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Human cognitive system privileges processing over short-term storage: Asymmetry in working memory limitations

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Abstract

The continuous flow of information in which we are immersed obliges our cognitive system to maintain accessible the relevant elements for the time necessary for their processing. The present study investigated how working memory balances the resource demands of this necessary storage in face of demanding processing. In four experiments using a complex span task, we examined the residual performance in memory and processing of individuals who performed at their best in the other component. Reciprocal dual-task costs pointed toward a resource sharing between the two functions. However, whereas prioritizing processing almost abolished participants' memory performance, more than 60% of their processing capacities were preserved while maintaining memory performance at span. We argue that this asymmetry might be adaptive in nature. Working memory might have evolved as an action-oriented system in which short-term memory capacity is structurally limited to spare the resources needed for processing the information it holds.

Key words: Working memory; Cognitive capacities; Dual task; Residual.

In its adaptive purpose, due to the poor temporal achievements of biological organisms noted by Rosenblueth, Wiener, and Bigelow (1943), human mind needs some temporal room to process the elements provided by an ever-changing and often unpredictable environment (Newell, 1990). This makes necessary to temporarily protect from forgetting some information with a view to their future use, while simultaneously processing other information relevant for on-going treatments and action. The need to coordinate the two antagonistic activities of preserving some mental objects from any modification while transforming others according to our current goals creates a constraint that affects any goal-directed human activity. For example, when reading a sentence, we need to maintain in mind its beginning while processing the further clauses. When reasoning, we must remember the premises while drawing intermediary conclusions, in the same way as in doing a mental calculation, the numbers to be added or multiplied must be maintained during the successive operations. Even in everyday life, cooking a recipe requires keeping in mind the ingredients and utensils needed for the following steps while performing some action, and multitasking in domestic life involves reminding children what they need to pack for their school day while preparing their breakfast.

It appears that Miller, Galanter and Pribram (1960) were the first to identify this central constraint of human mind and to suggest the existence of some cognitive system able to fulfill this dual function of maintenance and processing, a system they called working memory. Due to its crucial role in human cognition, the concept of working memory (WM) soon elicited seminal investigations (Atkinson & Shiffrin, 1968; Baddeley & Hitch, 1974), and has become in contemporary psychology a central concept commonly invoked in order to account for cognitive functioning (Baddeley, 2007), individual differences in intelligence (Mashburn, Tsukahara, & Engle, 2021), intellectual development (Camos & Barrouillet, 2018), the occurrence of neuropsychological conditions (Engle, Sedek, von Hecker, & McIntosh, 2005),

expertise acquisition (Hambrick, Burgoyne, & Araujo, 2021), academic achievement (Alloway & Alloway, 2010), and applied domains (Logie, Wen, Gathercole, Cowan & Engle, 2023)¹.

Probably the most striking characteristic of this central system is its limited capacity. As Turing noted, long before the emergence of the concept of working memory, “if we are trying to produce an intelligent machine, and are following the human model as closely as we can, we should begin with a machine with very little capacity to carry out elaborate operations” (Turing, 1948, p. 118). Accordingly, the limitations of human cognition in carrying out the elaborate operations involved in thinking (Logie & Gilhooly, 1998), learning (Cowan, 2014), reasoning (Gilhooly, 2004) or problem solving (Hambrick & Engle, 2012) have been attributed to limitations of the capacity of WM. However, the dual function of storage and processing fulfilled by WM makes the question of capacity and the problem of the limited resource fueling these two functions especially arduous. Are these two functions fueled by distinct pools of resources or do they compete for a unique resource? In this latter case, how do our cognitive system manage to share this resource between the two antagonistic functions? Does giving priority to one of the two functions lead to the collapsing of the other? Or is there some internal regulation that preserves a minimal performance level in any circumstances? Not surprisingly, the question of the resources and supplies that fuel this central cognitive system has been at the center of the very first inquiries in this domain (Baddeley & Hitch, 1974). However, it is still an unsolved issue.

