



Article scientifique

Article

2009

Published version

Open Access

This is the published version of the publication, made available in accordance with the publisher's policy.

Two maintenance mechanisms of verbal information in working memory

Camos, Valérie; Lagner, Prune; Barrouillet, Pierre Noël

How to cite

CAMOS, Valérie, LAGNER, Prune, BARROUILLET, Pierre Noël. Two maintenance mechanisms of verbal information in working memory. In: Journal of memory and language, 2009, vol. 61, n° 3, p. 457–469. doi: 10.1016/j.jml.2009.06.002

This publication URL: <https://archive-ouverte.unige.ch/unige:88277>

Publication DOI: [10.1016/j.jml.2009.06.002](https://doi.org/10.1016/j.jml.2009.06.002)



Two maintenance mechanisms of verbal information in working memory

V. Camos^{a,b,*}, P. Lagner^a, P. Barrouillet^c

^a Université de Bourgogne, LEAD-CNRS, Pôle AAFE, Esplanade Erasme, B.P. 26513, 21065 Dijon Cedex, France

^b Institut Universitaire de France, France

^c Université de Genève, FPSE, 40 Boulevard du Pont d'Arve, 1211 Genève, Switzerland

ARTICLE INFO

Article history:

Received 30 October 2008
revision received 16 June 2009
Available online 12 July 2009

Keywords:

Working memory
Maintenance
Rehearsal
Refreshing

ABSTRACT

The present study evaluated the interplay between two mechanisms of maintenance of verbal information in working memory, namely articulatory rehearsal as described in Baddeley's model, and attentional refreshing as postulated in Barrouillet and Camos's Time-Based Resource-Sharing (TBRS) model. In four experiments using complex span paradigm, we manipulated the degree of articulatory suppression and the attentional load of the processing component to affect orthogonally the two mechanisms of maintenance. In line with previous neurophysiological evidence reported in the literature, behavioral results suggest that articulatory rehearsal and attentional refreshing are two independent mechanisms that operate jointly on the maintenance of verbal information. It is suggested that these two mechanisms would affect different features that result from various levels of encoding. Moreover, time parameters should be carefully considered in any study on maintenance of verbal information in working memory.

© 2009 Elsevier Inc. All rights reserved.

Introduction

Working memory can be described as a system dedicated to the maintenance of information in face of any distracting events (Baddeley & Hitch, 1974; Engle, Kane, & Tuholski, 1999). Indeed, irrelevant information either issued from the environment or stored in long-term memory could interfere with the information to maintain (Oberauer & Kliegl, 2006; Oberauer & Lewandowsky, 2008), whether this information is maintained only for temporary storage purpose or because it is required for processing. Furthermore, the memory traces of the information to be maintained could decay with time (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Page & Norris, 1998). Thus, some mechanisms are needed to temporarily maintain these transient representations in face of interference and decay. In the literature, two streams of research emphasize different mechanisms for the maintenance

of verbal information. Following the classic framework of the multi-component model of working memory, a large number of studies showed the influential role of articulatory rehearsal by the phonological loop (Baddeley, 1986; Baddeley & Hitch, 1974; Baddeley, Lewis, & Vallar, 1984; Baddeley & Logie, 1999; Baddeley, Thomson, & Buchanan, 1975). This mechanism is modality-specific and relies on the overt or covert vocalization of verbal information in a sequential manner by articulatory motor programs. Other authors favor an attentional mechanism of maintenance based on retrieval and reactivation of memory traces through the focus of attention (Barrouillet et al., 2004; Cowan, 1995; Johnson, 1992). Recently, Hudjetz and Oberauer (2007) proposed and tested two versions of our Time-Based Resource-Sharing (TBRS) model, one called TBRS-a in which maintenance relies on an articulatory rehearsal and another, TBRS-r, with an attentional refreshing mechanism. Their findings brought strong evidence for the latter. However, we will propose here an alternative version of the TBRS model in which a peripheral and a central level of maintenance can be distinguished, articulatory rehearsal and attentional refreshing being jointly responsible for the maintenance of verbal information.

* Corresponding author. Address: Université de Bourgogne, LEAD-CNRS, Pôle AAFE, Esplanade Erasme, B.P. 26513, 21065 Dijon Cedex, France.

E-mail address: valerie.camos@u-bourgogne.fr (V. Camos).

Articulatory rehearsal

In the classic model of working memory (Baddeley, 1986), the maintenance of verbal information relies entirely on the phonological loop. The model comprises an attentional control system, the central executive, aided by two subsidiary slave systems, the phonological loop and the visuospatial sketchpad. Originally, within the multi-component model of working memory, it was assumed that storage and maintenance of information are served by modality-specific systems, namely the phonological loop for verbal and acoustic information and the visuospatial sketchpad for visuospatial information. The loop comprises a phonological store and an articulatory rehearsal mechanism. The evidence for the phonological nature of the store came from the phonological similarity effect (PSE, phonologically similar items are more difficult to maintain than are phonologically dissimilar items; Conrad, 1964). The word length effect (WLE, longer words are more difficult to maintain than are shorter words; Baddeley et al., 1975) is assumed to reflect the process of rehearsal, although a strong controversy still concerns the interpretation of this effect (see Lewandowsky & Oberauer, 2008). The role of this rehearsal mechanism received considerable attention during the past 30 years. More specifically, rehearsal of verbal information relies on processes that overlap with those involved in speech production (Baddeley & Logie, 1999). Thus, this process of rehearsal can be blocked by articulatory suppression (AS), i.e., a concurrent articulation of irrelevant verbal material. For example, in an immediate serial recall task, asking participants to repeatedly utter the word “the” during encoding prevents rehearsal and impairs recall performance, even though articulating this word involves a minimal cognitive load (Murray, 1968). Moreover, AS removes both the PSE and the WLE (Baddeley et al., 1975). However, even when phonological recoding is avoided by AS, “participants still recall an average of three or four digits suggesting the need to assume a substantial contribution to digit span from one or more sources” (Baddeley, 2007, p. 51).

Attentional refreshing

Echoing this remark, other views of working memory emphasize its relationship with attentional processes and, more specifically, suggest that the maintenance of information relies on refreshing of the memory traces through attentional focusing (Barrouillet & Camos, 2001; Barrouillet et al., 2004, 2007; Cowan, 1999, 2005; Johnson, 1992). In Cowan’s model, keeping an item in the focus of attention serves to maintain memory traces active. Cowan (1992) proposed that the process of searching through a set of items can help to reactivate them, because they recirculate through the focus of attention. However, central executive processes may carry out other particular operations (e.g., retrieval) that reactivate memory traces (Cowan, 1999). Among these various executive functions (Johnson, 1992; Johnson, Raye, Mitchell, Greene, Cunningham, & Sanislow, 2005; Raye, Johnson, Mitchell, Greene, & Johnson, 2007; Raye, Johnson, Mitchell, Reeder, & Greene, 2002) emphasizes the role of refreshing, i.e., thinking

briefly of a just-activated representation. Directing reflective attention to a target briefly augments or extends activity associated with a recently activated representation. Johnson describes it as the minimal maintenance process that prolongs the availability of an active representation.

These suggestions (Cowan’s recirculation through the focus of attention, and Johnson’s refreshing mechanism) are very akin to what we suggested as the maintenance mechanism in the TBRS model (Barrouillet & Camos, 2007). In the TBRS model, the memory items to be recalled in working memory span tasks suffer from a time-related decay when attention is switched away from maintenance. Refreshing these items before their complete disappearance necessitates their reactivation by attentional focusing. In other words, maintaining items in short-term memory in view of their further recall requires frequent switching’s of attention away from processing to prevent forgetting.

Are there two mechanisms to maintain verbal information?

