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Developmental Increase in Working Memory Span: Resource Sharing or Temporal Decay?

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Working memory span tasks require participants to maintain items in short-term memory while performing some concurrent processing (e.g., reading, counting, and problem solving). It has been suggested that the difficulty of these tasks results either from the necessity of sharing a limited resource pool between processing and storage (Case's cognitive space hypothesis) or from the fact that the memory traces suffer from a temporal decay while the concurrent task is being performed (Towse and Hitch's memory decay hypothesis). We tested these two hypotheses by comparing children's performance in tasks in which the processing component always had the same duration but varied in cognitive cost (counting or problem solving vs repeatedly saying "baba"). The results indicate that both time and limitation of resources constrain performance in working memory tasks. We discuss their implications regarding current models of working memory.

Key Words: working memory; cognitive development; counting; operation span.

In recent years, cognitive psychologists have been paying increasing attention to the concept of working memory (WM) as an explanatory device for the limitations of high-level cognitive processes, cognitive development, and individual and developmental differences (Cowan, 1995; Engle & Oransky, 1999; Logie & Gilhooly, 1998; Miyake & Shah, 1999). Working memory is thought to be a devolved system for the temporary storage and processing of information during the accomplishment of cognitive tasks (Baddeley, 1986). The numerous models which have been proposed differ in the type of structure involved (Baddeley, 1986; Case, 1985; Cowan, 1988, 1995; Ericsson & Kintsch, 1995; Just & Carpenter, 1992; La Pointe & Engle, 1990; Schneider & Detweiler, 1987); the existence or not of a single resource pool (Daneman & Carpenter, 1980, 1983; Daneman & Green, 1986; Cantor & Engle, 1993; Engle, Cantor & Carullo, 1992; Turner & Engle, 1989); or the nature of the resources, the quantity of which is thought to be limited (Anderson, Reder, & Lebiere, 1996; Conway & Engle, 1994; Engle, Conway, Tuholski, & Shisler, 1995; Cowan, 1995).

Despite these differences, a number of models suggest that the storage and processing activities compete for limited WM capacity (e.g., Anderson, Reder, & Lebiere, 1996; Baddeley, 1986; Case, 1985; Daneman & Carpenter, 1980; Just & Carpenter, 1992). Consequently, a large number of tasks which require simultaneous processing and storage have been devised in order to evaluate subjects' WM capacity, e.g., reading span (Daneman & Carpenter, 1980), counting span (Case, 1985), and operation span (Turner & Engle, 1989). These measures have proved to be better predictors of performances in complex cognitive abilities, such as reasoning, problem solving, or reading comprehension, than the traditional short-term memory span measures (digit span and word span). Thus, it has been suggested that working memory tasks evaluate some cognitive capacity that is involved in high-level cognitive processes and which might account for individual differences (Conway & Engle, 1994; Engle & Oransky, 1999).

Within this context, one crucial objective is to determine whether this cognitive capacity in-

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creases with age (Cowan, 1997). If this is indeed the case, then this increase in cognitive capacity may be a factor in the explanation of cognitive development (Case, 1985; Halford, 1993; Halford, Wilson, & Phillips, 1998; Pascual-Leone, 1970). Of course, performance in WM span tasks might well provide an indication of the growth of this capacity with age. In a seminal study, Case, Kurland, and Goldberg (1982) presented children with a counting span task. The children were asked to count out loud dots on cards and then recall the number of dots present on each card. The experimenters varied the number of cards to be counted and consequently also the number of values to be recalled following counting. The maximum number of cards the children were able to remember constituted their counting span. Case et al. (1982) have shown that this counting span increases with age and that it is linked to the maximum counting speed: The faster the counting, the higher the counting span. The explanation proposed by Case is that each individual possesses a Total Processing Space (TPS), which is subdivided into an Operating Space (OS), which is required for the counting operation, and a residual space, which remains available for storing the results (Short-Term Storage Space or STSS). Thus, the Total Processing Space is expressed as follows:

$$\text{TPS} = \text{OS} + \text{STSS}.$$

Moreover, the TPS is thought to remain constant across age. Indeed, Case et al. (1982) asked adults to perform a counting task using terms learned prior to the experiment instead of the traditional sequence of numbers. In this condition, which increases the difficulty of the counting task and consequently the required OS, adults exhibited a counting span equivalent to that of 6-year-old children. This would suggest that the age-related span increase is due to an improvement in the efficiency of the counting operation, which demands a smaller proportion of TPS as the age of the subject increases. This reduction in OS would mean that more STSS is available. The lower the cognitive cost of the task to be performed, the greater the space available for storage, hence the increase in the counting span with age. Case's hypothesis was therefore that there is a trade-off between two activities (processing and storage) which compete for a single, limited cognitive space, Total Processing Space.

This trade-off hypothesis has recently been called into question by Towse and Hitch (1995), who proposed an alternative to Case's limited cognitive space hypothesis. Indeed, the counting span task fails to differentiate between the cognitive cost of the counting activity and the temporal period of storage. As the authors have pointed out, it might be supposed that the strength of the memory trace in the short-term storage space would weaken as the interval between storage and recall increases. The higher counting span of older children might be due to the fact that they count more quickly and that this speed reduces the period during which the information has to be retained. This reduction would then lead to improved recall performance. This hypothesis appears all the more plausible in view of the fact that Case et al. (1982) observed that counting speed increases with age and that this speed is correlated with the counting span. Towse and Hitch pointed out that their alternative hypothesis (i.e., memory decay hypothesis) obviates the need for recourse to the notions of Operating Space or the sharing of a Total Processing Space for processing and storage in order to account for the difficulty of the counting span task.

To decide between these two hypotheses, Towse and Hitch (1995) manipulated the difficulty of the counting task while keeping its execution time constant. The traditional counting span task consists of counting target objects which are mixed up with other objects. It is easy to distinguish between the former and the latter since they generally differ in color. It is, however, possible to manipulate the difficulty of the counting task by making the target objects less easily identifiable. To do this, the authors compared one condition in which the target objects differed from the others in one characteristic such as color (single feature) and a condition in which they were distinguished by a combination of characteristics (e.g., a combination of orientation features). In the experiment, the subjects in the first condition (termed "feature") had to count blue squares which were mixed up with orange triangles, whereas those in the second condition (termed “conjunction”) had to count blue squares which were presented alongside blue triangles. An initial experiment involving 12 adult participants revealed that the counting time and the number of errors were higher in the conjunction condition. The authors interpreted this increased error level as being indicative of greater task difficulty.

In Experiment 2, children ages 6, 7, 8, and 10 were asked to perform the counting span task in three experimental conditions: (a) the feature condition described above in which the number of target objects varied between 3 and 7, (b) the conjunction condition with a number and arrangement of target objects which was identical to that used in the preceding condition, and (c) a so-called feature-slow condition identical to the first condition except that the number of objects to be counted was greater and varied between 6 and 10. The aim of this final condition was to create a situation in which the counting time was equivalent to that in the conjunction condition as determined in a pretest using 7-year-old children. According to the authors, Case’s cognitive space hypothesis predicts that the counting span should be greater in the feature condition than in the conjunction condition. The memory decay hypothesis defended by the authors predicts the same effect but goes on to predict that performances will be equivalent in the conjunction and feature-slow conditions because the counting time, and consequently the retention period, is identical in both cases. The authors argued that this second prediction is at odds with the prediction derived from the cognitive space hypothesis (i.e., poorer performance in the conjunction condition than in the feature-slow condition since the counting operation is less costly in the latter condition).