Because WM has been defined, from its very inception, as a cognitive system devoted to the maintenance and processing of information (Atkinson & Shiffrin, 1968; Baddeley & Hitch, 1974), its structure and capacity have been investigated, for now about fifty years, by

¹ A rapid survey in the Web of Science (19th April 2023) indicated that for the year 2022 alone, the number of articles with the phrase “working memory” in their title amounted to 1096, which corresponds to a mean of three articles published per day.

examining variations in performance when people have to simultaneously maintain information for subsequent recall while performing a distracting task. From the absence, or the negligible size, of dual-task costs between processing and storage, some authors came to the conclusion that the two functions are underpinned by separate systems fueled by different resource pools (Baddeley, 1986; Baddeley & Logie, 1999; Duff & Logie, 2001; Logie, 2011, 2018; Logie, Belletier, & Doherty, 2021). Others, observing more substantial dual-task costs, concluded to a resource sharing between processing and storage and to the existence of some unitary system in charge of both functions (Barrouillet, Bernardin, & Camos, 2004; Barrouillet & Camos, 2015, 2021; Case, Kurland, & Goldberg, 1982; Chen & Cowan, 2009; Cowan, Morey, & Naveh-Benjamin, 2021; Daneman & Carpenter, 1980; Turner & Engle, 1989). As surprising as it may seem, this question has not yet been settled and these two theoretical options still coexist today (Logie, Camos, & Cowan, 2021, for a review). As we will see, the most recent empirical investigations led to mixed and seemingly contradictory results as they revealed at the same time evidence for some resource sharing testified by the reciprocal detrimental effect of processing on storage and *vice versa*, while suggesting some autonomy of each function (Belletier, Camos, & Barrouillet, 2021; Doherty et al., 2019; Rhodes et al., 2019). Indeed, despite suffering from reciprocal dual-task costs, individuals proved able to keep information in mind while performing at their best in a concurrent task, and to maintain a decent level of performance in this same task while maintaining a short-term memory load at span.

However, if processing and storage drew on a single shared resource as suggested by the reciprocal dual-task costs between processing and storage, shouldn't people be unable to maintain even one single item in WM while performing a concurrent task depleting this single common resource? For example, if people perform a concurrent demanding task at their maximum capacity, shouldn't any memory trace disappear from WM, or is there still some

memory residual that persists? Does such a memory residual exist, and if so, what are the cognitive structures and mechanisms responsible for its preservation? In the same way, shouldn't loading WM at its maximum storage capacity result in a complete collapsing of performance on any other controlled activity? Does such a collapsing occur, and if it is not the case, what are the cognitive structures and mechanisms responsible for this residual performance? In addressing these questions, the aim of the present series of experiments was to get a better understanding of how our cognitive system resolves the challenge of maintaining information while carrying out concurrent and potentially distracting activities, and conversely, of achieving decent performance in demanding tasks while maintaining the information needed for their resolution. More generally, how does our mind manage to fulfill its adaptive function as a dynamic information processing system under temporal constraints?

Exploring the effects of the depletion of resources

As we recalled above, to what extent individuals are still able to successfully perform concurrent tasks while maintaining a memory load or, conversely, what are their capacity to maintain information while they are occupied by some concurrent treatment has always been at the heart of the study of WM. The well-known multi-component model developed by Baddeley (1986; Baddeley, Hitch, & Allen, 2021; Baddeley & Logie, 1999) was initially inspired by the fact that a memory load at span does not dramatically impair concurrent processing (Baddeley & Hitch, 1974). In the same way, the first measures of WM capacity revealed that individuals are able to maintain several memory items while achieving complex cognitive activities like reading sentences for comprehension (Daneman & Carpenter, 1980), counting arrays of dots (Case et al., 1982), or solving arithmetic problems (Turner & Engle, 1989). It could be argued, as Barrouillet and Camos (2015; Barrouillet, Bernardin, & Camos, 2004) did, that this apparent robustness of the cognitive system is, at least in part, due to the fact that most of the tasks used to assess WM capacities were self-paced, leaving participants

free to develop strategies to overcome the difficulties of the processing-and-storage dual tasks. For example, before reading a new sentence in the reading span task, or solving a new equation in the operation span task, individuals might surreptitiously turn their attention toward the memory traces for refreshing them. However, when using computer-paced complex span tasks intended to hinder these strategies, and even in the most demanding conditions of these tasks, adults proved still able to recall more than two items (Barrouillet et al, 2004, Exp. 7; Barrouillet, Portrat, & Camos, 2011).