In a recent study, Hudjetz and Oberauer (2007) tested two versions of our TBRS model in which the mechanisms of maintenance was either the attentional refreshing we hypothesized or the more classically described articulatory rehearsal. Using a reading complex span task inspired by Saito and Miyake (2004), participants had to read sentences divided in four segments of constant length, and to memorize the last word of each sentence for further recall. The pace of presentation of the segments was varied with each segment presented during 1890 ms for the slow pace and 1323 ms for the fast pace. Whereas one group of participants read aloud the segments “normally”, i.e., at their own pace, the other group had to read continuously following a computer-paced tone. In the normal reading condition, participants could take advantage of the slow presentation pace and use the duration available after reading to rehearse the to be maintained words. By contrast, whatever the pace, the continuous reading condition was assumed to block any possibility of rehearsing the words, as a control experiment showed. The authors reasoned that, if maintenance relies on articulatory rehearsal, the pace of presentation should interact with the reading conditions with an effect of pace in the normal reading condition but no effect in the continuous reading condition. By contrast, if attentional refreshing is responsible for the maintenance of verbal items, no interaction was expected, the slow pace condition resulting in better recall in both reading conditions because more time is available for attentional refreshing in the slow pace condition. The results confirmed this latter prediction: the reading conditions did not interact with the pace, with slow pace inducing better recall performance than fast pace in both reading conditions. Based on this finding, the authors ruled out rehearsal as a maintenance mechanism in the TBRS model, and added that they “see no alternative explanation for the beneficial effect of slower processing rates” (p. 1681) than an attentional refreshing mechanism. However, we should note that their results also showed that a reading condition that blocked rehearsal impaired recall, this effect being roughly additive with the pace effect.

It would then be overly simplistic to believe that maintenance relies only on attentional refreshing, ignoring the immense amount of evidence for an articulatory rehearsal mechanism. We prefer to conceive that, aside from the attentional refreshing we hypothesized and evidenced in previous works (Barrouillet et al., 2004, 2007), a second mechanism specialized on the maintenance of verbal codes works in parallel with attentional refreshing. Whereas attentional refreshing could be applied to any representational code, even non-phonological, it has repeatedly been demonstrated that rehearsal is only dedicated to the maintenance of verbal codes due to the very specific and modular nature of language representations. Thus, our proposal is that refreshing is a central and general-purpose mechanism because it relies on attention, whereas rehearsal would be peripheral because it involves a subvocal articulatory process operating on a domain-specific code (i.e., phonological) and superficial levels of encoding. Such framework could account for both the impact on recall of any variation of the attentional demand of concurrent processing (Barrouillet et al., 2004, 2007), and for selective interference observed within the language domain (Baddeley, 1966; Conrad & Hull, 1964). Thus, instead of establishing the type of maintenance in the TBRS model, Hudjetz and Oberauer (2007) raised new questions on these mechanisms and their relationships. Can these two mechanisms be distinguished and their respective effects on maintenance be disentangled? Are they independent, as we assume, affecting different levels of representation? Could they work jointly to maintain verbal information?

Neurophysiological studies suggest that rehearsal and refreshing are two different mechanisms implemented in distinct brain areas. For example, using brain imagery techniques, Raye et al. (2002, 2007) showed that rehearsal and refreshing are neurally distinguishable processes. In several experiments, these authors showed an increased activation of the dorsolateral prefrontal cortex [DLPFC, Brodmann's area (BA) 9] when healthy young adults have to refresh (i.e., think briefly) words compared to when they have to repeat or read silently these words, or to press a button. Moreover, when specifically contrasting refreshing with rehearsal, Broca's area (ventrolateral prefrontal cortex, VLPFC, BA 44) was selectively activated in rehearsal condition whereas refreshing condition selectively involved activation of the DLPFC (Raye et al., 2007, Experiment 2). Similarly, Smith and Jonides (1999) have linked the activation of the VLPFC to the use of rehearsal strategy. Raye et al. (2007) concluded that VLPFC reflects a subvocal articulatory rehearsal of phonological information, while DLPFC is assumed to reflect attention to various types of activated information (e.g., its activation did not differ between verbal and non-verbal information, Johnson et al., 2005).

These neurophysiological evidence echoes the distinction we proposed above between a central mechanism of refreshing and a more peripheral system dedicated to the maintenance of verbal information. Whereas Broca's area is a specialized structure dedicated to language, the DLPFC is more broadly involved in executive control (D'Esposito et al., 1995). This neurological distinction between a specialized peripheral and an executive central structure ech-

oes in turn the differentiation between the phonological loop and the central executive introduced by Baddeley in his multi-component model of working memory. Although the central executive was thought of as a capacity-limited control system responsible for the manipulation of information and the allocation of attention without storage or maintenance functions (Baddeley, 1986), this conception has changed with the recent addition of a new component, the episodic buffer (Baddeley, 2000). Interestingly, the episodic buffer has some storage function because it is capable of binding information from the subsidiary systems and of storing it temporarily in multimodal code. More importantly, the buffer might not be separated from the central executive because maintenance of its content would be accomplished through attentional refreshment (Repovs & Baddeley, 2006). Thus, the addition of this new component could reconcile the evidence sustaining the TBRS model and its attentional maintenance mechanism with Baddeley's view of working memory, both models ending up with a general-purpose attentional maintenance system supplemented with a language-specialized mechanism when phonological information has to be maintained. These two mechanisms should thus be independent, underpinned by different neural substrates and affecting different representational codes.

The present study

The aim of the present study was then to bring behavioral evidence that these two maintenance mechanisms are both responsible for the maintenance of verbal information, and that they can operate jointly and independently. For this purpose, an experimental manipulation of the opportunities to use independently articulatory rehearsal and attentional refreshing in a dual task requiring processing and verbal storage was needed. Though the reading span task used by Hudjetz and Oberauer (2007) was particularly clever and carefully designed, it does not meet this commitment. In the normal condition of reading, a slow pace induces both a low level of articulatory suppression (fewer syllables have to be uttered per unit of time) and a low cognitive load. Maintenance can thus benefit from both rehearsal and refreshing. Conversely, a fast pace involves both a high level of articulatory suppression and a high cognitive load, and is thus detrimental for both systems of maintenance. Of course, continuous reading as used by the authors would only impede articulatory rehearsal, and variation of pace would enlighten the impact of attentional refreshing. However, such a paradigm does not permit to evaluate how articulatory rehearsal and attentional refreshing interact and cooperate.

For a more accurate investigation, the present study independently manipulated the availability of refreshing by varying the attentional demand of the processing component of a working memory span task, and the availability of rehearsal by varying the degree of articulatory suppression this processing component involves. For this purpose, we used our computer-paced complex span task paradigm because it allows strict control of time, which is the major constraint to attentional refreshing (Barrouillet et al., 2007). The rationale of the two first experiments was

to vary the opportunity of using one of the two maintenance mechanisms while the other was in some way impeded. In Experiment 1, participants had to maintain letters for further recall while articulatory rehearsal was impeded by processing aloud arithmetic operations. The opportunity to use attentional refreshing to maintain the to be remembered letters was manipulated by varying the attentional demand of the arithmetic task, participants being asked either to read (e.g., $5 + 3 = 8$) or solve the same operations ($5 + 3 = ?$), solving the arithmetic problems involving a higher attentional demand than reading them. The hypothesis of two different and independent mechanisms of maintenance predicts that, even under articulatory suppression, reducing the opportunity of attentional refreshing by increasing the attentional demand of the task should still have an impact on recall performance and result in poorer recall. Conversely, Experiment 2 explored the impact of articulatory suppression in tasks involving a high attention demand that impedes attentional refreshing. For this purpose, participants were asked to maintain letters while their attention was occupied by judging the parity of a series of digits presented successively on screen at a constant pace. This task was performed either silently by pressing keys for response or aloud by uttering either “odd” or “even”, in which case, additional articulatory suppression is involved. The hypothesis of two different and independent mechanisms of maintenance predicts that, even when attentional refreshing is impeded by a demanding task, any concurrent articulation still has a damaging effect on maintenance and results in poorer recall.

