. Thus, the results suggest that the way they perform the working memory task reflects the task-switching process described by Towse et al. (1998), who proposed that the main determinant of working memory span is the duration of the processing episodes rather than the cognitive load that this processing involves. It can also be noted that the absence of any difference between the two- and four-color conditions contradicts the idea that the effect of the amount of material to be processed in the intervening task is due to representation-based interferences.

By contrast, 7-year-old children's performance is in line with the TBRS model account of working memory, with recall performance being a function of the proportion of time during which the processing component occupies attention. Thus, the present experiment indicates that the reactivation of memory traces through the rapid switching process hypothesized by our model is not a universal mechanism. It appears only somewhere between ages 5 and 7. As Experiments 1 and 2 demonstrated, its efficiency and maybe its frequency of use increase with age until late adolescence, thus producing large developmental differences in the amount of information that can be maintained active, especially when the concurrent activities involve a moderate cognitive load that allows free pauses to reactivate memory items. As a consequence, this experiment also lent strong support to Hitch's (2006) hypothesis of a developmental switch from serial control and task switching to parallel processing, if we consider the rapid switching described by the TBRS model as a form of "parallel" processing, at least at a macro-level of analysis.

General Discussion

The TBRS model (Barrouillet et al., 2004) assumes that, within working memory, resource sharing is achieved through a rapid and frequent switching of attention between processing and maintenance to reactivate decaying memory traces and prevent their complete loss. The aim of this study was to investigate the impact of this reactivation process on working memory development. The results support the hypothesis that this process appears at about 7 years of age and then develops during childhood and adolescence. Thus, as Hitch (2006) surmised, there is a developmental shift from a serial control in young children to a flexible resource sharing, leading to a seemingly parallel processing at a macro-level. Experiment 3 demonstrated that working memory span in young children suffers from the need to perform a concurrent activity while maintaining memory traces but that this effect does not depend on the cognitive load of this activity. This pattern of results reflects the task-switching mechanism described by Towse et al. (1998) by which children operate in serial fashion, with their attention being concentrated on the processing part of the working memory span task and switched to storage only when a memory item is presented. In this account, there is no attempt to maintain active memory traces during processing. However, from 7 or 8 years of age, the reactivation of memory traces during processing is effective, as testified by the smooth decrease in span that results from any increase in the pace at which the processing component of the working memory task must be performed. This latter phenomenon lends strong support to the TBRS model by demonstrating that not only in adults but also in children working memory spans are a function of the proportion of time during which the processing occupies attention (i.e., the cognitive load). This permanence across ages of the refreshing mechanism through rapid switching, which is central in working memory functioning, echoes the observations of Gathercole, Pickering, Ambridge, and Wearing (2004) about the stability of the working memory structure from 6 years of age. From this age on, it seems that structure and functioning of working memory are fairly stable, although development induces a sizable expansion in its capacity. This development would thus be underpinned by a strong increase in functional efficiency.

Accordingly, we observed that younger children are less able than their older peers to take advantage from the pauses that can be freed during processing. This suggests that the efficiency of the reactivation process progressively increases from an initial state of unavailability to the mature level that is not reached until late adolescence. This developmental improvement in efficiency could be due to two main sources. As Bayliss et al. (2005) suggested, the first is an age-related increase in the reactivation rate when attention is focused on memory items. This reactivation could consist in rehearsing the verbal material to be maintained within the phonological loop or in refreshing memory traces through a covert retrieval process. The age-related increase in rehearsal speed has been extensively documented (Hitch, Halliday, & Littler, 1989, 1993; Hulme, Thomson, Muir, & Lawrence, 1984; Hulme & Tordoff, 1989), and Cowan et al. (1994; see also Cowan et al., 1998) showed that age affects the speed of the covert memory search used to reactivate items by attentional focusing. Though these two rates are uncorrelated (Cowan et al., 1998) and involve different brain areas (Raye et al., 2007), both correlate with memory span as Cowan et al. (1998) demonstrated and probably contribute to the age-related increase of the reactivation rate. The second source is a developmental increase in the capacity to shift attention toward the memory traces, something related to the development of executive functions. Time analyses in Experiment 2 suggest that the age-related increase in refreshing efficiency goes beyond the simple developmental increase in processing speed. Young children would have not only a lower reactivation rate but also a lower capacity to control and switch attention during free pauses.

A surprising consequence of this developmental increase in the efficiency of the reactivation process is that young children were less affected by variations in the difficulty of the working memory task. In Experiment 2, we observed that the effect on span of the variations in cognitive load was commensurate with performance level. This phenomenon is perfectly in line with our model. One can consider performance P as a direct function of the individual's capacity C and an inverse function of the difficulty of the task D, with performance increasing as capacity increases and difficulty decreases. With additional parameters set aside, this relation can be expressed as $P = C/D$. Thus, it is simple to verify that the ratio we calculated in Experiment 2 between the gain in performance from the higher to the lower level of cognitive load ($P_1 - P_2$) and the performance in former condition P_2, that is, $(P_1 - P_2)/P_2$, which is equal to $(C/D_1 - C/D_2)/C/D_2$, does not depend on capacity C but on the difficulty of the two tasks under comparison $(D_2 - D_1)/D_1$. The fact that this value in Experiment 2 was a constant indicates that the ratio in difficulty between the conditions was the same in both age groups. This suggests that cognitive load, as the TBRS model defines it, is a valid and reliable measure of task difficulty. Keeping constant the proportion of time during which attention is occupied resulted in the same level of difficulty across ages. By contrast, the gain in performance when cognitive load decreases is a direct function of the available capacity. Thus, an age-related increase in capacity would explain why the increase in span resulting from lower cognitive loads was larger in older children and commensurate with their span level.

