Adult counting is resource demanding

Valérie Camos* and Pierre Barrouillet

1Université René Descartes—Paris V, France
2Université de Bourgogne, France

Several recent studies on both the development of counting and working-memory span tasks have provided results that could be interpreted as ruling out any cognitive resource model for counting. The aim of this study was to test the hypothesis that, even in adults, counting is a demanding task that requires the allocation of cognitive resources. In a first experiment, we asked adults to count arrays of dots while maintaining 5 items in memory (either digits or letters). As we predicted, the concurrent memory load did not increase the rate of errors but induced longer counting times. In a second experiment, we asked adults to count using either the numeric chain or the alphabet while they maintained 1, 3 or 5 items in memory (digits or letters). First, we replicated the load effect observed in Experiment 1. Second, though both types of counting required similar amounts of time, counting with the less automatized chain (i.e. the alphabet) resulted in a poorer recall performance. Finally, this detrimental effect in recall was all the more pronounced the greater the number of items to be recalled. These results are interpreted within theoretical frameworks that consider cognitive resources as attentional capacities.

*Correspondence should be addressed to Valérie Camos, Laboratoire Cognition et Développement, Université René Descartes—Paris 5, Institut de Psychologie, 71, avenue Edouard Vaillant, 92774 Boulogne-Billancourt Cedex, France (e-mail: valerie.camos@uni5-paris5.fr).
coordination should then induce an extra cognitive load which is added to the cost of the two component activities and which would result in a deterioration of performance (Baddeley, 1990). Furthermore, this coordination should be all the more demanding as the cognitive cost of each component activity increases.

Many recent studies have investigated this coordination hypothesis (Camos, 1998; Camos, 2003; Camos, Barrouillet, & Fayol, 2001; Camos, Fayol, & Barrouillet, 1999; Towse, 1993; Towse & Hitch, 1997). Although they used different paradigms and tested different age ranges (7- and 9-year-old children in Towse’s studies, 5-year-olds to adults in Camos’ studies), their results led to similar conclusions. The increased difficulty of both pointing and saying always affected the counting performance. However, it appeared that the coordination of these two activities does not have any cognitive cost whatever the age group studied. The development of counting from childhood to adulthood (i.e., increase in both speed and accuracy) cannot therefore be conceived of as the result of a coordination that becomes less and less demanding with age.

This latter result could be interpreted as ruling out any resource model as an account for complex activities, even in young children. Indeed, resource models assume that the coordination of two costly activities should induce an additional cognitive cost (Baddeley, 1990; Case, 1985, 1992; Halford, 1993, 1999). Counting is just such a complex activity that has often been used to support the resource theory. For example, Case (1985) assumed that during development, the cognitive load involved in counting decreases with both practice and maturation. Case, Kurland, and Goldberg (1982) addressed this point by asking children and adults to count dots on cards out loud 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 participants were able to remember constituted their counting span. Case et al. (1982) observed a steep increase in counting span with age. They reasoned that counting dots and maintaining previous values in memory share a common, limited pool of resources. Counting span would increase with age because counting becomes less and less demanding, thus sparing an increasing volume of resources that are then available for maintaining the items to be recalled in memory. However, this trade-off hypothesis has recently been challenged by Towse and Hitch (1995) and Towse, Hitch, and Hutton (1998, 2000) who argued that the age-related increase in counting span simply results from shorter retention delays in older children. Indeed, counting is faster in older than in young children (Camos et al., 1999, 2001; Towse & Hitch, 1995). As a consequence, older children exhibit shorter retention delays in the counting span task. Because memory traces suffer from a time-related decay, the shorter the retention delay, the better the recall performance. Towse et al. went on to argue that the developmental increase of counting span (and other working-memory spans) could be accounted for without resorting to any resource hypothesis. Thus, recent studies on both counting performance and counting span tend to question the well-established resource framework.