Finally, the opportunity of using articulatory rehearsal and attentional refreshing was orthogonally varied in Experiments 3 and 4, participants having to maintain letters while performing either silently or aloud a concurrent task that varied in attentional demand (simple vs. choice reaction time tasks in Experiment 3; target detection vs. verification of additions in Experiment 4). The hypothesis of independence of attentional refreshing and articulatory rehearsal predicts that the effect of the articulatory suppression is additive to the effect of the attentional demand involved by the processing component.

Experiment 1

The aim of this experiment was to determine if an increase in attentional demand that impedes attentional refreshing has an effect on concurrent maintenance when articulatory rehearsal is already hindered by concurrent articulation. For this purpose, we designed a working memory span task in which participants were presented with series of letters for further recall, each letter being followed by arithmetic problems. In one condition, participants were asked to read these problems (e.g., $5 + 3 = 8$), whereas in the other condition they had to solve them aloud by calculating their answer (i.e., $5 + 3 = ?$). Both conditions involved the pronunciation of the same words, and thus exactly the same level of concurrent articulation, whereas the solving condition required calculating or retrieving the answers from long-term memory, thus resulting in a higher attentional demand than the reading

condition. According to the hypothesis of independence of the two mechanisms of maintenance, impeding attentional refreshing should result in a memory loss and poorer recall performance even when rehearsal is already impeded by concurrent articulation. This effect should be observed whatever the level of articulatory suppression. We manipulated this level by varying the pace at which the arithmetic operations were processed, presenting either two or four operations within the same inter-letter interval. We expected that a fast pace results in a decrease of recall performance because it allows less time to refresh the items to be maintained (Barrouillet et al., 2004, 2007), but also because the amount of articulatory suppression is higher. Nonetheless, even in the fast pace condition that involved a high level of articulatory suppression (one syllable uttered every 333 ms), an effect of the increased attentional demand induced by the solving condition was expected.

Method

Participants

Eighty-five undergraduate psychology students (12 males; mean age = 20.4 years; $SD = 2.0$ years) at the Université de Bourgogne received a partial course credit for participating and were randomly assigned to one of the four experimental groups defined by the factorial design 2 tasks (solving vs. reading operations) \times 2 paces (slow vs. fast).

Materials and procedure

Participants in each of the four experimental groups were presented with the same series of consonants of ascending length (from 1 to 7) with three series of each length. Among each series, each letter was followed by strings of two or four operations. These operations were simple additions or subtractions of two one-digit numbers, for which the answer was always between 1 and 10.

Participants were asked to focus for 1000 ms on a signal centered on screen, which was replaced, after a delay of 500 ms by the first letter to be remembered. The letters were displayed on screen for 1500 ms and followed by a delay of 500 ms before the stimuli to be processed appeared. In the inter-letter intervals, operations were presented during 3200 ms with a delay of 800 ms for the two-operation conditions and during 1600 ms with a delay of 400 ms for the four-operation conditions. The inter-letter duration was then kept constant at 8000 ms. At the end of the string of operations, either the word “Rappel” (recall) or a second letter appeared and so on.

The participants were asked to read aloud and to remember the letters. According to the task they were assigned to, they had either to read aloud and solve the operations (e.g., for “ $7 - 3 = ?$ ”, they said “seven minus three equal four”) or to read aloud the operations presented with the result (e.g., “ $7 - 3 = 4$ ”, they said “seven minus three equal four”). In such a way, in both tasks, participants uttered the same words, and thus the amount of articulatory suppression was constant across tasks. The experimenter noted the responses given aloud to verify that participants did the task correctly, especially when solving operations.

When the word “Rappel” (recall) appeared, the participants had to recall aloud the series of letters in the correct order. There was no stop rule and all participants performed the 21 series. Each correctly recalled series counted as one third; the total number of thirds was added up to provide a span score (Barrouillet et al., 2004, 2007; Conlin, Gathercole, & Adams, 2005). For example, the correct recall of all the series of 1, 2, and 3 letters, of 2 series of 4 letters and 1 series of 5 letters resulted in a span of $(3 + 3 + 3 + 2 + 1) \times 1/3 = 3.67$. Before the experimental session, participants performed two 1-letter and two 2-letter training series of the span task at the same pace and with the same task as in the forthcoming experiment.

Results and discussion

The data of five participants were discarded because they committed more than 10% of errors on the arithmetic task while the mean rate of errors was less than 2% ($SD = 2\%$) in the entire sample and 3% ($SD = 2\%$) in their own group (solving operations condition at the fast pace).¹

We performed a 2 (tasks: reading vs. solving) \times 2 (paces: slow vs. fast) analysis of variance (ANOVA) on mean spans. As we already observed in previous studies (Barrouillet et al., 2004), increasing the pace of the arithmetic task resulted in lower spans (3.62 vs. 4.59 for fast and slow paces, respectively), $F(1, 76) = 15.29$, $\eta_p^2 = .64$, $p < .001$ (Fig. 1). More importantly, and as we predicted, recall performance was lower when participants had to solve instead of just to read the operations (3.74 vs. 4.47, respectively), $F(1, 76) = 8.45$, $\eta_p^2 = .35$, $p < .01$. The interaction was not significant, $F < 1$.

Thus, as the hypothesis of independence between articulatory rehearsal and attentional refreshing predicted, increasing the attentional demand of a concurrent task, and thus impeding refreshing, resulted in memory loss even when rehearsal through overt or covert articulatory processes was already hindered.

Experiment 2

This experiment was the converse of Experiment 1. Its aim was to determine if an additional concurrent articulation has an impact on maintenance when attentional refreshing is already impeded by a demanding task. For this purpose, participants performed a working memory span task in which they had to maintain letters while judging the parity of series of digits presented successively on screen after each letter. This demanding intervening task was performed either silently by pressing keys on the keyboard or aloud by responding “odd” or “even”, involving a concurrent articulation. The hypothesis of independence of attentional refreshing and articulatory rehearsal would predict that, even when attention is occupied by the parity judgment task, an additional articulatory suppression would block rehearsal and lead to further memory loss.

¹ The same pattern of results occurred when the data of the entire sample were analyzed. Even when the stronger criterion was used and the data of 12 participants who committed more than 5% of error were discarded, the results were similar.

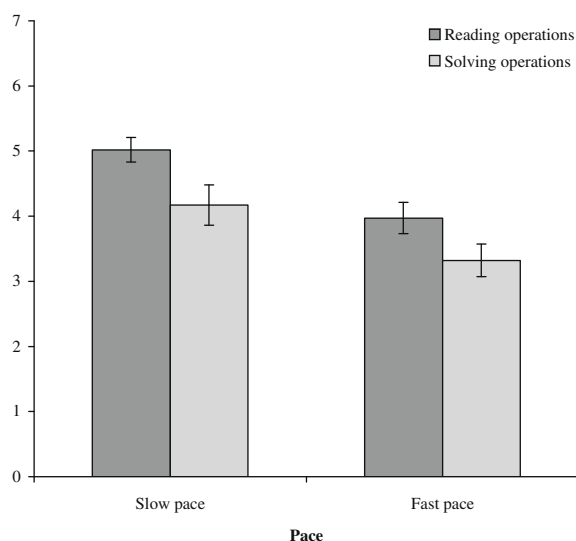


Fig. 1. Mean spans according to the task (reading vs. solving operations) and the pace in Experiment 1.

As in the previous experiment, this prediction was tested at two different paces of the intervening task, the independence hypothesis predicting that even under high cognitive load condition where attentional refreshing is prevented almost completely, articulatory suppression should still have a detrimental effect on recall. Thus, in both conditions of pace, we expected recall performance to be lower when participants had to respond aloud instead of by pressing keys.