In fact, the counting span was significantly greater for the feature cards than for the conjunction cards but there was no difference between the values observed for the conjunction and feature-slow cards. Separate analyses of variance showed that this pattern was repeated at all ages. The authors therefore concluded that the ability of subjects to store count totals while counting arrays reflects not the amount of workspace that has to be devoted to count operations, but the time period over which the totals may be forgotten. Thus, they suggested that instead of actively combining storage and processing operations, children may alternate between counting during display presentation and storing results at display offset.

Towse, Hitch, and Hutton (1998) have tested this task switching hypothesis in a series of experiments in which they used an adaptation of a paradigm used by Cowan et al. (1992). For example, in the counting span task, children were presented with sequences of cards to count, where the array numerosity of the first card was small (and that of the last card large) or the numerosity of the first card was large (and the last card small). The numerosity of the intervening card remained unchanged. The authors argued that in both condition (small-final and large-final), the overall processing demands of array counting should be identical since the same set of cards has to be processed and remembered (only the order of completion was changed). However, the manipulation of the completion order changes the time during which representations are maintained in working memory. Because only the product of the count has to be retained, the duration of the first card had no effect on the retention period, whereas the duration of the last card did because all the preceding totals had to be retained. Thus, the large-final condition involved a longer retention period than the small-final condition. As predicted by the memory decay hypothesis, recall performances were poorer in the large-final than in the small-final condition, providing evidence that counting span relies heavily on retention period but not on cognitive demand. The same result was observed in reading or operation span tasks in which the length of the sentence to be read or the operation to be performed were varied.

Although the authors have demonstrated remarkable ingenuity in designing their experiments, these two sets of experiments do not provide such strong evidence in favor of the memory decay hypothesis as Towse and Hitch have claimed. As far as Towse and Hitch’s

(1995) experiments are concerned, the results support the memory decay hypothesis only if we assume that the counting of a larger number of elements (feature-slow condition) affects only the duration of the task without modifying its cognitive cost. However, it is possible that counting a larger number of items constitutes, at least for young children, a more difficult task both in terms of the verbal production of the series of numbers (Dehaene & Mehler, 1992) and in terms of the pointing activities which oblige the individuals to distinguish between the objects which have already been and those which remain to be counted (Beckwith & Restle, 1966; Potter & Levy, 1968). Indeed, since the sequence of numbers is learned gradually starting with the lowest, it is possible that the greater the number of objects there are to be counted, the greater the cognitive cost of the production of each successive number (Fuson, 1988; Fuson & Hall, 1983; Fuson, Richards, & Briars, 1982). In the same way, keeping track of a larger number of already counted dots could result in greater memory load (Engle, Kane, & Tuholski, 1999), especially in children. Several developmental studies have shown that both pointing and counting performance are greatly affected by variations in the number of objects (Camos, Barrouillet, & Fayol, 2001; Camos, Fayol, & Barrouillet, 1999; Gelman & Meck, 1983; Potter & Levy, 1986). As a consequence, it is possible that the counting of larger arrays results not only in longer times, but also in a higher cognitive load. In this latter case, Towse and Hitch's results might be explicable in terms of Case's cognitive space hypothesis.

As far as Towse, Hitch, and Hutton's (1998) experiments are concerned, the same argument holds. Let us recall that the authors manipulated the order of completion of the cards and reasoned that the overall cognitive demand was equivalent in the large-final and small-final conditions because the same set of cards had to be processed. However, as pointed out by the authors, only the product of the count has to be retained and there is no memory load associated with counting the first card. As a consequence, the time duration of this card is irrelevant not only to the retention period but also to the question of cognitive load because the "real" working memory task (i.e., processing + storage) begins only at the end of the first card. Thus, if it is more demanding to count large than small arrays, the large-final condition involves a greater cognitive demand than the small-final condition. The same argument could be used for the reading span and the operation span used by Towse, Hitch, and Hutton (1998). It is quite possible that reading longer sentences or performing longer operations involve greater cognitive demand.

Thus, a more direct paradigm is needed in order to test the memory decay hypothesis. One possible approach is to compare the recall performance obtained in the traditional working memory tasks (processing + storage) such as the counting span task and in situations in which children have to retain the same items in memory with concurrent articulation (saying "bababa") for periods identical to the duration of the task (Fig. 1). Indeed, counting involves both a cognitive demand and an articulatory suppression effect. The former is due to the control and the coordination of the components of counting (saying and pointing), the latter is due to the saying of the number words. According to the memory decay hypothesis, the cognitive load has no role in recall performances which depend only on the duration of the articulatory suppression involved in counting. As a consequence, we chose to compare recall performances impaired by counting with recall performances hampered by a simple articulatory suppression.

This comparison makes it possible to disentangle the two competing hypotheses because the articulatory suppression does not involve any cognitive load (Baddeley, 1986). Baddeley (1990) argued that the articulatory suppression effect on short-term memory performance does not result from attentional demands but from the fact that articulatory suppression cuts out the process of subvocal rehearsal. For example, Baddeley, Lewis, and Vallar (1984) demonstrated that nonarticulatory secondary tasks which are similar in level of demand as articulatory suppression (e.g., tapping) have no effect on short-term memory performance. Vallar and Baddeley (1984) described patient PV, who did

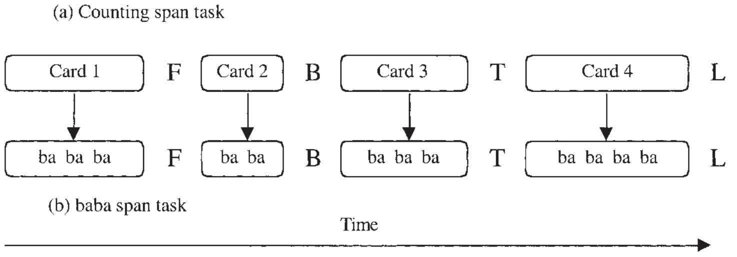

FIG. 1. Diagram of the design used to disentangle time and cognitive load effects in working memory tasks. In the counting span task (a), the participant was presented with cards containing either dots to be counted or a letter to be remembered. The length of the different boxes (cards 1, 2, 3, and 4) indicates the duration of counting for each card. In the baba span task (b), empty cards were used and the participant was asked to repeat "bababa" during the same time he or she took to count dots on the corresponding card.

not appear to use the articulatory loop and who was not impaired in memory performance by suppression. Furthermore, even if we suppose that saying "baba" involves some cognitive load, this load is lower than that in counting. Camos, Barrouillet, and Fayol (2001) compared in children (6- and 9-year-old) and adults saying repeatedly "baba" and counting dots. In each age group, the performance in saying "baba" was always far better than that in counting. Response times were faster in the saying task (381 ms at 6 years of age, 197 ms at 9 years of age, and 188 ms in adults to say each "ba" compared to 515, 307, and 235 ms respectively to count one dot) and the rates of errors were better (no errors in saying but 35, 14, and 11% errors in counting). Thus, the experiments presented here compared children's counting span (counting dots on cards and remembering letters to be recalled) and operation span (solving addition problems and remembering letters to be recalled) with a measure of span in which subjects had to repeat "bababa" aloud instead of counting dots or solving addition problems. We called this measure the "baba span."