Though the recent studies on counting that have investigated either the cost of the coordination or counting span development have led to disconcerting results, we would like to suggest that it would be premature to jettison the resource hypothesis. Indeed, we have already suggested that many of these results can be accounted for by assuming that counting is an early acquired procedure (Camos et al., 1999, 2001). The formation of a procedure through a compilation process, as described in Anderson’s ACT-R model, enables the integrated mobilization of pointing and saying without the need for attentional control of their coordination (Anderson, 1993; Anderson & Lebière,
1998). This would explain why many studies failed to find any cognitive cost related to the coordination of pointing and saying in counting (Camos et al., 1999, 2001; Towse, 1993; Towse & Hitch, 1997). However, though the coordination of pointing and saying has a negligible cost, these components themselves could remain resource demanding. For example, Tuholski, Engle, and Baylis (2001) have found that counting arrays of dots is faster in high than in low-working-memory-span adults. The authors explained this difference by suggesting that the differentiation between uncounted and counted objects is a process that requires attention. In the same way, the memory retrieval of the number-words probably requires the allocation of attentional resources (Anderson, 1993). Thus, even if the coordination of pointing and saying does no longer consume resources in adults, both components could remain resource demanding.

Experiment 1 tested this hypothesis. If counting is a resource-demanding procedure, a concurrent memory load should have a detrimental effect on counting performance. Indeed, both counting and storage would draw resources from a common and limited pool. Thus, the resources needed to maintain memory items should be unavailable for counting, and performance should deteriorate. In order to create the most unfavourable conditions, this experiment involved adults for which the pointing and saying are highly automatized and thus less resource demanding than in children. Thus, if Experiment 1 showed that counting is a resource-demanding activity in adults, the obvious consequence would be that counting definitively requires allocation of attention in younger individuals. In Experiment 1, we asked adults to count arrays of dots either while they simultaneously maintained 5 items in memory (5 letters or 5 digits) or without any memory load. We predicted a lower performance (accuracy or speed) when counting under memory load.

Moreover, the effect of memory load in counting should be stronger when counting is more demanding. Camos et al. (2001) showed that the use of a verbal chain (i.e. an organized sequence of words like the alphabet) that is less automatized than the numeric chain provoked an increase in counting times and often an increase in the number of errors as well. We assume that this increase in times and errors results from an increase in the cognitive load involved in counting. Slower counting when the alphabet is used might result from longer access times for letters (as opposed to numbers in a ‘numeric counting’). This slower retrieval suggests that the volume of attentional resources required to retrieve verbal items from memory is greater for the alphabetic chain than for the numeric chain. Thus, independently of the fact that the coordination of the components of counting has a negligible cost, the cognitive cost of counting would be greater when participants count with letters rather than with numbers. As a consequence, the effect of memory load should be stronger in alphabetic than in numeric chain.

Experiment 2 tested this hypothesis. In Experiment 2, adults counted arrays of dots using either the alphabetic or the numeric chain while simultaneously maintaining in memory a series of 1, 3, or 5 items (either letters or numbers) which they had to recall after counting. As in Experiment 1, Experiment 2 involved adults counting alphabetically to create the most unfavourable conditions for detecting the expected difference in cognitive cost between different types of counting. Indeed, the level of automatization of the alphabetic chain should be higher in adults than in children. Thus, if the experiment were to yield results compatible with the hypothesis that the cognitive cost of alphabetic counting is greater than that of numeric counting, these results could, a fortiori, be generalized in two ways: On the one hand, to children, due to their lesser automatization of the alphabetic chain and, on the other, to other verbal chains that are
less highly automatized (e.g. foreign languages as in Camos et al., 2001, or artificial series of words as in Case et al., 1982).

EXPERIMENT I

Method

Participants
Thirty-six psychology students from the Université René Descartes—Paris V (27 females and 9 males, Mean age = 23.5 years, SD = 4.7 years) were volunteers for taking part in the experiment. They were all native French speakers, and none of them were colour-blind.