Method

Participants

Eighty-two undergraduate psychology students (15 males; mean age = 21.1 years; $SD = 2.2$ years) at the Université de Bourgogne received a partial course credit for participating and were randomly assigned to one of the four experimental groups defined by the factorial design 2 types of response (key vs. oral) \times 2 paces (slow vs. fast).

Materials and procedure

As in Experiment 1, participants in each of the four experimental groups were presented with the same series of consonants of ascending length (from 1 to 7) with three series of each length. The 21 resulting series contained a total of 84 letters. Each letter was followed by digits (1–9) displayed in their Arabic form with as many even as odd numbers among each length.

First, the participants were asked to focus for 1000 ms on a signal (an asterisk) centered on screen, which was replaced, after a delay of 500 ms by the first letter to be remembered. The letters were displayed on screen for 1500 ms and followed by a delay of 500 ms before a string of 4–8 digits to be processed appeared. Within these strings, each digit was displayed on screen for either 600 ms or 1125 ms and followed by a delay of either 200 ms or 375 ms for the fast (800 ms) and slow

(1500 ms) pace conditions, respectively. At the end of the string of digits, either the word “Rappel” (recall) or a second letter appeared and so on.

The participants were asked to read aloud and to remember the letters. According to the response type condition they were assigned to, they had to judge the parity for each digit either by pressing one of two keys on the keyboard (right for “even” and on the left for “odd”) or by saying aloud “pair” (even) or “impair” (odd). The computer recorded the nature of the response for the key responses, whereas the experimenter noted the responses given aloud. When the word “Rappel” (recall) appeared, the participants had to recall aloud the series of letters in the correct order. They were presented with increasingly long series of letters until they failed to recall the letters of all three series at a particular length. Testing was terminated at this point. The span was computed as in Experiment 1. Before the experimental session, participants were given a training phase in which they performed the parity judgment task at the same pace and with the same type of responses as in the forthcoming experiment on five series of eight digits each. They received feedback for errors. Then, two 1-letter and two 2-letter training series of the working memory span task were presented.

Results and discussion

The data of three participants were discarded because they committed more than 30% of errors on the parity judgment task, whereas the mean rate of errors was 7% ($SD = 8\%$) in the entire sample. These participants were in the fast pace and keyed response condition, a condition in which the mean rate of error was 17% ($SD = 8\%$).²

As already observed in Experiment 1 and in previous studies, increasing the pace of the parity task strongly reduced recall performance (mean spans of 4.59 vs. 3.31 for the slow and fast pace conditions, respectively), $F(1, 75) = 21.23$, $\eta_p^2 = .25$, $p < .0001$ (Fig. 2). More importantly and in line with the independence hypothesis, recall performance was lower when participants had to respond aloud (2.86 vs. 5.03 for oral and keyed response conditions, respectively), $F(1, 75) = 61.57$, $\eta_p^2 = .74$, $p < .0001$. This decrease in recall performance did not interact with the pace, $F < 1$.

This experiment demonstrated that even when attention is occupied by concurrent processing, thus impeding attentional refreshing of memory traces, articulatory rehearsal is still available for maintenance, as testified by the detrimental effect on recall performance of a concurrent articulation added up to the attentional capture. Importantly, this effect remained unchanged with the pace, although one judgment every 800 ms at fast pace probably occupied attention almost continuously. This suggests that rehearsal is largely independent from attention, or at least that it can be used with a minimal

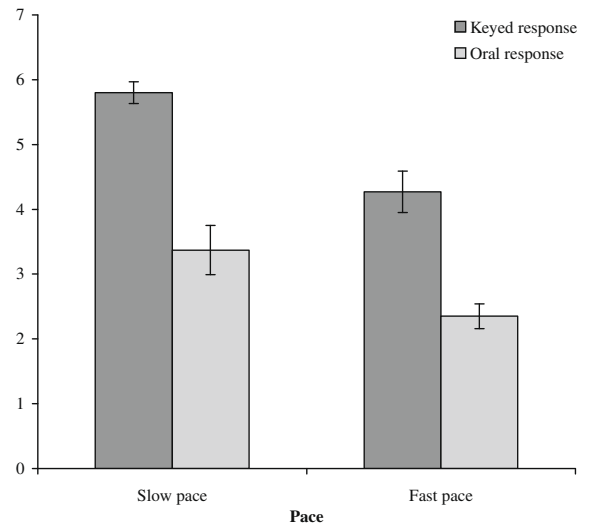


Fig. 2. Mean span according to the type of response (keyed vs. oral responses) and the pace in Experiment 2.

involvement of attentional capacity. Thus, the two first experiments provided strong evidence for the existence of two different mechanisms of maintenance that can operate independently to maintain verbal memory traces active. Even when a concurrent activity impedes the use of one mechanism, the other can still be used to counteract memory loss. The following experiments investigated the interplay of the two mechanisms by manipulating in a factorial design the attentional demand and the level of articulatory suppression involved by a concurrent processing task while maintaining verbal information for further recall.

Experiment 3

In Experiment 3, we examined the effects on the maintenance of verbal information of both cognitive load and concurrent articulation that were manipulated in an orthogonal design. On the one hand, the implication of refreshing mechanism was varied as in Experiment 1 by comparing two tasks with different attentional demand, a Choice Reaction Time (CRT) task vs. a Simple Reaction Time (SRT) task. In the latter, participants were asked to react to squares appearing on screen, whereas the former was the parity judgment task already used in Experiment 2. Barrouillet et al. (2007) established that a SRT task such as pressing a key each time a stimulus appears on screen involves a negligible cognitive load that has no impact on concurrent maintenance, whereas selecting the appropriate response in a CRT task involves a cognitive load and has a disruptive effect on memory. On the other hand, the implication of articulatory rehearsal was varied as in Experiment 2 by asking participants to respond either silently by pressing keys or aloud to the SRT and CRT tasks. Both attentional demand and concurrent articulation were expected to have proper effects on recall. As in Experiment 1, we predicted that the increase in attention demand

² The same pattern of results occurred on the entire sample. Even when the data of 10 participants who did not reach 90% of correct response in the parity task were discarded, the results were similar.

would reduce the possibility of attentional refreshing and thus result in poorer recall. As in Experiment 2 and in many studies on articulatory suppression, we predicted that oral response would block rehearsal and lead to lower recall performance. The lack of interaction in both Experiments 1 and 2 leads us to believe that refreshing and rehearsal might be independent, but it was only indirect evidence. Specifically to the present experiment, the hypothesis of independence between the two mechanisms of maintenance predicted that the manipulation of the attention demand and the type of response should have additive effects on recall performance. As in the previous experiments, these effects were expected whatever the pace at which the processing task was performed. This pace was here manipulated as in Experiment 2 by reducing the duration available to perform the task.

Method

Participants

One hundred and seventy-six undergraduate psychology students (22 males; mean age = 20.8 years; $SD = 2.0$ years) at the Université de Bourgogne received a partial course credit for participating and were randomly assigned to one of the eight experimental groups defined by the factorial design 2 tasks (SRT vs. CRT) \times 2 types of response (key vs. oral) \times 2 paces (slow vs. fast).

Materials and procedure

The materials and procedure for this experiment were adapted from Experiment 2. The four CRT conditions in which the intervening task was the parity judgment were the same as in Experiment 2. The other four conditions in which the task was the SRT task were created from the previous conditions by replacing each digit by a black dot appearing in the centre of screen. In the SRT task, participants had to either press a key or say a word aloud as soon as the dot appeared according to the type of responses they were assigned to. To make the conditions as similar to each other, participants had to press alternatively the two keys used for the CRT task. For the oral responses, they had to say “odd” and “even” alternatively, thus equating the level of articulatory suppression between the CRT and the SRT tasks as participants uttered the same words. The stop rule, the way spans are computed, and the training phase were the same as in Experiment 2.