Provided that the duration of processing (counting or problem solving, on the one hand, saying "baba," on the other) and the series of letters to be remembered were held constant across tasks, poorer recall performance in counting (or operation) span compared to baba span would argue in favor of the cognitive space hypothesis and, additionally, the size of this difference might constitute an indicator of the cognitive load involved in counting and problem solving. If, as suggested by Case (1985), the age-related increase in working memory span is due to an increase in processing efficiency and the resulting reduction of the operating space occupied by the tasks, then the difference between working memory span and baba span should be all the lower the older the children are. Indeed, we assume that counting dots or solving additive problems should involve a higher cognitive load than saying "baba." Thus, the former processes should be more conducive to a reduction in operating space than the latter. On the other hand, an absence of difference between working memory span and baba span would argue in favor of the memory decay hypothesis and against the cognitive space hypothesis.

EXPERIMENT 1

The aim of this experiment was to verify that, as suggested by Towse and Hitch (1995, Towse, Hitch, & Hutton, 1998), counting span relies only on the time duration of counting but not on a trade-off between processing and storage. In a first session, 8- and 11-year-old children were asked to perform a counting span task in which they had to count out loud dots on cards. After each card, they were presented with a letter to be remembered. The series of cards varied in length, from two- to six-card series (i.e., from two to six letters to be remembered). At the end of each series, the children had to recall the letters in the correct order. Recalls as well as counting time for each card were recorded. A second session took place 3 weeks later, in which the same children had to perform a baba span task in which they were required to say “baba” instead of counting dots. To this end, they were presented with the same series of letters as used in the first session. However, the cards used in the first session were replaced by white cards in such a way that any given white card was presented for the same amount of time that the child had taken to count the dots on the corresponding card during the first session. Thus, for each child in each series, the retention period was exactly the same in both tasks while, however, the processing component was manipulated (either counting or saying “baba”).

According to Case’s developmental theory, counting dots is far more demanding than saying “baba” because the former activity is a dimensional stage achievement, whereas the latter requires only sensory-motor schemes. In consequence, Case’s cognitive space hypothesis should predict higher spans in the “baba” span task than in the counting span task. In order to control for a possible learning effect between the first and the second sessions, control groups performed the “baba” span task in both sessions. In these groups, the duration of presentation of each white card was equal to the mean counting time for the corresponding card recorded in the experimental groups in the first session. Thus, the cognitive space hypothesis predicted a greater increase in span between the two sessions in the experimental groups (counting span first and then baba span) than in control groups (baba span performed twice). Moreover, this difference should be higher in the younger children because the difference in cognitive cost between counting and saying “baba” should be higher in these children, since counting becomes increasingly efficient with age. In contrast, since the retention periods are equal in both tasks, the memory decay hypothesis does not predict any difference, except for an age-related increase in span due to faster counting and thus shorter retention periods in older children.

Method

Participants

Thirty-two children from each of the second (Mean age = 7,10 years, range = 7,5–8,4 years; hereafter 8 years old) and fifth grades (Mean age = 10,10 years, range = 10,5–11,4 years; hereafter 11 years old) of a primary school in Dijon (France) were randomly assigned to either the experimental or the control groups.

Material and Procedure

All children took part in two sessions. The children in the experimental groups performed the counting span task first and the baba span task 3 weeks afterward, whereas the children in the control groups performed the baba span task twice.

Counting span task. The material consisted of 148 × 210-mm cards with varying numbers of red target dots (*n* from 6 to 10) and green dots (*n* × 2) stuck on them. These cards were presented one at a time in series of ascending length, from 2 to 6 consecutively. After each dotted card, a card with a printed letter to be remembered was inserted. All the letters used were consonants. These cards were presented for approximately 1 s. Each series ended with a card with the word “recall.” The length of series took the form of 3 sets of cards: there were 3 series of 2 cards to be counted (and 2 letters), followed by 3 series of 3 cards to be counted (and 3 letters), 3 series of 4 cards, and so on. The cards were bound in a booklet, the pages of which were turned by the experimenter. The children were instructed to point at and count out loud the red dots on the cards, to read and remember the letters, and then to recall them in the correct order on seeing the “recall” card. When a participant failed to recall the letters on each set of a given length series correctly, the series of higher length was not presented and the task was interrupted. Two training series of two cards to be counted and one series of three cards preceded the experimental series.

The entire production of each participant was recorded with a dictaphone in order to it subsequently measure the time he or she took to count each dotted card.

Baba span task. This task was administered using HyperCard software on a Macintosh computer. The same series as in the counting span task were used, except that the dotted cards were replaced by white cards presented on screen and children were asked to say “bababa” as regularly as possible while these cards were displayed (approximately two “ba’s” per second). For each participant in the experimental groups, the duration of presentation of each white card was determined by the time he or she took to count the dots on the corresponding counting span card. For the control groups, this time was the mean time recorded in the experimental group. For each group, the series of letters were the same as those used in the counting span task.

For both groups and tasks, the span was the maximum-length series at which all the recalls were correct (i.e., in each of the three series) minus 0.33 for each shorter series which was not correctly recalled and plus 0.33 for each longer series correctly recalled. For example, a child who correctly recalled all the 3-card series plus 2 series of 4 cards but failed in 1 series of 2 cards was credited with a span of 3.33 (i.e., $3 + 2 \times 0.33 - 1 \times 0.33$).

Results

A 2 (Age: 8 vs 11 years old) × 2 (Condition: experimental vs control) × 2 (Session: first vs second) ANOVA with Session as the within-subject factor was performed on the span. Only the age and the session effects were significant. Older children had a higher mean span (4.36) than younger children (3.39), $F(1, 60) = 35.74$, $p < .001$, $MSe = .85$, and the performance on the second session (4.13) was better than that in the first session (3.63), $F(1, 60) = 38.89$, $p < .001$, $MSe = .20$ (Table 1). Contrary to Case’s cognitive space hypothesis prediction, there was no interaction between condition and session at any age (F’s < 1). When the first session was considered separately, there was no significant difference between the mean counting span in the experimental groups (3.31 and 4.17 for 8- and 11-year-old children respectively) and the mean baba span in control groups (2.94 and 4.10 for 8- and 11-year-old children respectively), $F(1, 60) = 1.37$, $p = .25$, $MSe = .56$. The children who performed the counting span task even slightly outperformed the children who performed the baba span task.

Thus, these results contradicted Case’s hypothesis but were in line with the memory decay hypothesis. Indeed, counting speed was higher in 11-year-old children (346 ms per dot) than in 8-year-old children (474 ms per dot), $F(1, 30) = 30.74$, $p < .001$, resulting in shorter retention periods. As Towse and Hitch (1995) observed, there was a significant overall correlation between counting span and speed of counting, $r = -.35$, $p = .05$, that turned out to be nonsignificant when the effect of age was partialed out, $r = .05$.