It might be concluded from these findings that, although there is ample evidence that processing and storage compete for a shared resource (see Barrouillet & Camos, 2015, for a review), the two functions draw also on distinct peripheral resources and supplies explaining that performance never collapses. Nevertheless, as demanding as the processing was in the computer-paced dual tasks evoked above, it cannot be assumed that it entirely depleted the resources in all the participants. Some of them could have had higher resources or more efficient skills and managed to spare some resources for maintaining items in WM. It is also possible that individuals prioritized the memory component of the dual task and directed their attention to a subset of memory items while strategically targeting a slightly suboptimal performance in the processing component for maintaining active some memory traces until recall. Allen and colleagues have largely documented these strategies of prioritization (Allen & Ueno, 2018; Atkinson, Baddeley, & Allen, 2017; see also Belletier et al., 2023).

These issues were recently addressed by Belletier, Camos, and Barrouillet (2021) who aimed at assessing dual-task costs between processing and storage while controlling the potential effects of individual differences in resources and abilities and avoiding the effect of any strategy of prioritization of one task over the other. Following a study by Doherty et al. (2019), they used a Brown-Peterson paradigm in which participants had to recall in correct order series of letters after a retention delay of 10 s filled with a parity judgment task on digits

presented successively on screen. However, instead of leaving participants free to neglect one component of the task to warrant a good performance on the other, they only measured performance in one component when people performed at their maximum individual capacity in the other. For this purpose, they first assessed, through a titration procedure, the memory and the processing spans of each participant (the maximum number of letters they were able to recall after an empty delay of 10 s, and the maximum number of digits the parity of which they were able to correctly judge in 10 s, respectively). Then, each participant performed in isolation both memory and processing tasks set at span, and the Brown-Peterson dual task with both components also set at span. In some trials of the Brown-Peterson task, they were asked to prioritize processing; their memory performance was assessed only on those trials in which they performed in the parity task at the same level as in the single parity task. In other trials, they had to prioritize memory, performance in the parity task being measured only when recall was at least as good as in the single memory task.

This procedure revealed large dual-task costs in both memory and processing. When the demand of the other component was pushed at its maximum, memory and processing performance was lower in dual than in single tasks. However, despite this clear degradation, substantial residual performance in both components was observed. While their mean memory span reached 6.54 letters, participants were still able to correctly recall 3.27 letters when simultaneously performing at their best in the parity task. In the other way round, their performance in this latter task only dropped from 12.38 to 7.86 digits correctly judged in 10 s while they successfully maintained a memory load at span. It is worth noting that theories assuming a resource sharing between processing and storage in WM such as the embedded processes model (Cowan et al., 2021) or the time-based resource sharing model (TBRS, Barrouillet & Camos, 2015, 2021) suppose that, along with an attentional mechanism of maintenance, verbal items can also be maintained in WM through verbal rehearsal. Because

the parity task did not prevent them to use the verbal rehearsal strategy, Belletier et al. (2021) surmised that the maintenance of some memory items through verbal rehearsal could partly account for these residuals. Thus, in order to prevent participants to use this strategy, they replicated the entire procedure with single and dual tasks performed under concurrent articulation. Nonetheless, a substantial memory residual of 2.34 letters remained, and participants were still able to process 9.13 digits in 10 s while maintaining a memory set at their own span.

A resource sharing, but of what kind?

The detrimental effect of processing on storage, and of storage on processing, observed in Belletier et al. (2021) is certainly in line with models assuming a resource sharing between processing and storage (Barrouillet & Camos, 2015; Cowan, 2005; Cowan et al., 2021), and at odds with those that assume distinct and separate resources for the two functions (Baddeley & Logie, 1999; Logie, 2011). However, the fact that, while performing at their maximum in one of the two components, individuals were still able to maintain a decent performance on the other poses a massive challenge to the resource-sharing hypothesis. Indeed, if this resource was a continuous supply shared in parallel between the two functions, such as a given amount of some source of energy like attention (Anderson, 1993), or some mental space shared by storage and processing (Case, 1985, 1992), depleting it by an optimal performance on one of these two functions should have devastating effects on the other. This is not the case.

Belletier et al.'s (2021) results rather suggest a kind of resource sharing that preserves WM from a complete collapsing of one of its functions even when the other is solicited at its maximum capacity. This could be achieved by the existence of different kinds of resource or supplies, with a shared resource on which both processing and storage could indifferently draw, along with additional and separate pools of resource for each function. It is also possible that there is only a unique common resource for both functions, but that, for

functional or structural reasons, none of the two functions can completely deplete this resource, even when individuals allocate their maximum capacity in processing or storage. For example, within the time-based resource-sharing model (TBRs, Barrouillet & Camos, 2015, 2021), both processing and storage are fueled by a unique attentional resource shared on a temporal basis. Due to a central bottleneck, when attention is occupied by processing episodes, it is not available for the encoding and maintenance of memory traces, and vice versa, attention rapidly switching from one activity to the other. However, some activities might not continuously occupy attention, leaving room for some flexibility of the system. For example, the parity task, even when performed at a high rate, involves processing steps such as carrying out motor responses once response selection has been made that would not require attention and during which some maintenance activities could take place. In the same way, even maintaining a memory load at span could spare periods of time available for other activities.