Results and discussion

The data of one participant were discarded because she committed more than 30% errors on the CRT task at the fast pace with keyed response, whereas the mean rate of errors in her group was 12% ($SD = 7\%$).³

We performed a 2 (tasks: SRT vs. CRT) \times 2 (types of response: key vs. oral) \times 2 (paces: slow vs. fast) ANOVA on spans in a complete between-subject design. This analysis revealed three main significant effects. As in the two previous experiments, the fast pace resulted in poorer recall performance than the slow pace (3.50 vs. 4.50, respectively), $F(1, 167) = 45.51$, $\eta_p^2 = .35$, $p < .0001$ (Fig. 3). More importantly, the two main effects of attentional demand and articulatory suppression observed in previous experiments were replicated here. As in Experiment 1, the more demanding task, the CRT task, induced lower recall performance than the SRT task (3.62 vs. 4.39, respectively), $F(1, 167) = 27.16$, $\eta_p^2 = .21$, $p < .0001$. As it was already observed in Experiment 2, the mean span was lower when participants had to respond aloud rather than silently (3.50 vs. 4.51, respectively), $F(1, 167) = 46.98$, $\eta_p^2 = .36$, $p < .0001$. It should be noted that, as predicted by the hypothesis of independence between refreshing and rehearsal, these two effects did not interact, $F < 1$.

However, the task \times type of response \times pace interaction was significant, $F(1, 167) = 7.71$, $\eta_p^2 = .06$, $p < .01$. As Fig. 3 makes clear, the effects of attentional demand (tasks) and articulatory suppression (types of response) were over-additive in the slow pace condition, although task \times type of response interaction just failed to reach significance, $F(1, 80) = 3.46$, $\eta_p^2 = .11$, $p = .07$. By contrast, these effects were under-additive in the fast pace condition, the task \times type of response interaction being significant, $F(1, 87) = 4.28$, $\eta_p^2 = .08$, $p = .04$.

This 3-way interaction questioned the independence between rehearsal and refreshing. Indeed, as we hypothesized, this independence should lead to an additive effect of the articulatory suppression and the attention demand of the task whatever the pace of this task is. More intriguingly, in each pace, the articulatory suppression and the attention demand interacted, but in different direction for the slow and fast paces. Before discussing the potential implication of such results, we re-examined the effect of the cognitive load and the concurrent articulation for two different paces in the following experiment. Although Experiment 4 had the same aim as Experiment 3, several changes were made, because they might be causes of this obscure 3-way interaction. First, we abandoned the use of any stop rule that could underestimate participants' performance, especially in most difficult conditions. Second, we made the two tasks as similar as possible while still differing in attention demand. By choosing the SRT and CRT tasks for Experiment 3, we maximized the difference in load they imposed, but it led to present fairly different stimuli. In the SRT task, participants were presented with a single black dot coming on screen in a regular rhythm, while for the CRT task, different digits appeared successively. This variability on stimuli might cause supplementary source of forgetting, as digits might interfere more with letters than a black dot because digits and letters relies on phonological encoding. Thus, in the following experiment, the same stimuli were presented in the same order, and we varied the task participants of different groups had to perform on them. Moreover, in Experiment 3, the articulatory suppression depended on the task and this relation varied between the two tasks. To block

³ Discarding one participant did not affect the overall pattern of results. However, discarding the 20 participants who committed more than 10% errors changed slightly the pattern of results. In the slow pace when response were keyed, the difference of recall between the SRT and the CRT conditions now reached significance, $F(1, 38) = 5.38$, $\eta_p^2 = .15$, $p = .02$.

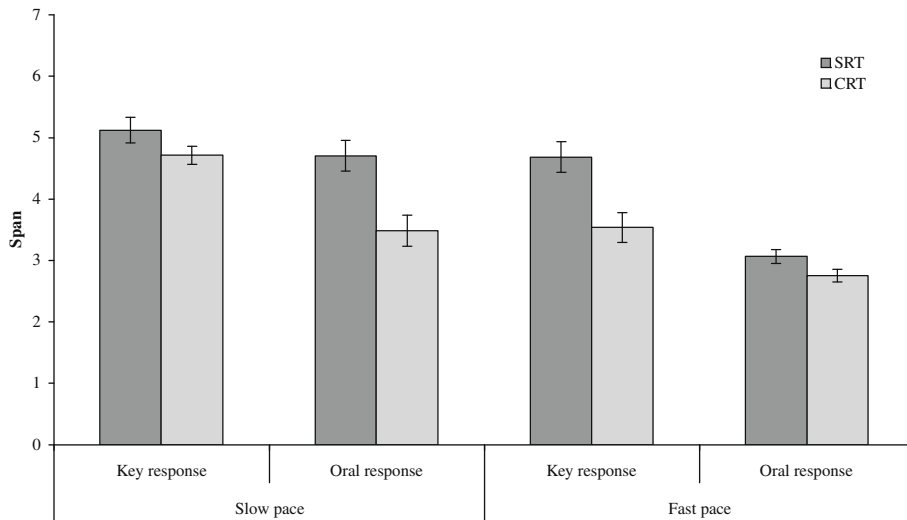


Fig. 3. Mean span according to the task (SRT vs. CRT), the type of response (keyed vs. oral responses) and the pace in Experiment 3.

rehearsal, participants said aloud their response for the CRT task, and they alternated words that were irrelevant for the task in the SRT condition. We then disentangled the relation between the articulatory suppression and the task in Experiment 4. Responses were always given by pressing keys and concurrently participants had to read silently or aloud all the stimuli appearing on screen. Finally, response times were measured to evaluate more precisely the attention demand imposed by the two compared tasks. This measure was made without any concurrent maintenance of verbal information to avoid that response times were affected by the switching between processing and storage in the complex span paradigm.

Besides the puzzling 3-way interaction that was re-examined in Experiment 4, it should be noted the strong effect of pace on recall performance. We have already documented the fact that increasing the pace of a demanding processing task results in an increased cognitive load and lower working memory spans (in Experiment 1 of the present study, but also in Barrouillet et al. (2004, 2007)). This effect was also observed here. While increasing the pace of a silent non-rhythmic SRT task did not affect recall performance, $F(1, 44) = 1.78$, $\eta^2 = .04$, $p = .19$, increasing the pace of a silent CRT task resulted in a decrease in recall performance, $F(1, 45) = 15.64$, $\eta^2 = .35$, $p < .001$. Interestingly, the same phenomenon was observed for the articulatory suppression. Increasing the pace of the SRT task had no significant effect when this task was performed silently, but resulted in a strong decrease in span when performed aloud, $F(1, 40) = 37.14$, $\eta^2 = .93$, $p < .0001$. This effect echoes an observation by Barrouillet et al. (2004; Experiment 7) who observed that varying the pace at which participants repeated the syllable “ba” while maintaining letters had a significant effect on recall. These facts suggest that, while being largely independent, both mechanisms of maintenance are affected by temporal factors and thus share some common characteristics. This point will be discussed in the general discussion.