However, it should be stressed that the memory decay hypothesis was only supported in the present experiment by a null result: there was no difference between baba span and counting span. Thus, it is always possible that this absence of difference merely results from a lack of sensitivity of the paradigm we used, which is perhaps insensitive to any difference between conditions. In order to rule out this hypothesis, we performed a control experiment in which 8- and 11-year-old children were presented with the same letters at the same rate as in the control groups of Experiment 1, except that they did not have to perform any concurrent task. We hypothesized that saying “baba” and counting dots aloud had the same detrimental effect in recall because both concurrent tasks block rehearsal strategies. Thus, we predicted that performance in recall without concurrent task should be higher than in both the “baba” and the counting conditions.

CONTROL EXPERIMENT

Fourteen children from each of the second (Mean age = 8,0 years, range = 7,6–8,10 years; hereafter 8 years old) and the fifth grades (Mean age = 11,11 years, range = 10,6–11,5 years; hereafter 11 years old) participated as volunteers in this control experiment. The material and the procedure were the same as in the previous “baba” span condition for the control groups, except that the children were not asked to say “bababa.” They were only instructed to

TABLE 1

Mean Spans (and Standard Deviations) Observed in Experiment 1 as a Function of Age, Experimental Condition, and Session

	Age			
	8		11	
Session	First	Second	First	Second
	Counting span	*Baba span*	*Counting span*	*Baba span*
Experimental group	3.31 (.81)	3.75 (.69)	4.17 (.58)	4.73 (.49)
	Baba span	*Baba span*	*Baba span*	*Baba span*
Control group	2.94 (.78)	3.56 (.98)	4.10 (.80)	4.46 (.53)

look carefully at the screen, to try to remember the successive letters that will appear on it, and recall them in the correct order when the word "Rappel" was displayed. The experimenter did not give any instruction about possible strategies like rehearsal or chunking. The span was calculated in the same way as previously done.

We compared the mean span in each of the two age groups with the mean spans observed in the first session of both the experimental (counting span) and the control (baba span) groups of Experiment 1. The children in this control experiment clearly outperformed their peers who performed either the counting or the baba span task in Experiment 1. The mean span in the 8-year-old children (4.31, $SD = 0.63$) was significantly higher than both the mean counting span (3.31), $F(1, 43) = 13.16$, $p < .001$, $MSe = .56$ (Dunnet's test), and the mean baba span (2.94), $F(1, 43) = 24.93$, $p < .001$, $MSe = .56$. In the same way, the mean span in 11-year-old children (5.29, $SD = 0.50$) was significantly higher than both the counting span (4.17), $F(1, 43) = 22.45$, $p < .001$, $MSe = .42$, and the baba span (4.10), $F(1, 43) = 25.03$, $p < .001$, $MSe = .42$. The effect of age was significant, $t(26) = 4.52$, $p < .001$. A 2 (Age) × 3 (Conditions: counting, "baba," and control) did not reveal any interaction between age and conditions, $F < 1$.

Thus, saying "baba" or counting dots aloud had a detrimental effect in recall performance, probably because these two concurrent tasks prevented the children from using a rehearsal strategy between each letter presented. Indeed, most of the children who took part in the control experiment used such a rehearsal strategy, whispering the letters they had already read. However, the detrimental effect on recall of saying "baba" on the one hand and counting dots on the other did not differ.

Discussion

The results of these experiments clearly support Towse and Hitch's memory decay hypothesis. As predicted by this hypothesis, the experimental groups which performed an easier task in the second (baba span) than in the first (counting span) session did not exhibit a greater increase in span between the two sessions than the control groups which performed the baba span task twice. As far as the first session was concerned, the participants in the control groups, who performed the baba span task, did not outperform participants in the experimental groups who performed the counting span task. Thus, provided that the retention period is kept constant across tasks, counting dots or just saying "ba, ba, ba" results in identical levels of correct recall, at least in 8- and 11-year-old children. This result suggests that the effect of the counting process in the counting span measure is very similar to a concurrent articulation effect (Baddeley, 1986). The requirement to count the dots aloud would block any rehearsal strategy which could preserve the memory traces of the letters to be remembered. This fact was clearly demonstrated in the control experiment. When the children did not have to pronounce “baba” or number words during the interletter intervals, their recall performances were far better, resulting in a mean span increase of one unit.

In contrast, these results argue strongly against Case’s cognitive space hypothesis. Indeed, the age-related increase in span we observed in this experiment can no longer be explained by an increase in counting efficiency, as a simple comparison between the two tasks we used makes clear. On the one hand, the counting task requires at least the enunciation of the number words, pointing to the objects, and the coordination of these two processes. On the other, the processing component of the “baba” span task simply requires subjects to pronounce “baba,” which is an activity akin to one of the components of the previous task (i.e., saying number words). Thus, counting involves additional constraints compared to saying “baba.” Even if one considers that the efficiency of each of these different activities (i.e., pronunciation, pointing, and coordination) increases with age, it remains the fact that (a) the counting task should be more demanding than just saying “baba”; and (b) the increasing efficiency of each activity should result in a larger reduction in the cognitive space demand in the case of counting than in the case of saying “baba.” Therefore, the counting span should be lower than the “baba” span and this difference should decrease with development, two phenomena which we did not observe. Thus, as suggested by Towse and Hitch (1995), the age-related increase in counting span can only result from faster counting in older children.

Moreover, the strong learning effect observed between the two sessions is in line with Towse and Hitch’s proposals. Of course, this effect could be due to the retrieval from long-term memory of the series of letters previously learned in the first session. However, the delay of 3 weeks between the two sessions weakens this hypothesis. Towse, Hitch, and Hutton (1998) suggested that instead of a resource-sharing process between the two components of working memory tasks (i.e., processing and storage), their results argued in favor of a task-switching strategy: Children may alternate between counting during display presentation and storing the results at display offset. The learning effect could be due to an increasing ability from trial to trial, and from the first to the second session, to manage this switching strategy efficiently.

Only one fact was at odds with the memory decay hypothesis: the absence of a correlation between counting speed and counting span. Indeed, if the span depends on the retention period of the letters, it might be supposed that the faster the counting, the higher the span. However, when the age effect was partialed out, the correlation was virtually nil. However, it is possible that developmental and individual differences are underpinned by different mechanisms, as Jenkins, Myerson, Hale, and Fry (1999); and Cowan, Wood, Wood, Keller, Nugent, and Keller (1998) have recently suggested. It is possible that the developmental increase in span is due to faster counting and, subsequently, shorter retention periods, whereas individual differences result from another, undetermined, mechanism.

Though the results of Experiment 1 argued against Case’s cognitive space hypothesis, it is possible that this hypothesis is correct but that the cognitive load involved in counting is not high enough to provoke the predicted difference between baba span and counting span. Indeed, counting could be such an automatized skill in 8-year-old children that its cognitive load does not require larger operating space than saying “baba.” Towse and Hitch (1997) have shown that the coordination between saying and pointing in counting has no cognitive cost from the age of 7 onward. Thus, the predicted difference between baba span and counting span should be more likely to occur in younger children than in those we tested in Experiment 1 because the younger the children, the less automatized the counting skill. To this end, Experiment 2 compared counting span and baba span in 6-year-old children.