Material
The arrays used were similar to those of the Counting Span Task (Case et al., 1982). Three sets of 10 arrays were constructed by sticking red and green round stickers (dots) of 16-mm diameter onto 24 × 32-cm white sheets. Eight to 17 target items (red dots) were randomly located among distractors (green dots), and there were one third more distractors than targets. Ten series of items to be remembered were constructed for each of the 2 types of items (letters or digits) conditions. These series were constructed by randomly choosing either consonants within the alphabet or digits excluding zero. Series including abbreviations and acronyms were discarded.

Each set of arrays was assigned to the 3 conditions (no load, 5 letters, 5 digits) thus defining 6 different associations between sets and conditions. The series of letters or digits in the load condition were randomly assigned to the arrays to be counted. Each of the 36 participants was confronted with a different order of presentation defined by 6 possible orders for the 3 experimental ×6 associations between sets of memory items and experimental conditions.

Procedure
For the no-load condition, participants were asked to count aloud the red dots as quickly and correctly as possible for each of the arrays. For each trial on the 5-letters and 5-digits conditions, the to-be-remembered lists were presented aloud by the experimenter at the rate of one item per second, and the participants were then immediately presented with the array to be counted. They were instructed first to count aloud the red dots as quickly and correctly as possible, and then to recall the list of items in the correct order. The need to succeed in both tasks (counting and recall) was similarly emphasized.

Omissions and double-countings of dots, as well as recall errors for the 5-letters and 5-digits conditions were noted on-line for each participant and trial. Errors in saying the number chain while counting and counting times were recorded from an audio-taped recording of each participant’s performance. Because participants counted aloud or subvocalized, a manual timing method was used as in previous counting studies (Camos et al., 1999, 2001; Towse & Hitch, 1997). A digital stopwatch measured counting times to an accuracy of a hundredth of a second. In order to achieve a precise measure, three independent measures of the counting time were made for each participant and trial. The counting time used in the analyses was the average of these three measures (Camos et al., 1999, 2001).
Results
As far as counting errors were concerned, none of the two load conditions (5-letters and 5-digits) differed from the no-load condition, and the two load conditions did not differ, $F_s < 1$. A similar comparison was performed on recall errors for the 5-letters vs. 5-digits conditions. Only the trials in which counting was correct were taken into account. Indeed, any incorrect counting suggested that the participants were not paying sufficient attention to the counting task. This analysis did not reveal any significant effect, $F(1, 35) = 1.48, p = .25, MSE = 292$ (Table 1).

Table 1. Counting mean times (s), mean rate of errors in counting (%) and mean rate of correct recall when counting was correct (%) in Experiment 1 (respective SD in parentheses)

<table>
<thead>
<tr>
<th></th>
<th>Without</th>
<th>Five letters</th>
<th>Five digits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>3.35 (0.86)</td>
<td>3.94 (0.97)</td>
<td>3.97 (1.06)</td>
</tr>
<tr>
<td>Errors</td>
<td>7 (9)</td>
<td>7 (8)</td>
<td>7 (11)</td>
</tr>
<tr>
<td>Recall</td>
<td>–</td>
<td>62 (19)</td>
<td>67 (23)</td>
</tr>
</tbody>
</table>

Comparisons were made on counting times averaged across the 10 trials for which the memory load was identical. Only the trials in which counting was correct were taken into account. Contrary to the analysis on errors, and as we predicted, both memory load conditions (5 letters: 3.94 s; 5 digits: 3.97 s) significantly increased counting times compared with the no-load condition (3.35 s), $F(1, 35) = 32.09$, $p < .0001$, $MSE = 0.20$ and $F(1, 35) = 27.10$, $p < .0001$, $MSE = 0.25$, respectively. There was no significant difference between the two load conditions, $F < 1$.