Experiment 4

As in Experiment 3, the cognitive load and the concurrent articulation were orthogonally manipulated at two different paces. While participants had to maintain letters, they had to perform two different tasks on series of digits successively displayed on screen. According to the group they were assigned to, participants had either to detect the digit 5 or to verify if the 3rd and the 6th digits were the sum of the two previous digits. Although the two tasks require maintenance of a digit, they differ in attention demand. In the target detection, participants had to constantly maintain the target through the task. When the task was verifying additions, they had to maintain the first digit for further processing. The appearance of the second digit triggered the retrieval of the sum of this digit with the first one, and the sum should be maintained for comparison with the third digit. Thus, at each digit appearance, participants maintained a digit as in the detection task, but this digit had to be updated at each step. This continuous updating induced a high attention load compared to the mere maintenance of the same digit for the detection task. To estimate this difference in demand between the two tasks, we measured the time needed either to correctly detect the target or correctly verify the addition in a paradigm similar to the complex span task, but without any concurrent load. For all tasks, the answer was made by pressing keys, and to vary the implication of rehearsal, we asked participants to read either silently or aloud all the digits, the latter blocking rehearsal. With this procedure, the articulatory suppression did not depend on responses, and was identical for both detection and verification of additions. As in the previous experiment, the increase in attention demand and the concurrent articulation should reduce the recall of the letters. The hypothesis of independence between refreshing and rehearsal should lead to the lack of interaction between attention demand and concurrent

articulation, as well as the absence of the task \times reading \times pace interaction.

Method

Participants

Sixty-nine undergraduate psychology students (5 males; mean age = 21.0 years; $SD = 2.0$ years) at the Université de Bourgogne received a partial course credit for participating and were randomly assigned to one of the two task conditions (detecting a target vs. verifying additions). Twenty-four of them did the task without the concurrent maintenance of letters to evaluate the attention demand of the tasks through response time measures. The other 45 participants performed the complex span task.

Materials and procedure

Two lists of 12 series of consonants of lengths 2–6 were created. For half of the participants, one list was associated with one pace and the other with the other pace when participants had to read the stimuli aloud. The reverse matching was used when participants had to remain silent. For the other half of the participants, this order was reversed. We also built two lists of 108 series of six digits. Each list was associated to one type of reading (silent vs. aloud). This order was counterbalanced across participants.

For the complex span task, participants in each of the two groups were presented with 24 conditions resulting from the crossing of six lengths of consonants (from 2 to 7) \times 2 types of reading (silent vs. aloud) \times 2 paces (fast vs. slow). The presentation of these conditions was random with two series presented in immediate succession in each condition. Within each series of letters, each letter was followed by a string of six digits (1–9). All digits appeared with an equal frequency in each position with the constraint that the 3rd and the 6th digits in the strings were either the correct sum of the two previous digits or differed from this correct sum by 1. Thus, for the verification of additions, half of the sums were correct, and for the detection task, 11% of the digits were the target 5.

Before the start of the experiment, the experimenter specified to participants which task they were assigned to (detection or verification). Each series began by a 2000-ms first screen indicating the number of letters to be remembered, the type of reading, and the pace (e.g., “3 Letters Aloud Slow”). A ready signal (an asterisk) centered on screen for 1000 ms was followed by the first letter lasting 1500 ms. The six digits appeared successively for 1600 ms in the slow pace and for 800 ms in the fast pace. Each digit was followed by a 250 ms delay. The following consonant then appeared for 1500 ms followed by a new series of six digits, and so on. At the end of each series, the word “Rappel” (recall) was displayed on screen.

The participants were asked to read aloud and to remember the letters. When “aloud” was specified in the first screen, they also had to read aloud the digits. According to the task they were assigned to, they had either to detect the target 5 by pressing the space bar, or to verify that the 3rd and the 6th digit were the correct sum of the two previous digits by pressing one of the two keys on the

keyboard (right for correct and on the left for incorrect). When the word “Rappel” (recall) appeared, the participants had to recall aloud the series of letters in the correct order. There was no stop rule and all participants performed the 48 series. As in the previous experiment, each correctly recalled series counted as one third. The total number of thirds was added up to provide a span score. Before the experimental session, participants performed eight training series of the span task (length 1 and 2 \times 2 paces \times 2 types of reading) with the same task as in the forthcoming experiment.

For measuring the response times, the same materials and procedure were used, except that no letter was presented. We collected the response times when participants pressed either the space bar in the detection task, or one of the two keys for the 3rd and the 6th digits in the verification task.

Results and discussion

The data from one participant in the complex span tasks were discarded because she committed more than 20% of errors in verifying additions while the average rate of errors in this group was 11.49% ($SD = 4.94$).⁴ This rate of errors in verification did not differ from the rate in detection (9.94%, $SD = 5.52$), $t = .98$, $p = .33$.

To attest that the verification of additions induced a higher attention demand than the detection of a target, we compared the mean response time for correct responses in the two tasks when no concurrent maintenance of letters was required. As it might be expected, verification induced significantly longer response times (547 ms, $SD = 68$) than the detection (467 ms, $SD = 62$), $F(1, 22) = 8.99$, $\eta^2 = .39$, $p = .007$. This effect most probably underestimated the difference of attention demand between the two tasks, because in the verification, the step in which the choice was made is not the only demanding step of processing. When the 2nd and the 5th digits appeared, participants had to retrieve the sum which also required attention.

As in Experiment 3, we performed a 2 (tasks: detection vs. verification) \times 2 (types of reading: silent vs. aloud) \times 2 (paces: slow vs. fast) ANOVA on spans with the tasks as between-subject factor and the two other variables as within-subject factors. The three main effects were significant as in the previous experiments (Fig. 4). The verification of additions that produced the longer response times also induced the lower spans (4.38 vs. 4.93), $F(1, 42) = 5.43$, $\eta^2 = .08$, $p = .025$. The mean span was also lower when participants had to concurrently read the digits aloud (3.79 vs. 5.51), $F(1, 42) = 381.25$, $\eta^2 = .77$, $p < .0001$. Finally, increasing the pace reduced recall performance (4.32 vs. 4.98), $F(1, 42) = 39.22$, $\eta^2 = .11$, $p < .0001$. More interestingly for the hypothesis of independence between refreshing and rehearsal, the interaction between tasks and types of

⁴ Discarding one participant did not affect the overall pattern of results. However, when the data of 11 participants were discarded because they committed more than 15%, the task \times pace interaction just failed significance, $F(1, 32) = 3.81$, $\eta^2 = .01$, $p = .06$.

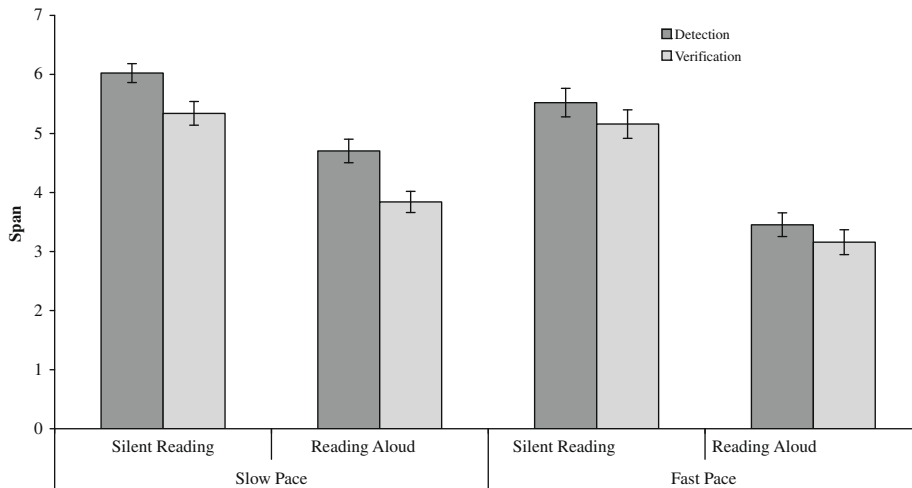


Fig. 4. Mean span according to the task (detection vs. verification of additions), the type of reading (silent vs. aloud) and the pace in Experiment 4.

reading was not significant, $F < 1$, as well as the task \times reading \times pace interaction, $F < 1$.