On the size of the memory residuals

Although the memory and processing residuals observed by Belletier et al. (2021) are not incompatible with the hypothesis of a single shared resource, such a hypothesis is weakened by the size of these residuals. Participants preserved 63% of their processing performance while maintaining a memory load at span. In the same way, whereas their memory span was 6.54 letters, participants were still able to recall 3.27 (i.e., 50%) of these letters while concurrently performing the parity task at the same level as when performed in isolation. When the tasks were performed under articulatory suppression, these values were 3.54 and 2.33 (66%), respectively. We argued that memory residuals could result from the possibility to take advantage of some processing steps of the concurrent task for refreshing memory traces. However, it is surprising that the strong increase in cognitive load resulting from the necessity to perform the concurrent task at the same level as when performed alone

leads to such a small decrease in recall performance. More modest variations in cognitive load have already resulted in stronger effects in recall. For example, in a reading digit span task in which participants remembered letters while reading digits successively presented on screen, increasing the rate of their presentation from 0.4 to 2 digits per second resulted in a decrease of recall performance of 51% in Barrouillet, Bernardin, and Camos (2004, Exp. 7). Hence, should other resource pools for memory be envisioned in Belletier et al.'s study that could have contributed to maintain memory residual at a high level and, at the same time, alleviated the demand of storage in WM and allowed participants to preserve substantial processing performance?

When assessing the suitability of several verbal WM capacity models to fit experimental data from participants studying and recalling words, Cowan, Rouder, Blume and Saults (2012) noted that the addition to the most successful model of an activated capacity-unlimited LTM component was needed. Such a LTM component could account for the memory residual in Belletier et al.'s study. However, the contribution of this LTM component was deemed as small by Cowan et al. For example, the WM capacity having been estimated at about 3 chunks, only a single additional chunk was attributable to this LTM component when six words were to be memorized (see condition 1x6 in Experiment 1 in Cowan et al., 2012). By contrast, the memory residuals of 3.28 and 2.33 letters (without and with articulatory suppression, respectively) observed by Belletier et al. (2021) cannot be considered as small when compared to recall performance in the memory task performed in isolation. They constitute 60% or more of this performance and largely exceed the single item estimated by Cowan and colleagues. So, how can we understand such large residuals within the resource-sharing hypothesis?

The adequacy of paradigms in measuring memory residual

Are there some aspects of the paradigm used by Belletier et al. (2021) that could explain this surprising robustness of the cognitive system? Belletier et al. wondered whether participants strategically did not choose to only maintain a subset of the letters presented, as described by Atkinson et al (2018), and managed to spare, during the parity task, some free time for refreshing these few memory traces. As we noted above, this could be achieved by taking advantage of the periods of motor responses that do not involve strong attentional capture after response selection has been made (Pashler, 1994). Even short periods during which attention is free could be sufficient for refreshing a restricted number of memory items (Camos et al., 2019; Portrat, Barrouillet, & Camos, 2008; Vergauwe, Camos, & Barrouillet, 2014). Another possibility might be that the use of a Brown-Peterson paradigm helped participants to rely on LTM storage. The presentation of all the memoranda before the intervening task that characterizes this procedure might have facilitated strategies of grouping or chunking. Memory traces of these groups or chunks could have survived the 10s delay without active maintenance, and could have been retrieved from LTM at the end of the processing phase.