EXPERIMENT 2

This experiment compared the counting and the baba span in 6-year-old children. Provided that there was no difference between the groups in the first session of Experiment 1, we adopted a between-subject design in which one group was asked to perform a counting span task and the other a baba span task. This design resulted in a shorter experimental session which seemed more appropriate for these young children. The mean retention period was held constant across the two groups by means of the same method as in Experiment 1 for the experimental and control groups in the first session. Case's cognitive space hypothesis predicts higher baba span than counting span, whereas the memory decay hypothesis predicts equal spans in the two tasks.

Method

Participants. Thirty-three kindergarten children were randomly assigned either to the counting span group (n = 17, Mean age = 5,9 years, *SD* = 4.4 months) or to the baba span group (n = 16, Mean age: = 5,8 years, *SD* = 4.2 months). Before the experiment, the experimenter verified that each child was able to read the letters used in this experiment.

Material and procedure. The material and procedure used for both the counting span and the baba span tasks were the same as in Experiment 1, except that (a) the letters to be remembered were presented before instead of after the cards in order to control that young children are able to maintain at least one item while counting a card; (b) the six-card series was dropped and three series of one card only (and therefore one letter to be remembered) were added because we thought that some young children would possibly fail to recall a series of two cards, whereas a counting span of 6 was very unlikely in 6-year-old children; and (c) the experimenter read out loud each presented letter at the same time as the participant did. For the baba span task, the duration of presentation of each white card was the mean time to count the dots in the corresponding card recorded in the counting span group. For both tasks, the span was calculated in the same way as in Experiment 1 (possible span range from 0 to 5).

Results

The mean span was 1.14 in the counting span group (*SD* = 0.65, range from 0 to 2.33) and 1.35 in the baba span group (*SD* = .70, range from 0 to 2.67). This difference was not significant, $t(31) = 0.92$, $p = .36$. Thus, as we observed in Experiment 1, there was no difference between the baba span and the counting span, even in very young children. However, the participants in the baba span group slightly outperformed those in the counting span group. A power analysis revealed a d of .321, which corresponds to a small effect (Cohen, 1988), and a δ of .923, indicating that the test did not have sufficient power to detect a possible difference. Given an α level of .05, a large pool of participants would be necessary to obtain a power test of .80 (152 participants per group; Howell, 1997). Thus, even if we cannot assume that there is no difference between the two span measures, the difference is probably too small to be interpreted as confirming the cognitive space hypothesis which predicted a large difference between the baba span and the counting span.

The mean counting time per dot in the counting span group (536 ms) was higher than that observed in 8-year-old (474 ms) and 11-year-old children (346 ms) in Experiment 1 and was very close to Case, Kurland, and Goldberg's (1982) results with a similar age group (545 ms). As in Experiment 1, the correlation between the time needed to count the cards and the counting span did not reach significance, $r(15) = .31$, $p = .23$, but this lack of significance could result from the small size of the group.

Discussion

Once more, the results of this experiment supported Towse and Hitch's memory decay hypothesis and contradicted Case's cognitive space hypothesis. Indeed, according to Case's theory of cognitive development, counting should be a highly demanding task for 6-year-old children because they are only at the beginning of the dimensional stage, a developmental stage at which counting span is thought to be a reliable measure of operational efficiency. Thus, especially at the beginning of the dimensional stage in Case's theory, the counting span should be far lower than the baba span because counting should be far more demanding than saying "baba."

Moreover, it should be noted that as far as the counting span task is concerned, our participants conformed to the predictions issuing from Case's developmental theory. Case (1985) used a counting span task in which participants had to remember the results of their successive counts instead of letters presented before counting each card. Thus, in Case's design, children have just finished to count the last card when they have to recall the series, a fact that should facilitate recall. We can thus suppose that Case's design should result in a higher span (approximately of one unit, i.e., the last card counted) than the one we used. As a consequence, the performance of our sample of participants was very similar (mean span: 1.14) to what the theory predicts (i.e., a span of 2 with Case's design; Case, 1985) and what is usually observed in 6-year-old children (2.5 in Case, 1985; 1.65 in Case, Kurland, & Goldberg, 1982). Thus, our results could not be due to a peculiarity of the children who participated in the experiment.

Consequently, the results of Experiments 1 and 2 suggest that the increase in counting span observed during childhood cannot be due to an increase in operational efficiency that would free an increasing amount of cognitive space for storage. As we stressed in the introduction, counting is thought to involve more complex processes than saying "baba." Thus, counting should require a larger cognitive space than saying "baba," especially in young children, and any increase in operational efficiency should be more effective in connection with counting than with saying "baba." In consequence, the baba span should be higher than the counting span in young children, and we should observe a more pronounced increase for counting span than for baba span with age. The results contradicted these two predictions.

The competing memory decay hypothesis seems far more plausible. In each of the three age groups (i.e., 6-, 8-, and 11-year-old children), there was no clear difference between the baba span and the counting span when the retention period was held constant across tasks. This fact suggests that the retention period is the main factor that constrains performance in the counting span task. As Towse and Hitch (1995) suggested, the counting speed increases with age (536, 474, and 346 ms per dot for 6-, 8-, and 11-year-old children respectively), resulting in shorter retention periods and thus in better recalls.

As far as the counting span task is concerned, it is clear that, following Towse's work, our results strongly support the memory decay hypothesis. However, it should be stressed that this conclusion concerns only the counting span measure and the use Case made of its evolution with age in order to understand cognitive development. Now, are these results, and more generally Towse and Hitch's observations (Towse & Hitch, 1995; Towse, Hitch, & Hutton, 1998), sufficient to definitively rule out the general cognitive resources hypothesis in accounting for working memory spans increase and cognitive development? There are at least two arguments that point to a negative answer.

First, both our and Towse and Hitch's (1995) results would provide evidence against the resources hypothesis only if we assume that counting is a demanding task. Though a componential analysis of this ability (i.e., saying number words + pointing + coordinating these two activities) would suggest that counting requires considerable cognitive resources, especially in order to coordinate pointing and saying, it could be argued that counting is an early automatized activity, even in young children. It should be remembered that counting is one of the first and most extensively practiced arithmetic skills which provides a foundation for further arithmetic achievements. Various studies have failed to demonstrate that the coordination of saying and pointing involves a cognitive cost, even in young children (Camos, 1998; Camos, Barrouillet, & Fayol, 2001; Camos, Fayol, & Barrouillet, 1999; Miller & Stigler, 1987; Towse & Hitch, 1997). Thus, it could be argued that there is no difference between the baba span and the counting span because counting is not demanding enough to impede storage and recall any more than saying "baba" does.