Finally, and contrary to the previous experiments, the interactions task \times pace and reading \times pace were significant, $F(1, 42) = 4.51$, $\eta^2 = .01$, $p = .04$, and $F(1, 42) = 9.45$, $\eta^2 = .03$, $p < .004$, respectively. Although the effect of the tasks on spans get smaller with the increase of the pace until being non-significant in fast pace [$F(1, 42) = 8.82$, $p = .005$ in slow pace, and $F(1, 42) = 1.64$, $p = .21$ in fast pace], the effect of the types of reading increased at fast pace [$F(1, 42) = 87.84$, $p < .0001$ in slow pace, and $F(1, 42) = 304.05$, $p < .0001$ in fast pace]. We observed similar trends in Experiment 3 in which the effect of task was reduced in the more difficult condition (see Fig. 3), and the effect of articulatory suppression was stronger at a fast pace for the SRT task. Thus, both the effect of tasks and of articulatory suppression were affected by time manipulation in Experiment 4, but they did not produce the same effect on spans, which is in favor of the implication of two different processes.

In summary, this experiment reinforced the findings previously observed by confirming that both attentional demand and articulatory suppression have a detrimental effect on concurrent maintenance, and that these effects do not interact. Moreover, when carefully controlling for material and tasks, the three-way interaction observed in Experiment 3 no longer appeared. This strongly suggests that attentional demand and articulatory suppression hinder two different mechanisms that work together in maintaining verbal material in working memory. We shall address the implications of these findings for our understanding of working memory structure and functioning in the following general discussion.

General discussion

This study aimed at investigating the interplay between two different mechanisms of maintenance of verbal information in working memory, articulatory rehearsal and attentional refreshing. In the two first experiments, the

availability of either refreshing (Experiment 1) or rehearsal (Experiment 2) was manipulated while the other mechanism was impeded in working memory span tasks. In both experiments, this manipulation resulted in memory loss, suggesting that each mechanism can act independently from each other. Experiments 3 and 4 directly assessed the interplay of the two mechanisms through the manipulation of their availability by requiring participants to perform a processing task that varied in attention demand either silently or aloud. The results replicated the findings of the two previous experiments, and additionally revealed that rehearsal and refreshing have additive effects on working memory maintenance.

Two independent mechanisms of maintenance that can work jointly

Two main conclusions can be drawn from these findings. The first concerns the independence of the two mechanisms. As Experiment 1 demonstrated, increasing the attentional demand of processing when rehearsal is impeded reduces recall of verbal information, bringing evidence for a supplementary mechanism of maintenance that does not rely on articulatory rehearsal but on attentional focusing. Vallar and Baddeley (1982) already speculated on the existence of a second rehearsal mechanism that could operate without covert speech, probably implicating the central executive. In the same way, Hudjetz and Oberauer (2007) observed that a maintenance mechanism that relies on central cognitive processes can operate concurrently with overt articulation. In the other way round, Experiment 2 showed that even when the processing component of the working memory span task was highly demanding, blocking rehearsal resulted in a significant memory loss. This latter result shows that articulatory rehearsal does not require strong attentional involvement. Similarly, Baddeley (2007) suggests that rehearsal relies on retrieval of the memory traces to be strengthened, a process that proved to necessitate attention (Barrouillet et al., 2004, 2007; Portrat, Barrouillet, & Camos, 2008).

However, these retrievals take place only on the first steps of rehearsal (Baddeley, 2007). The paradigm used in the present experiments left room for this phenomenon. Indeed, these first steps of rehearsal could be initiated before the beginning of the secondary task, i.e., at the onset of the memory items.

The second conclusion is that, though being independent, the two mechanisms can work jointly on the same memory traces. In both Experiments 3 and 4, a processing component combining a concurrent articulation and a substantial attentional demand resulted in a greater memory loss than a task involving only one of these two constraints. This suggests that vocal or subvocal rehearsal and attentional refreshing are used jointly to maintain verbal memory traces active in working memory, an idea already suggested by Chen and Cowan (2008). Whereas these authors admitted that they cannot specify the exact nature of the collaboration between the two holding mechanisms, the present study was able to evaluate their joint effect because it was the first one to manipulate orthogonally the opportunity of using these two mechanisms. When the articulatory and attentional demands of the secondary task were not too important, their respective effects proved to be additive, emphasizing both the independency of the mechanisms and the possibility to use them concurrently. The fact that two independent mechanisms can operate on the same representations has consequences for both the functioning and the structure of working memory, and more precisely for the nature of the representations held in working memory.

The nature of the representations in working memory

Because two qualitatively different mechanisms operate concurrently on the same memory traces, these traces are probably multimodal, containing phonological features, but also orthographic, visual, spatial and semantic features. Thus, mechanisms dedicated to the strengthening of particular features could operate either separately or jointly on these representations. In the former, memory traces could be reconstructed from that part of their features that have been preserved by a specialized maintenance mechanism, whereas in the latter, different mechanisms could reinforce different features of the same representation to ensure its maintenance. As a consequence, we might imagine a multimodal buffer instead of separate and specialized slave systems and their dedicated mechanism of maintenance. The idea of a multimodal buffer was also introduced by Baddeley (2000) with the addition of an episodic buffer within his multi-component framework, although he preserved a specific role to the slave systems. However, the present results implied that multimodal representations could be partially reactivated through attentional focusing. Thus, this buffer should be a central system of maintenance closely related with the central executive.

Implications for working memory theories

The multimodal nature of these representations points to theories assuming that working memory involves a

unique short-term memory space (Cowan, 2005; Engle et al., 1999) rather than theories assuming separate memory stores for each modality of representation with their own refreshing mechanism (Baddeley & Logie, 1999), including theories that contain a multimodal buffer which integrates information for these different systems, as is the episodic buffer hypothesized by Baddeley (2000). For example, Engle et al. (1999) assumed that working memory is this part of long-term memory activated above threshold, thus containing multiple-code representations maintained through a variety of domain-specific strategies. Within this framework, the phonological loop is not anymore a structural characteristic of working memory, but rehearsal is one strategy among other means of maintenance. Such a theory could easily accommodate the fact that two different strategies operate on different aspects of a multiple-code representation for maintenance purpose. Among these strategies, the role of attentional focusing to reactivate memory traces was primarily emphasized in Cowan's (1988, 1999, 2005) model. Indeed, items recirculate within the focus of attention, which increases their level of activation, hence resulting on more enduring traces in face of temporal decay. However, this model is less specified concerning the existence and role of any code-specific maintenance mechanisms. Nonetheless, representations are created through binding of various activated features that can rely on different codes. Thus, Cowan's embedded process model assumes that various maintenance processes may work together (Cowan, 1999), a covert articulatory mechanism reactivating the phonological features within these representations.

By contrast (Baddeley & Logie, 1999; Baddeley's 1986) multi-component model does not account easily for the present findings. Indeed, verbal information is maintained in a temporary verbal store through a specific rehearsal mechanism. The domain-general component of the model in charge of the control of attention, namely the central executive, is not involved in temporary storage. However, with the addition of an episodic buffer, the last version of the multi-component model (Baddeley, 2000) is fairly compatible with the independence of the two mechanisms. This episodic buffer binds different codes in integrated multimodal representations maintained through attention under control of the central executive (Repsovs & Baddeley, 2006). Such a framework could account for the independence of the two maintenance mechanisms, because verbal information can be maintained by either articulatory rehearsal in the phonological loop or an attentional system in the episodic buffer. Nonetheless, this framework could have difficulties in accounting for the fact that they can operate jointly. Indeed, it should be assumed that representations of verbal memory traces are maintained simultaneously in the phonological store, where they can be maintained by the articulatory loop, and in the episodic buffer where they could be reactivated through attentional focusing. Though possible, this structural conception lacks parsimony.