However, it should be noted that the Brown-Peterson paradigm is not the most common way of examining WM capacity, which is more often assessed through complex span tasks (Wilhelm, Hildebrandt, & Oberauer, 2013). These tasks were the first tasks designed to measure WM capacity (Daneman & Carpenter, 1980; Turner & Engle, 1989), and many studies that have focused on individual differences in this capacity exclusively used them (e.g., Conway et al., 2002, 2005; Hambrick & Engle, 2002; Kane et al., 2004, 2007; Unsworth & Engle, 2007; Unsworth, Miller, & Robison, 2021a, 2021b; Unsworth & Spillers, 2010). In complex span tasks, participants are presented with a series of items for further serial recall (e.g., letters, words, digits, spatial locations), but contrary to the Brown-Peterson paradigm, each item is followed by an intervening task (reading sentences, solving arithmetic problems,

judging numbers parity or symmetry of visual patterns). Such a way of presenting memory items might hinder the strategies of grouping or chunking and allow a better estimate of the memory residual by presumably minimizing the recourse to LTM. As we noted above, even in complex span tasks involving a processing component inducing a high cognitive load, WM spans rarely fell below 2 (e.g., Barrouillet et al., 2004). However, to the best of our knowledge, there is no study having used a titration procedure to present participants with a complex span task in which both memory and processing components were set at span. In the same way, the potential recourse to LTM for recalling the memoranda in the Brown-Peterson paradigm when priority had to be put on memory could have facilitated the resolution of the parity task and possibly increased the processing residual. Consequently, we do not yet have an adequate measure of the processing and memory residuals issued from the gold-standard WM task.

The present study

Thus, the aim of the present study was to explore WM structure and functioning by measuring both processing and memory residuals in a complex span task in which the demand of the other component was pushed at its maximum. Although the present study aimed at measuring residuals whereas Belletier et al. (2021) simply investigated the existence of a resource sharing between processing and storage and the resulting dual-task costs, we used the same parity judgment task and the same memory for letters as in Belletier et al. (2021). According to the TBRS model, WM span is an inverse function of cognitive load in such a way that WM span would virtually drop to zero when the cognitive load of the concurrent task is at its maximum (i.e., when processing continuously occupies attention). Barrouillet et al. (2011) provided evidence in favor of this hypothesis in complex span tasks. However, this was achieved by extrapolating their data toward such a maximum level of cognitive load, but has never been directly tested. The TBRS model would hence predict the disappearance of

any memory residual when the parity task is performed at the highest participants' capacity. However, even if the rare remaining periods of free time in the task are too short for permitting the refreshing of even a single item, this would not necessarily involve the complete disappearance of any memory residual if some memoranda can be retrieved at recall from an LTM component, as hypothesized by Cowan et al. (2012). We have hypothesized that this recourse to an LTM component should be less effective with a complex span than a Brown-Peterson paradigm. Thus, assuming that the parity judgement task performed at span should largely prevent attentional refreshing, we expected a memory residual reduced to the LTM component as estimated by Cowan et al. (2012), namely a residual that should not exceed one item. The reduced contribution of the LTM component in the complex span task should make memory maintenance more demanding than in the Brown-Peterson paradigm used by Belletier et al. (2021). Consequently, a reduction of the large processing residual observed in this latter study could be expected when assessing residuals through a complex span task procedure.

Following the same logic as Belletier et al. (2021), we used in a first experiment a complex span task in which the demand of one of the two components, processing or storage, was pushed at its maximum. For this purpose, first, the maximum capacity of each participant in the processing and storage tasks was assessed through a titration procedure. Second, participants were asked to perform each task at their span level (single-task conditions). Finally, they performed the two tasks in dual-task conditions in prioritizing either processing or storage. In order to verify the compliance to the prioritization instructions, we only took into account those trials in which participants achieved a level of performance in the prioritized task at least equal to what they did in the corresponding single-task condition. This is what we call "perfect trials", in which residual of the non-prioritized task can be measured.

As explained above, we expected smaller memory and processing residuals than in Belletier et al. (2021). We mentioned earlier that Belletier et al. suggested that the memory residual they observed might also result from the strategic maintenance of only a subset of the presented memory items. For example, though being presented with memory load at span, participants could have restricted their mnemonic efforts to the two or three first items of the series, as shown by Belletier et al. (2023). One way to thwart this strategy could be to ask participants to recall only the items located at a few serial positions that vary from one trial to another in an unpredictable way, participants being obliged to pay attention to all the items presented. Thus, a second experiment involved the same complex span task as in the first experiment, but instead of requiring a serial recall systematically beginning by the first serial position, the task would require a partial and unpredictable serial recall. This latter manipulation was intended to provide us with the closest approximation of the size of the residual in WM when maintenance strategies and mechanisms are made ineffective. Because these two experiments allowed the use of articulatory rehearsal for the maintenance of some memory items, a third experiment used the same procedure as in the first experiment, but the titration, the single and the dual tasks were performed under concurrent articulation in order to impede the maintenance of memory items through verbal rehearsal.