To summarize, though no significant increase in the error rates was observed, counting under memory load induced longer counting times independently of the type of material to be maintained (letters or digits). These results confirm the hypothesis that counting is a resource-demanding activity, even in adults. Indeed, because both counting and storage are resource demanding, the amount of resources required to maintain memory items is not available for counting. Thus, adults slowed down their counting when they had to maintain items.

EXPERIMENT 2
Our second prediction issuing from the hypothesis that counting is a resource-demanding activity was that the effect of a concurrent memory load should be all the more detrimental when the counting activity is more demanding. Because Camos et al. (2001) showed that counting with a less automatized chain (i.e. the alphabet) induces longer times and often higher error rates, we assumed that these increases result from an increasing resource demand in counting. Thus, we compared the effect of a memory load on adults’ performance in numeric vs. alphabetic counting. In this experiment, adults were asked to count arrays of dots using either the numeric chain or the alphabet while maintaining 1, 5 or 5 items (letters or digits). In line with the previous experiment, we expected that the detrimental effect in counting should be a function of the concurrent memory load, i.e. the number of items to be maintained: The higher this number, the slower and the more difficult the counting. Moreover, we predicted that
this effect should be stronger in alphabetic than in numeric counting performance and
that this difference should be all the more pronounced the higher the memory load.

Method

Participants
Thirty-six psychology students from the Université de Bourgogne (31 females and 5
males, mean age = 21; 11 years, SD = 2; 0 years) received a partial course credit for
taking part in the experiment. They were all native French speakers, and none of them
were colour-blind.

Material
The arrays used were similar to those of Experiment 1. Two arrays were constructed for
each of the 9 sizes from 8 to 16 target items, resulting in 18 different arrays. Three series
of items to be remembered were constructed for each of the 3 lengths (1, 3 or 5 items)
× 2 types of items (letters or digits) conditions, resulting in 18 series, and each of which
was associated with one array. The mean array size was 12 for each of the 3 different
length series (1, 3 and 5) and for both types of items (letters and digits). These 18 arrays
(and their associated list of items to be remembered) were randomly ordered, and 18
different orders of presentation were then obtained by a circular permutation. Two
participants were assigned to each of these 18 presentations orders.

Procedure
The participants were asked to count each of the 18 arrays twice. Half of the participants
began the task by counting the 18 arrays with the numeric chain and then with the
alphabet. The reverse order was used for the other half. As far as alphabetic counting
was concerned, the participants were instructed to use the letters of the alphabet as tags
rather than numbers. For each trial, the list to be remembered was presented aloud by
the experimenter at the rate of one item per second, and the participants were then
presented with the array to be counted. They were instructed first to count aloud the
red dots as quickly and correctly as possible, and then to recall the list of items in the
correct order. The need to succeed in both tasks (counting and recall) was similarly
emphasized. Counting times, saying and pointing errors in counting as well as recall
errors were recorded using the same methods as in Experiment 1.

Results
A 2 (chain used in counting: Alphabetic vs numeric) × 2 (type of items to be maintained:
Letters vs. numbers) × 3 (span: 1, 3 and 5 items) ANOVA with repeated measures for all
factors was first performed on counting errors. As in Experiment 1, this analysis did not
reveal any significant effect, but one effect just failed to reach significance (Table 2).
According to our hypothesis, the alphabetic counting induced more errors than numeric
counting (10 and 7%, respectively), $F(1,35) = 3.86, p = .058, MSE = 193$.

An ANOVA with the same design was performed on the counting times averaged
across the three trials for which the chain used in counting, the type of items to be
maintained, and the span were identical. Only the trials in which counting was correct
were taken into account. As we predicted, there was a significant effect of the memory load in counting times, $F(2,70) = 4.09, p = .02$, $MSE = .08$. Counting times were significantly longer when 5 items (3.26 s) were to be maintained rather than 1 or 3 (3.17 s and 3.18 s, respectively). Moreover, alphabetic counting (3.23 s) was slower than numeric counting (3.18 s), but this anticipated difference failed to reach significance, $p = .11$, and there was no interaction between the chain used in counting and the number of items to be maintained, $p = .35$. No other effect was significant.