Second, contrary to a general tendency in all domains of cognitive psychology to contrast two alternative hypothesis, the resource hypothesis is absolutely not incompatible with a memory decay hypothesis. For example, Cowan (1995, 1999) proposed that working memory functioning is constrained in two ways: by the limited number of items of knowledge that can be maintained in the focus of attention (due to a kind of resource limitation), but also by the temporal decrease of activation suffered by the items of knowledge as soon as they leave this focus, which is a memory decay phenomenon. Thus, the results of Towse, Hitch, and Hutton (1998), who manipulated the retention period and held the cognitive cost of the task constant, clearly argue in favor of a memory decay phenomenon but do not exclude a limited resources hypothesis.

In order to evaluate the resources hypothesis more precisely, a working memory task involving highly demanding processing is needed. An operation span task (Turner & Engle, 1989) that requires subjects to perform arithmetic operations while remembering letters for recall seems appropriate for this purpose. Indeed, studies in cognitive arithmetic have shown that even for the simplest additions (i.e., both operands from 1 to 9), young children use algorithmic strategies. Though these simple additions become automatized and are solved through direct retrieval of the answer from memory (about 9 years of age), additions involving large numbers would still require computational strategies. These strategies are thought to be highly demanding because they involve the control of complex algorithms (e.g., solving 9 + 7, doing 10 + 7 – 1) and they require individuals to perform accurate memory retrievals (e.g., solving 14 + 8 doing 10 + 4 + 8 may require the retrieval from memory of the answer to 8 + 4) and to keep track of many intermediate results.

In Experiment 3, we compared the operation span and the baba span in 9- and 11-year-old children while keeping the duration of the tasks constant, as we did in the earlier experiments. If working memory measures are only a matter of retention period, there should be no difference between the two span measures. On the other hand, if working memory span measures depend on some kind of resource limitation, then the baba span should be higher than the operation span, assuming that solving additions is more demanding than saying “baba.” An additional hypothesis which derives from the limited resource hypothesis would be that the difference between the two spans should be all the more pronounced the younger the children are. Indeed, as suggested by several developmental theories, both the capacity of the pool of cognitive resources (Halford, 1993, Pascual Leone, 1970) and the level of automatization of arithmetic computations (Siegler, 1996) should increase with age. Thus, provided that the retention period is kept constant between the operation span task and the baba span task, the additional cognitive cost involved in performing calculations should be all the less damaging the older the children are.

EXPERIMENT 3

Method

Participants. Forty-eight children in each of the third (M = 8,8 years, SD = 5.6 months, hereafter 9-year-old children) and fifth (M =10,7 years, SD = 4.6 months, hereafter, 11-year-old children) grades of primary school were randomly assigned to the baba span and the operation span groups.

Material and procedure. Both tasks were presented on a screen. As far as the operation span task was concerned, participants were presented with series of ascending length (from one to six operations) in which each operation was preceded by a consonant to be remembered. There were 3 series of each length. The operations were 54 three-operand additions (e.g., 4 + 7 + 8) and 9 two-operand additions (e.g., 9 + 8). Half of these problems had a correct answer (e.g., 4 + 7 + 8 = 19), and the other half had an incorrect answer (correct answer ± 1). These problems were selected from a pool of about 90 additive problems administered to 20 third-graders in a pretest in which participants were asked to write down the answer. The selected problems elicited a correct response higher of over 80% and did not take longer than 14 s to be solved. The 63 problems were randomly assigned to the 18 series.

All the series had the same structure. First, the participants were asked to focus for 500 ms on a signal (an asterisk) centered on the screen that was replaced, for a period of 1 s, by a letter which they were asked to remember. When the letter disappeared, a problem was displayed on screen. The participants had to evaluate the answer and give their response (true or false) by pressing one of two keys labeled on the computer keyboard. Reaction times and type of response were recorded. As soon as the participant pressed a key, the problem was replaced by the signal and a new trial began. At the end of the series, the word "rappel" ("recall") was displayed on screen and the participants were asked to recall the letters in the correct order.

As far as the baba span task was concerned, the sequence of events was the same except that the problems to be verified were replaced by empty screens during the presentation of which the children were asked to say "ba, ba, ba" as regularly as possible (approximately two "ba's" per second). The duration of presentation of each empty screen was the mean time recorded in the operation span group for verification of the corresponding problem. Both operation span and baba span were calculated in the same way as in Experiment 2.

Results

As far as the operation span groups were concerned, the problem evaluation task elicited a high rate of correct responses (93.5 and 92.5% in 9- and 11-year-old respectively). The mean solution time per problem was 12705 ms (SD = 3502 ms) in 9-year-old children and 8497 ms (SD = 3174 ms) in 11-year-old children. Both these mean rates and solution times corresponded to what was observed in the pretest, suggesting that the children paid sufficient attention to the problem solving component of the operation span task. Moreover, the evaluation of the operations took no longer whether this evaluation turned out to be correct or incorrect (12179 and 14352 ms respectively in 9-year-old children; 8110 and 8930 ms in 11-year-old children, F's (1, 23) < 1). Thus there is no reason to suppose that errors in the evaluation of problems facilitated ensuing recall because it took slightly longer to give an incorrect than a correct response. In consequence, performances in recall were taken into account whatever the responses given in the evaluation task (Table 2).

A 2 (age: 9- vs 11-year old) × 2 (task: operation vs baba span task) ANOVA was performed on the spans. The oldest children exhibited a higher mean span (3.04) than the younger (1.91), $F(1, 92) = 33.78$, $p < .001$, $MSe = 0.91$. More importantly, and contrary to what we observed in the previous experiments, there was a main effect of tasks: the mean baba span (2.75) was higher than the mean operation span (2.19), $F(1, 92) = 8.33$, $p < .005$, $MSe = 0.91$. Though this difference was higher in 9-year-old children [2.26 and 1.56 for the baba and operation spans respectively, F (1, 46) = 8.93, $p < .005$, MSe = 0.68], than in 11-year-old children [3.25 and 2.83, $F(1, 46) = 1.82$, $p = .18$, $MSe = 1.15$], the age × task interaction did not reach significance, $F(1, 92) < 1$.

Though the difference between the operation and the baba span was clear, it was possible that part of this difference was due to a weakness in the paradigm we used. Indeed, all the participants in the baba span group saw the letters to be remembered at the same pace because the time duration of the empty screens was the same for all the participants (i.e., the mean duration time for solving the corresponding operation in the operation span group). However, the retention period in the operation span group varied from one participant to another (because these periods depended on the time required to solve the arithmetic operations). Thus, the difference between the two groups could be due, for example, to certain partici-

TABLE 2

Mean Spans (and Standard Deviations) Observed in Experiment 3 as a Function of Age and Task

	Tasks	
Age	Operation span	Baba span
9	1.56 (0.80)	2.26 (0.84)
11	2.83 (1.30)	3.25 (0.78)

pants who solved the problems very slowly and had to deal with long retention periods that might result in poor recall performance. In order to control for this possible flaw, a further analysis was conducted in which the participants in the operation span groups who exhibited either excessively short or excessively long mean solution times were discarded. Only the participants whose mean solution time was close to the mean of the group (± 0.67 *SD*) were retained ($n = 12$ in each age group).