A potential way to solve this drawback is to shift from structural to functional distinction in describing working memory. For example, the distinction proposed by Chen and Cowan (2008) of a central general-capacity-limited

and a code-specific time-limited storage mechanisms that can work together in a complementary fashion could account for both the independence and the joint use of refreshing and rehearsal. A very similar conception can be found in Engle's model (Engle et al., 1999), which conceives maintenance processes as strategies (see also Salamé & Baddeley, 1986). Such a functional framework permits hypotheses regarding different levels of encoding (Craig & Lockhart, 1972), either superficial (phonological features, phonemes), or deeper (semantic), within a unique storage component on which different processes can operate to reactivate memory traces.

The nature of verbal working memory limitations

Although two mechanisms are available to maintain verbal information, a striking phenomenon remains the low level of recall performance in complex span tasks, indicating that these mechanisms are strongly constrained. Some consensus has recently appeared between Baddeley's and Cowan's approaches on the capacity limit of the central system, and on the time limit of the phonological loop. However, the present results go further by revealing that both mechanisms share the same temporal constraints. In many studies (Barrouillet et al., 2004, 2007), we demonstrated that the efficiency of refreshing through attentional focusing strongly depends on the pace at which the intervening task is performed, and the present results confirmed this phenomenon. In all the studies, increasing the pace of the secondary task resulted in poorer recall. Interestingly, the same phenomenon affects articulatory rehearsal. When performing aloud an undemanding task like the SRT task in Experiment 3, increasing the pace of this articulatory suppression resulted in a strong decrease in recall (compare conditions of oral responses in the SRT task in Fig. 3), showing that rehearsal is a time-based mechanism, whose efficiency depends on the time available to covertly articulate memory material. The maintenance of verbal information is thus strongly constrained by temporal parameters, whatever the mechanism of maintenance that is used.

Acknowledgments

This research was supported by grants from the ANR (05-BLAN-0346-01) and the Région Bourgogne (FABER). Part of this work was done when the first author was invited fellow at University of Bristol funded by the Leverhulme Trust. We thank Stéphanie Massol, Karine Tosi, and Caroline Gauffroy for collecting data. This study was presented at the Psychonomic Society Meeting in 2006 at Houston. We thank Robert Greene and three anonymous reviewers for their thoughtful comments on previous versions of this manuscript.

References

- Baddeley, A. D. (1966). Short-term memory for word sequences as a function of acoustic, semantic and formal similarity. *Quarterly Journal of Experimental Psychology*, 18, 362–365.
- Baddeley, A. D. (1986). *Working memory*. Oxford: Oxford University Press.
- Baddeley, A. D. (2000). The episodic buffer: A new component of working memory. *Trends in Cognitive Sciences*, 4, 417–423.
- Baddeley, A. D. (2007). *Working memory, thought, and action*. New York: Oxford University Press.
- Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. A. Bower (Ed.), *Recent advances in learning and motivation* (pp. 47–89). New York: Academic Press.
- Baddeley, A. D., Lewis, V., & Vallar, G. (1984). Exploring the articulatory loop. *Quarterly Journal of Experimental Psychology*, 36A, 233–252.
- Baddeley, A. D., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 28–61). Cambridge: Cambridge University Press.
- Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior*, 14, 575–589.
- Barrouillet, P., Bernardin, S., & Camos, C. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, 133, 83–100.
- Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 33, 570–585.
- Barrouillet, P., & Camos, V. (2001). Developmental increase in working memory span: Resource sharing or temporal decay? *Journal of Memory and Language*, 45, 1–20.
- Barrouillet, P., & Camos, V. (2007). The time-based resource-sharing model of working memory. In N. Osaka, R. Logie, & M. D'Esposito (Eds.), *Working memory: Behavioral and neural correlates* (pp. 59–80). Oxford: Oxford University Press.
- Chen, Z., & Cowan, N. (2008). Core verbal working memory capacity: The limit in words retained without covert articulation. *Quarterly Journal of Experimental Psychology*, 62, 1420–1429.
- Conlin, J. A., Gathercole, S. E., & Adams, J. W. (2005). Children's working memory: Investigating performance limitations in complex span tasks. *Journal of Experimental Child Psychology*, 90, 303–317.
- Conrad, R. (1964). Acoustic confusion in immediate memory. *British Journal of Psychology*, 55, 75–84.
- Conrad, R., & Hull, A. J. (1964). Information, acoustic confusion, and memory span. *British Journal of Psychology*, 55, 429–432.
- Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin*, 104, 163–191.
- Cowan, N. (1992). Verbal memory span and the timing of spoken recall. *Journal of Memory and Language*, 31, 668–684.
- Cowan, N. (1995). *Attention and memory: An integrated framework*. New York: Oxford University Press.
- Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 62–101). Cambridge: Cambridge University Press.
- Cowan, N. (2005). *Working memory capacity*. Hove, UK: Psychology Press.
- Craig, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, 11, 671–684.
- D'Esposito, M., Detre, J. A., Alsop, D. C., Shin, R. K., Atlas, S., & Grossman, M. (1995). The neural basis of the central executive system of working memory. *Nature*, 378, 279–281.
- Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102–134). Cambridge: Cambridge University Press.
- Hudjetz, A., & Oberauer, K. (2007). The effects of processing time and processing rate on forgetting in working memory: Testing four models of the complex span paradigm. *Memory & Cognition*, 35, 1675–1684.
- Johnson, M. K. (1992). MEM: Mechanisms of recollection. *Journal of Cognitive Neuroscience*, 4, 268–280.
- Johnson, M. K., Raye, C. L., Mitchell, K. J., Greene, E. J., Cunningham, W. A., & Sanislow, C. A. (2005). Using fMRI to investigate a component process of reflection: Prefrontal correlates of refreshing a just-activated representation. *Cognitive, Affective & Behavioral Neuroscience*, 5, 39–361.
- Lewandowsky, S., & Oberauer, K. (2008). The word-length effect provides no evidence for decay in short-term memory. *Psychonomic Bulletin & Review*, 15, 875–888.
- Murray, D. J. (1968). Articulation and acoustic confusability in short-term memory. *Journal of Experimental Psychology*, 78, 679–684.

- Oberauer, K., & Kliegl, R. (2006). A formal model of capacity limits in working memory. *Journal of Memory and Language*, 55, 601–626.
- Oberauer, K., & Lewandowsky, S. (2008). Forgetting in immediate serial recall: Decay, temporal distinctiveness, or interference. *Psychological Review*, 115, 544–576.
- Page, M. P. A., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review*, 105, 761–768.
- Portrat, S., Barrouillet, P., & Camos, V. (2008). Time-related decay or interference-based forgetting in working memory? *Journal of Experimental Psychology: Learning, Memory and Cognition*, 34, 1561–1564.
- Raye, C. L., Johnson, M. K., Mitchell, K. J., Greene, E. J., & Johnson, M. R. (2007). Refreshing: A minimal executive function. *Cortex*, 43, 135–145.
- Raye, C. L., Johnson, M. K., Mitchell, K. J., Reeder, J. A., & Greene, E. J. (2002). Neuroimaging a single thought: Dorsolateral PFC activity associated with refreshing just-activated information. *NeuroImage*, 15, 447–453.
- Repos, G., & Baddeley, A. D. (2006). The multi-component model of working memory: Explorations in experimental cognitive psychology. *Neuroscience*, 139, 5–21.
- Saito, S., & Miyake, A. (2004). On the nature of forgetting and the processing–storage relationship in reading span performance. *Journal of Memory and Language*, 50, 425–443.
- Salamé, P., & Baddeley, A. D. (1986). Phonological factors in STM: Similarity and the unattended speech effect. *Bulletin of the Psychonomic Society*, 24, 263–265.
- Smith, E. E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science*, 283, 1657–1661.
- Vallar, G., & Baddeley, A. D. (1982). Short-term forgetting and the articulatory loop. *Quarterly Journal of Experimental Psychology*, 34A, 53–60.