Table 2. Counting mean times (s), mean rate of errors in counting (%), and mean rate of correct recall when counting was correct (%) in Experiment 2 (respective SD in parentheses)

<table>
<thead>
<tr>
<th>Type of items</th>
<th>Numeric</th>
<th>Alphabetic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Numbers</td>
<td>Letters</td>
</tr>
<tr>
<td>Span 1</td>
<td>Time</td>
<td>3.13 (0.32)</td>
</tr>
<tr>
<td></td>
<td>Errors</td>
<td>5 (12)</td>
</tr>
<tr>
<td></td>
<td>Recall</td>
<td>100 (0)</td>
</tr>
<tr>
<td>Span 3</td>
<td>Time</td>
<td>3.18 (0.37)</td>
</tr>
<tr>
<td></td>
<td>Errors</td>
<td>6 (13)</td>
</tr>
<tr>
<td></td>
<td>Recall</td>
<td>96 (12)</td>
</tr>
<tr>
<td>Span 5</td>
<td>Time</td>
<td>3.23 (0.35)</td>
</tr>
<tr>
<td></td>
<td>Errors</td>
<td>5 (14)</td>
</tr>
<tr>
<td></td>
<td>Recall</td>
<td>77 (20)</td>
</tr>
</tbody>
</table>

Expected effects on counting performance related to the type of chain used did not reach significance. However, this could be because participants favoured counting to the detriment of the memory activity. Indeed, predicted effects that just failed to appear on counting times were revealed on recall performance.

An ANOVA with the same design as that used for counting errors and times was performed on the rate of series correctly recalled after counting. Only those trials in which counting was correct were involved in this analysis. Apart from a trivial span effect (100, 92, and 67% of correct recall for spans 1, 3 and 5, respectively), $F(2,70) = 68.60, p < .0001, MSE = 608$, and in line with our hypothesis, recall was weaker after alphabetic counting than after numeric counting (84% and 89% of correct recall, respectively), $F(1,35) = 4.67, p = .038, MSE = 403$. Moreover, this effect interacted with the span size, $F(2,70) = 3.70, p = .029, MSE = 289$. While identical for span 1 (100% of correct recall for both counting modes), the recall rates differed increasingly as the span grew (93 and 91% of correct recall in span 3 for numeric and alphabetic counting, respectively, 72 and 62%, respectively, for span 5). Finally, it should be noted that contrary to Experiment 1 and according to the literature (Crannel & Parrish, 1957; Dempster, 1981), numbers were easier to maintain than letters (89% of correct recall with numbers vs. 84% with letters), $F(1,35) = 9.79, p = .004, MSE = 521$, and this was
all the more pronounced as the span increased, \( F(2,70) = 3.29, \ p = .045, \ MSE = 352 \).

No other effect was significant.

To ensure the present results, an ANCOVA was performed on recall errors with counting times as a covariate. Indeed, as we observed in Experiment 1, the maintenance of items during counting increases counting times. Thus, the decrease on correct recall with the number of items could be due to an increase in the duration of maintenance, as suggested by Towse et al.'s memory decay hypothesis. Similarly, the difference on recall between alphabetic and numeric counting could also be accounted by the memory decay hypothesis, although the present results showed a non-significant difference on times.

The results of the ANCOVA confirmed those from the ANOVA on recall errors. The analysis revealed a span effect, \( F(2,68) = 56.94, \ p < .0001, \ MSE = 614 \), and an effect of the type of items, \( F(1,54) = 9.55, \ p = .004, \ MSE = 530 \). More importantly, alphabetic counting induced less correct recall than numeric counting, \( F(1,54) = 4.19, \ p = .049, \ MSE = 414 \), although counting times were used as covariate. The difference between the two types of counting increased with the span, \( F(2,68) = 3.41, \ p = .039, \ MSE = 289 \).