This procedure led to the same results and conclusions. The mean operation span remained unchanged in the 9-year-old group (1.56, $SD = 0.86$) and even fell in the 11-year-old group (2.61 instead of 2.83, $SD = 1.25$). An ANOVA with the same design as the previous analysis was conducted and took into account the overall baba span groups ($n = 24$ per group) but only the reduced operation span groups ($n = 12$). The main effect of task was still significant, $F(1, 68) = 8.91$, $p < .005$, $MSe = 0.82$. Separate analysis on each age group confirmed that the baba span (2.26) was significantly higher than the operation span (1.56) in 9-year-old children, $F(1, 34) = 5.61$, $p < .05$, $MSe = 0.71$. This difference just failed to reach significance in 11-year-old children (3.25 and 2.61 for the baba span and the operation span respectively), $F(1, 34) = 3.57$, $p = .07$, $MSe = 0.92$. Thus, when the two task groups were more carefully equated on the retention period, the difference between the two spans appeared even more strongly.

Finally, there was no clear correlation in the operation span groups between the mean solution time per operation (i.e., the mean retention period) and the operation span: $r = -.06$ and $-.26$ for 9- and 11-year-old children respectively.

Discussion

According to a strong version of the memory decay hypothesis, the span would depend only on the retention period, whatever the competing task to be performed. The results of this experiment clearly argue against this view. Indeed, participants in the operation span groups exhibited poorer recall performances than those in the baba span groups even though the retention period was held constant. This difference appeared even more clearly when the retention period was carefully equated between the two experimental conditions.

On the other hand, these results are in line with the limited resource hypothesis. Indeed, it is very unlikely that children could solve three-operand additions, the main type of operation used, by a strategy of direct and automatic retrieval of the answer from memory. Developmental research in additive problem solving suggests that this kind of strategy is available in childhood, and even in adulthood, for simple two-operand additions only (operands from 1 to 9; Siegler, 1996). The other problems require algorithmic strategies, the use of which is demanding (Barrouillet & Fayol, 1998). The solution times recorded in both age groups (about 10 s) testified to the use of algorithmic strategies by our participants. These strategies require step-by-step computations, storage, and retrieval of intermediate results, i.e., processes thought to involve a cognitive cost (Anderson, Reder, & Lebiere, 1996). Thus, the difference between the baba span and the operation span could be accounted for by the cognitive load involved in solving arithmetic problems by algorithmic strategies.

Though these results support the limited resource hypothesis, they do not definitely rule out the potential impact of a memory decay phenomenon in accounting for the difficulty of complex span tasks (i.e., processing storage) for at least two reasons. First, although the difference between the two spans was significant, the size of the effect could be considered moderate (2.75 vs 2.19). Indeed, it should be remembered that we contrasted a task presumed to induce a high cognitive load (arithmetic problem solving) with a simple concurrent articulation thought to be load-free. Such a supposedly dramatic difference between the cognitive loads involved in the two tasks resulted in a rather small decrease in span (about 20%). In fact, this decrease reached significance only in 9-year-old children but not in 11-year-old children, although it cannot be supposed that the latter solved the problems by an automatic and direct retrieval from memory (mean solution time about 8.5 s). Second, the fact that an additional cognitive load hampers recall does not mean in any way that the memory traces of the letters do not suffer from a temporal decay. The results of this experiment simply suggest that we cannot jettison any notion of cognitive load or resource in accounting for performances in working memory tasks.

GENERAL DISCUSSION

Let us recall that this series of experiments was inspired by Towse and Hitch's (1995; Towse, Hitch, & Hutton, 1998) proposal concerning the increase in counting span with age, namely by a developmental concern. Is working memory span increase due to a trade-off between processing and storage, as Case (1985) has suggested, or to an increase in counting speed which prevents a memory decay phenomenon (Towse & Hitch, 1995)? The results of Experiments 1 and 2 clearly contradict Case's hypothesis and argue in favor of Towse and Hitch's memory decay hypothesis. In fact, we failed to find any clear difference between counting span and baba span, even in younger children (6 years of age).

This fact rules out Case's cognitive space hypothesis. Indeed, this hypothesis assumes (a) that the Total Processing Space remains constant across development and (b) that the developmental increase in counting span is due to a decrease in the operating space required to perform the counting task, which therefore releases increasing amounts of memory for the storage of items in the short-term storage space. Thus, this model postulates that younger children have low working memory spans because the counting task is highly demanding for them. Even if we suppose that saying "ba ba" involves some cognitive cost, Case's (1985, 1992) integrative approach to cognitive development (conceived of as a process of coordinating cognitive operations) predicts that counting should be more demanding than saying "baba," especially in young children, because counting involves the coordination of pointing at objects and saying number words. For the same reason, the increase in operational efficiency that would account for the increase in working memory span should be more pronounced for the counting task than for saying baba. As a consequence, Case's theory of cognitive development predicts (a) lower performances in counting span than in baba span tasks and (b) an age-related increase in span which should be more pronounced for the counting span than for the baba span. None of these predictions was verified.

As far as the counting span task is concerned, the memory decay hypothesis is far more convincing. As Towse and Hitch (1995) suggested, the memory traces of the items to be remembered fade as the counting process goes on because counting aloud prevents any rehearsal strategy that could refresh these traces in the phonological loop (Baddeley, 1986). Any task that involves articulation should have the same effect, as we observed with the baba span task. Thus, the counting span is only a matter of time. The older the children are, the faster their counting and consequently the better their recall. Towse, Hitch, and Hutton (1998) suggested that instead of actively combining processing and storage, children may alternate between counting during display presentation and storing results at display offset. Thus, developmental increase in working memory span could result from shorter retention periods and developmental differences in the way children manage the switching strategy.

However, the results of Experiment 3 indicate that the switching strategy hypothesis put forward by Towse et al. (1998) is an oversimplification. Indeed, if this switching occurred between processing and storage in a simple manner, that is at the display offset, then there would be no difference between operation span and baba span because the interletter durations were held constant between the two tasks. However, and contrary to what we observed when comparing counting span and baba span, there *was* a difference between operation span and baba span. Thus, though a simple short-term memory model coupled with a memory decay hypothesis is appealing, it is not sufficient to fully account for developmental increases in working memory span.

Obviously, a more sophisticated model is needed because it seems that two kinds of limitations have to be taken into account in working memory functioning. The first is a limitation in the time a given piece of knowledge can be kept active in working memory, as Towse, Hitch, and Hutton (1998) have demonstrated. The second limitation could result from a limited pool of resources, whatever we mean by "resources" (capacity for activation, for controlled attention, etc.), as suggested by the difference between operation span and baba span even when time parameters are held constant. In fact, many models of working memory permit this distinction between time and resource limitations such as the seminal model of Baddeley (1986; Baddeley & Logie, 1999) and more recent approaches put forward by Cowan (1995), Engle (Engle & Oransky, 1999; Engle, Kane, & Tuholski, 1999), and also the ACT-R model (Anderson, 1993, Anderson & Lebiere, 1998; Lovett, Reder, & Lebiere, 1999).