Concerning complex span tasks, this capacity would correspond to a compound between speed of processing, which determines both the time during which memory traces fade away and the time available to refresh them, and rate of reactivation that determines the efficiency of this refreshing. Regression analyses in Experiment 2 revealed that the development of the rate of reactivation cannot be totally accounted for by developmental changes in processing speed. This independence was confirmed by Bayliss et al. (2005), who observed that the contributions on complex spans of speed of processing and rate of reactivation were separable and their developmental variations distinguishable. However, the same authors noted that this independence contradicts the TBRS model in which processing and storage (including the refreshment of memory traces through covert memory retrieval) rely on the same limited attentional resource. In other words, our developmental results are in line with Bayliss et al.'s results, but accounting for them could necessitate abandoning one of the main proposals of our theoretical framework. Can the TBRS model be reconciled with this contradiction? We think so for two reasons.

First, as noted by Bayliss et al. (2005), the independence between processing speed and rate of reactivation is relative, and the two processes are likely to be related to a general factor, as the TBRS model assumes. Second, the same authors acknowledge that there is a general increase in basic cognitive speed but that this increase interacts with other cognitive processes as development continues, resulting in separate developmental trajectories for the processing speed and reactivation mechanisms. This proposal is not contradictory with the TBRS model. Assuming that both processing and storage are fueled by the same limited resource does not mean that processing speed and reactivation rate are necessarily highly correlated. Indeed, the processing components of working memory span tasks usually rely on knowledge and skills (e.g., reading, counting, reasoning). As a consequence, the speed at which these activities are completed depends on basic processing speed but also on learning and practice. In contrast, rate of reactivation depends on the efficiency of mechanisms such as covert memory retrieval described by Cowan et al. (1994) or verbal rehearsal, but also on children's capacity and propensity to switch their attention frequently from processing to storage. As a consequence, even if processing and storage rely on the same limited resource of attention, both processing speed and rate of reactivation are under the influence of several other factors such as academic achievement, level of practice, and motivation. Thus, even within the TBRS model, it can be assumed that processing speed and reactivation rate, though they are related to a general factor, which is attention, are relatively independent and can present, as Bayliss et al. (2005) suggested, separate developmental trajectories.

The developmental increase in the rate of reactivation observed in this study has also more general implications for theories of cognitive development. Contrary to Case's claim (Case, 1985; Case et al., 1982), and as Gavens and Barrouillet (2004) observed, the age-related increase in processing efficiency is not the sole factor responsible for the development of working memory. In the same way, it seems that this development cannot totally be accounted for by a global processing-speed mechanism as Kail and Salthouse (1994) suggested. A more efficient mechanism of refreshing allows older children to maintain active and ready for treatment a greater amount of information. Even if our TBRS model does not privilege a quantitative approach of working memory capacity in terms of a maximum number of items of knowledge that could be simultaneously maintained and used, the picture of working memory development that emerges from the present results echoes the continuous increase with age of the *M* capacity or *M* power hypothesized by Pascual-Leone (1970) and defined as the number of schemes that can be simultaneously boosted. However, although it could be tempting to take the spans observed at different ages in our experiments at face value for a mental capacity, our model assumes that spans depend on cognitive load and that other tasks would have probably led to different span levels. Rather than determine the number of schemes or items that can be maintained active, development determines the amount of attentional capacity that can be used to activate items of knowledge, perform concurrent processing, and refresh decaying memory traces.

This developmental increase in attentional capacity understood as an amount of energy available for activation could account for the remaining developmental differences we observed in Experiment 1 in the highest load condition (i.e., Rate 2 in Figure 2A). This effect cannot be due to age-related differences in processing efficiency or rate of reactivation because it is probable that reading two digits per second did not leave any time available for refreshing of the memory traces, even in the older children. However, greater attentional capacity in older children would result in higher levels of activation of the memory traces at encoding. This higher initial level of activation combined with a slower rate of decay would result in more enduring memory traces and better recall. Thus, the development of working memory capacity probably depends on a combination of factors. The present study suggests that, along with attentional capacity, processing efficiency, and speed of decay, an age-related increase in rate of reactivation concurs to working memory development.

This study provided support to the TBRS model and its main assumption of a resource sharing achieved through a rapid switching of attention that permits to reactivate memory traces while performing concurrent activities. An important finding is the strong age-related increase in the efficiency of this process of reactivation that underpins at least in part the developmental increase in working memory spans. However, other aspects of our results questioned our model. First, it appeared that Towse and Hitch's (1995) task-switching model is more appropriate to account for working memory in preschoolers than the TBRS model. Second, the three main sources of development of working memory—processing efficiency, storage ability, and amount of available attention—are probably, as Bayliss et al. (2005) demonstrated, more independent than the TBRS model assumes. Thus, further studies are needed to decipher the determinants of working memory development. As Towse et al. (2007) noted, we are still far from a developmental model of working memory, but the TBRS model could be a step in the right direction.

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Received May 24, 2007
Revision received September 19, 2008
Accepted September 30, 2008 ■

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