To summarize, as previously observed in Experiment 1, counting was slowed down by concurrent memory load. Contrary to our expectations, alphabetic counting did not result in a significantly lower performance than numeric counting. However, alphabetic counting induced a weaker recall, and this effect was all the more pronounced the greater the number of items to be maintained. This phenomenon confirms the hypotheses of a demanding counting activity in adults and of the higher cognitive cost involved in alphabetic counting.

Discussion

The results of both experiments are compatible with the hypothesis that, even in adults, counting is a resource demanding activity. Two main facts sustained this hypothesis. First, counting under memory load deteriorates performance and necessitates longer times. Second, the use of a less automatized chain increased the cognitive cost of counting as testified by the decrease in the correct recall rate. In line with the resource theory, this decrease was all the stronger the larger the volume of information to be concurrently maintained and recalled. These results are in line with the resource theory, which assumes that maintaining memory items while counting requires resources that are no longer available to perform counting. Such a reduction in the available resources resulted in impaired counting performance. Although we also predicted a stronger impairment in more demanding counting (i.e., alphabetic), such a phenomenon was not significant in counting times and errors, but was reflected in recall performance. This result could be considered as surprising because in Experiment 1, increasing the extrinsic memory load had an effect on counting, whereas in Experiment 2, increasing the intrinsic cognitive load of counting did not have a significant effect on counting speed but affected recall. This is probably due to strategic allocation of attention to one of the two tasks driven by the change that appeared salient to the participants. Indeed, in Experiment 1, participants counted dots while they had or not to maintain memory items. This manipulation drove attention to the storage part of the dual task, even if the need to succeed in both tasks was similarly emphasized. Thus, participants would allocate
more resources to the maintenance of the items, leaving fewer resources for counting. Similarly, in Experiment 2, participants maintained memory items while they had to count with the numeric chain or with the alphabetic chain (half of them starting by the numeric chain, the other half by the alphabetic chain). The most salient change occurred in the processing part of the dual task. Participants would try to keep their performance on counting at their best, even when they used a less automatized chain. Dual-task effects were then observed in the recall performance. Indeed, in line with the trade-off hypothesis from the general resource model, maintaining performance in a more demanding activity (counting with alphabet) requires more resources and then leaves fewer available resources for the concurrent storage activity (Case, 1985, 1992).

Nevertheless, though being not significant, the increase in counting times observed in Experiment 2 could account for the poorer recall performance. Indeed, Towse and Hitch's (1995) memory-decay hypothesis assumes that the differences in recall after performing a concurrent task are due to the duration of this task which determines the recall delay. The longer this delay, the stronger the decay of the memory traces, and thus the lower the probability of correct retrieval and recall. Then, the decrease in recall observed in Experiment 2 would be due to longer counting times, and not to increasing resource demand. However, two main reasons debar any possible explanation of the decrease in recall rate in terms of memory decay (Towse et al., 2000). First, the memory-decay hypothesis predicts that recall performance should depend on the time needed to count the arrays. However, an ANCOVA using counting times as covariate led to the same conclusion about the difference in recall between the two types of counting. Second, the correlation between the mean counting time and the rate of correct recall (computed both in correctly counted arrays for each participant) was not significant, with either alphabetic ($r = -.21, p = .23$) or numeric counting ($r = -.15, p = .59$), and even when the two types of counting were introduced in a single analysis ($r = -.24, p = .16$).

Thus, the cognitive-resources hypothesis seems to be more suited than the memory-decay hypothesis to account for the present results. However, the notion of cognitive resources is rather vague, and a precise account of the way in which counting impedes memorization and recall is needed. A first hypothesis, that in fact sustains the memory-decay hypothesis, can be easily discarded. This hypothesis supposes that participants focused their attention successively on one task (encoding the items to be recalled) and then on the other (counting). Indeed, in this case, memory traces would only suffer from a temporal decay during counting because the items to be recalled are set aside from the attentional focus (Gowan, 1988, 1995). As a consequence, recall performance should depend only on the duration of the counting task, which is clearly at odds with the results we observed. Thus, we assume that attention must be shared between maintenance and processing during counting. This sharing could involve two different mechanisms, either divided attention or rapid switching.