According to Baddeley and Logie (1999), working memory comprises multiple specialized components (a central executive and two systems for temporary storage, the phonological loop and the visuospatial sketchpad), each having constraints commensurate with the special function it provides. The authors state that the cognitive demands in working memory tasks (i.e., processing and storage) could be supported by different components of working memory (i.e., the central executive and the phonological loop respectively). Baddeley and Logie (1999) reported an experiment by Logie and Duff (1996), who demonstrated that even a demanding storage had virtually no impact on the capacity for arithmetic verification and that a demanding verification task had little effect on word span, suggesting that processing and storage do not compete for a single resource but are supported by separate components. These results echo our observation that counting span and baba span were equal and that the participants who performed a baba span task only slightly outperformed those who performed an operation span task. We might therefore imagine that in these tasks the letters are stored in the phonological loop, the maintenance of which suffers only from a temporal decay, whereas the processing component of the tasks is supported by the central executive.

However, this explanation is not as clear as it seems. Indeed, items in the phonological store are thought to fade rapidly (about 2 s) when they are not reactivated by a verbal rehearsal (Baddeley, 1986). Considering that concurrent articulation (saying "baba" repeatedly or counting aloud) prevents rehearsal (Baddeley, 1999) and that counting dots or solving operations took longer than 2 s in our experiments, we must suppose that the items to be remembered are not stored in the phonological loop. Thus, the fact that the counting span and the baba span are the same cannot be accounted for by the multicomponent architecture of Baddeley's model. Of course, as stressed by Baddeley and Logie (1999), the letters we presented could activate LTM representations that could be retrieved for recall. However, such encoding and retrieval processes would be supported by the central executive (Baddeley & Logie, 1999). Thus, the same working memory component would support both processing and storage and we could no longer take advantage of the multicomponent characteristic of the model.

The models of working memory that suppose that short-term memory is the part of long-term memory activated above threshold (Anderson, 1993; Anderson & Lebiere, 1998; Anderson, Reder, & Lebiere, 1996; Cantor & Engle, 1993; Cowan, 1995, 1999; Engle, Kane, & Tuholski, 1999; Engle & Oransky, 1999; Lovett, Reder, & Lebiere, 1999) seem more appropriate to account for both time and resource limitations in working memory. Indeed, these models assume that (a) both the activation and retention of items of knowledge which are readily available for processing are mediated by some kind of controlled attention of limited availability; and (b) that the loss of memory traces is a matter of time, being due either to decay of activation or to interference. The items present in the focus of attention receive activation, but this activation decays as soon as they leave the focus. Thus, complex span tasks, that require processing plus storage, are more difficult than simple STM span tasks because, in the former, attention is distracted from the items to be remembered by the concurrent task. Because the size of the attentional focus (Cowan, 1995; Engle, Kane, & Tuholski, 1999) or the total amount of attention (Anderson, 1993) are limited, only a small number of items receive increased activation from attention and any distraction from the items to be remembered leads to their decay. Furthermore, the reactivation of those traces that are fading would not necessitate a 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 et al., 1994). According to this general framework, “working memory capacity reflects the ability to apply activation to memory representations, to either bring them into the focus or maintain them in focus, particularly in the face of interference or distraction” (Engle, Kane, & Tuholski, 1999, p. 104).

How could this kind of model account for a developmental trend and the pattern of performance we observed across tasks? As far as development is concerned, both an increase in attentional capacity and a decrease in the speed of decay could account for the developmental increase in working memory span. Obviously, if speed of decay is higher for younger than for older children, as suggested by Keller and Cowan’s (1994) results, older children should have higher spans than younger ones. On the other hand, a developmental increase in the amount of attention available could result in faster processing (e.g., counting or problem solving) and thus in shorter retention periods, with more recall items being retrieved before they are irretrievably lost. This hypothesis is akin to those advanced by Towse and Hitch (1995) or Case (1985) because it is based on an explanation in terms of processing efficiency. However, if working memory span depended only on the duration of processing, we should observe a correlation between the time needed to complete the task and the resulting span. In fact, like Towse and Hitch (1995), we failed to find such a correlation, and Engle (Engle, Cantor, & Carullo, 1992; Conway & Engle, 1996) demonstrated that the correlation between working memory span and high-order cognitive tasks does not depend on the processing efficiency in the processing component of the working memory tasks.

A more plausible account would be that an increase in attentional capacities results in better resource sharing between processing and storage or in a better switching between the two components of the working memory tasks. Accordingly, Cowan, Nugent, Elliot, Ponomarev, and Saults (1999) have demonstrated that the capacity limit increases with age during childhood. In Towse and Hitch’s (1995) experiments, the mean counting time per card in 6- and 8-year-old children was approximately the same (about 4 s) but the former exhibited a lower counting span (2.8) than the latter (3.7). Thus, even when the time duration of processing is identical, older children achieve higher working memory spans than younger ones, thus suggesting that they have more resources to deal with the complex span tasks.

The attentional hypothesis could also account for the pattern of results we observed across working memory tasks. Case (1985) assumed that counting span is lower in younger than in older children because counting is a demanding task for young children. Towse and Hitch (1995) challenged this hypothesis by suggesting that counting span is only a matter of time and showed that counting span does not depend on the cognitive load involved in counting. However, there is ample evidence that counting is a highly automatized skill, even in young children (Towse & Hitch, 1996, 1997). Thus, it is possible that counting does not require more attentional resources than saying repeatedly “baba” or that the rhythmic nature of both tasks allows participants to switch their attention from processing to storage during the task. However, because both types of processing prevent subjects from continuously maintaining the letters in the focus of attention, their memory traces suffer from a decay which is all the more pronounced the longer the duration of processing is. As a consequence, the baba span and the counting span resulted in the same mean spans, and, as Towse and Hitch (1995; Towse, Hitch, & Hutton, 1998) demonstrated, counting span depends on the time needed to count the arrays of dots.

By contrast, the solution of three-operand additive problems cannot be considered to be an automatized skill in children because it involves many retrievals from memory at the same time as the calculation and maintenance of the intermediate results. We assume that these processes need attentional resources and sustained focusing that have a far more disruptive effect on the concurrent maintenance of items in memory than saying "baba," even if both processes prevent any rehearsal strategy. The fact that solving problems instead of saying "baba" did not result in any dramatic decrease in span suggests that the decay of activation is rather slow even in young children (Cowan, 1984, 1999, suggests time estimates about 10 to 30 s in adults) or that children can switch attention from the operations to the letters to be remembered, for example, when they reach some intermediate result. If this hypothesis is correct, a task that would require continuous attentional focusing on algorithmic computation should have a highly detrimental effect on span.

Despite the fact that counting span seems to be only a matter of time, whereas the operation span task seems to require resource sharing, it should be remembered that counting span remains highly predictive of performance in higher-order cognitive activities (Barrouillet & Lecas, 1999; Engle, Tuholski, Laughlin, & Conway, 1999), as does the operation span (Turner & Engle, 1989). These facts suggest, as stressed by Engle, Kane, and Tuholski (1999), that individual and developmental differences in working memory measures reflect differences in some fundamental capability involved in higher-order cognitive processes and that both counting span and operation span, and maybe baba span, provide appropriate measures of this capability. Thus, time and resource constraints would result from the same general limitation, probably a limited capacity for controlled attention, even if they reflect different aspects of working memory functioning.

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