As far as the divided attention hypothesis is concerned, it might be supposed that attention is a general cognitive resource, the amount of which is limited, and that can be divided between the different chunks of information to be processed (Anderson, 1993; Lovett, Reder, & Lebière, 1999). In Experiment 1, when participants had to maintain items in memory, attention would be divided between the items to be remembered and the management of the counting task. In the no-load condition, the total amount of attention is dedicated to counting. The longer times observed in the with-load
conditions should then result from the reduction of attention available to perform the counting. Similarly, in Experiment 2, attention was also divided, on the one hand, between the items to be remembered and, on the other, the retrieval of the verbal labels and the management of the visual tags associated with already-counted dots. Because the arrays were identical, alphabetic and numeric counting differed only in attention needed to activate and retrieve the verbal chain used. The observed difference in recall should then result from the fact that a greater amount of attention is needed to retrieve the successive letters of the alphabet compared with the number words. This greater amount of required attention should in turn depend on the lower base-level activation of the alphabet (Anderson, 1993; Anderson & Lebière, 1998). This mechanism could account for both the lower rate of correct recall after alphabetic counting and the increasing impact of the chain as the number of items to be recalled increased. Indeed, the greater the number of items to be kept active in working memory, the lower the amount of attention each of them can receive, and thus the lower their activation (Anderson, Reder, & Lebière, 1996).

The switching hypothesis does not require us to suppose that attention is divided. Participants might only attend to one task at a time but would switch their attention continuously between the counting task and the maintenance of items. The activation of items of knowledge that are temporarily outside of the attentional focus would then suffer from a time-related decline (Cowan, 1988, 1995). However, focusing attention on the maintained items, even briefly, would result in an updating of their memory traces. Thus, with the concurrent maintenance of items it is necessary to move attention away from counting. In this case, the increase in counting times observed under memory load corresponds to the duration during which participants switched their attention to the items to maintain. Within this framework, recall performance depends on the time devoted to update the memory traces during counting. Thus, the difference in recall performance between alphabetic and numeric counting would be due to longer periods of attentional focusing on counting and then to shorter periods to restore memory traces when the alphabet is used as the chain. These differences would be due to the longer time needed to retrieve verbal tags when the alphabet is used. This model accounts also for the interaction in recall performance between the verbal chain used in counting and the number of items to be maintained. Indeed, because updating requires time, the greater the number of items to be updated in a limited temporal interval, the poorer the quality of the memory traces and, consequently, the poorer the recall.

To conclude, both these cognitive resources hypotheses can account for the results of the present studies. Our experiments were not designed to enable us to judge between these two hypotheses. However, whatever the precise functionalist account adopted, it seems clear that the possible explanations are based on the theoretical framework of cognitive resources. It should be noted that the cognitive-resources hypothesis was confirmed in the most unfavourable conditions. Indeed, we chose an early acquired skill, counting, which is highly automatized in adults. We may therefore reasonably assume that the cognitive-resources hypothesis should also be confirmed in children for whom counting is a more complex and less automatized activity. Furthermore, we assumed that the alphabet we used as the alternative verbal chain is easier to retrieve than other chains such as the numeric chain in foreign languages. Thus, the cognitive-resources hypothesis could be generalized to counting with these other chains and, a fortiori, to other, more complex tasks than counting.
Acknowledgements

We would like to thank Tim Pownall for his help in improving the English writing style, Agnès Bontemps for collecting some of the data, Meredith Daneman, Andy Conway and two anonymous reviewers for their helpful suggestions and comments on previous versions of the manuscript.

References


Received 26 February 2001; revised version received 20 February 2003