This latter manipulation should reveal the size of the memory residual. Under the resource-sharing hypothesis favored by the TBRS and the embedded-processes models, this residual should be reduced to the contribution of the LTM component identified by Cowan et al (2012) and, consequently, should not exceed one item. Thus, the present study, through the use of a technique intended to deplete WM resource, can be considered as an experimental validation of the computational analyses proposed by Cowan and his colleagues of verbal WM capacity, and more specifically of its LTM component.

Finally, in a fourth experiment, we tested our hypothesis that the Brown-Peterson paradigm overestimates the memory residual by comparing the residuals issuing from the Brown-Peterson and the complex span paradigms in a single experiment. We predicted a smaller memory residual with the latter than the former paradigm. As explained above, the reduced contribution of a LTM component in the complex span task paradigm compared with the Brown-Peterson paradigm should make more demanding the maintenance of a memory load at span when concurrently performing the parity task. Thus, the reduction of the memory residual should be accompanied by a reduction of the processing residual in the complex span paradigm compared with the Brown-Peterson paradigm. Estimating these residuals should shed light on how resources are distributed between the two functions of WM, ultimately informing us about its structure.

Experiment 1

The aim of this experiment was to assess the memory and processing residuals in a complex span task when the demand of the other component was pushed at its maximum. ~~As in Belletier et al. (2021)~~ The complex span task used in the present study involved maintaining series of letters for serial recall, each letter being followed by digits presented successively on screen for parity judgment. The rationale was the same as in Belletier et al. (2021), residuals being measured by pushing the demand of one of the components to its limit. For this purpose, each component of the task was titrated according to the capacities of each participant. After having measured the individual memory and processing spans through a titration procedure, we assessed participants' performance in single tasks when the memory demand or the processing demand was set at span. Then, the two single tasks were mixed in a complex span task. Memory and processing residuals were assessed by asking participants to perform in the other component at a level at least equivalent to that which they had obtained in the single task.

Method

Participants

Participants were 24 undergraduate students (23 females and 1 male²; age ranging from 18 to 23 years) at the University of Clermont Auvergne (France) who received course credits for their participation. In this experiment as in Experiments 2 and 3, we used the same sample size as in Belletier et al. (2021) study. All had normal or corrected-to-normal vision. Ethic approval for this study was obtained from the institutional review board of University of Clermont Auvergne.

Material and general procedure

All the experiments of this study followed the same rationale. The task was run on a computer using the software PsychoPy (Peirce et al., 2019). The experimenter was sitting in the experimental cubicle during the entire experiment, in such a way that he or she could not see the participant's ongoing task. The experiment began with two titration procedures, one aiming at assessing participants' memory span for letters, the other assessing their processing span using a parity judgment task on digits. The results of these titration procedures were used to adapt the forthcoming tasks to participant's individual level. Because the titration was aimed at adapting the difficulty of both components of the forthcoming complex span task, and because in this task the number of processing sequences was the same as the number of letters to be memorized, memory span determined the number of processing sequences on which the processing titration was based. Thus, the titration on memory was systematically performed first. Then, participants performed a memory and a processing single task at span, each involving five trials. These single tasks were followed by two dual tasks, one in which they had to prioritize memorization, and the other in which they had to prioritize processing.

² In accordance with the ethical approval obtained for this study, only sex as a binary category and date of birth have been collected.

At the end of the experiment, participants were asked to answer a survey on different mnemonic strategies (verbal rehearsal, elaboration strategy, associative strategy, acoustic strategy, visual strategy, reduction strategy) they could have used during the single memory task and the two dual tasks. This survey was similar to the one used by Belletier et al. (2023). For each strategy, the participants answered using the computer mouse on a five-point Likert-type scale expressed in percentages.

Titration on memory

The memory titration task followed a “staircase” procedure including eight steps of two trials each in which participants had to maintain and recall series of letters drawn at random without replacement from the set of consonants except W that is trisyllabic in French and Y and Z to avoid problems between QWERTY and QWERTZ keyboards. The first step involved four letters presented sequentially on screen for further serial recall. Following a first screen indicating the length of the series to be remembered, each letter was presented for 1000 ms and followed by a blinking circle displayed five times (950 ms on and 250 ms off) in the center of the screen during a period of 6 seconds corresponding to the duration of the processing phases in the forthcoming complex span task (see Figure 1a for the timeline of the events).

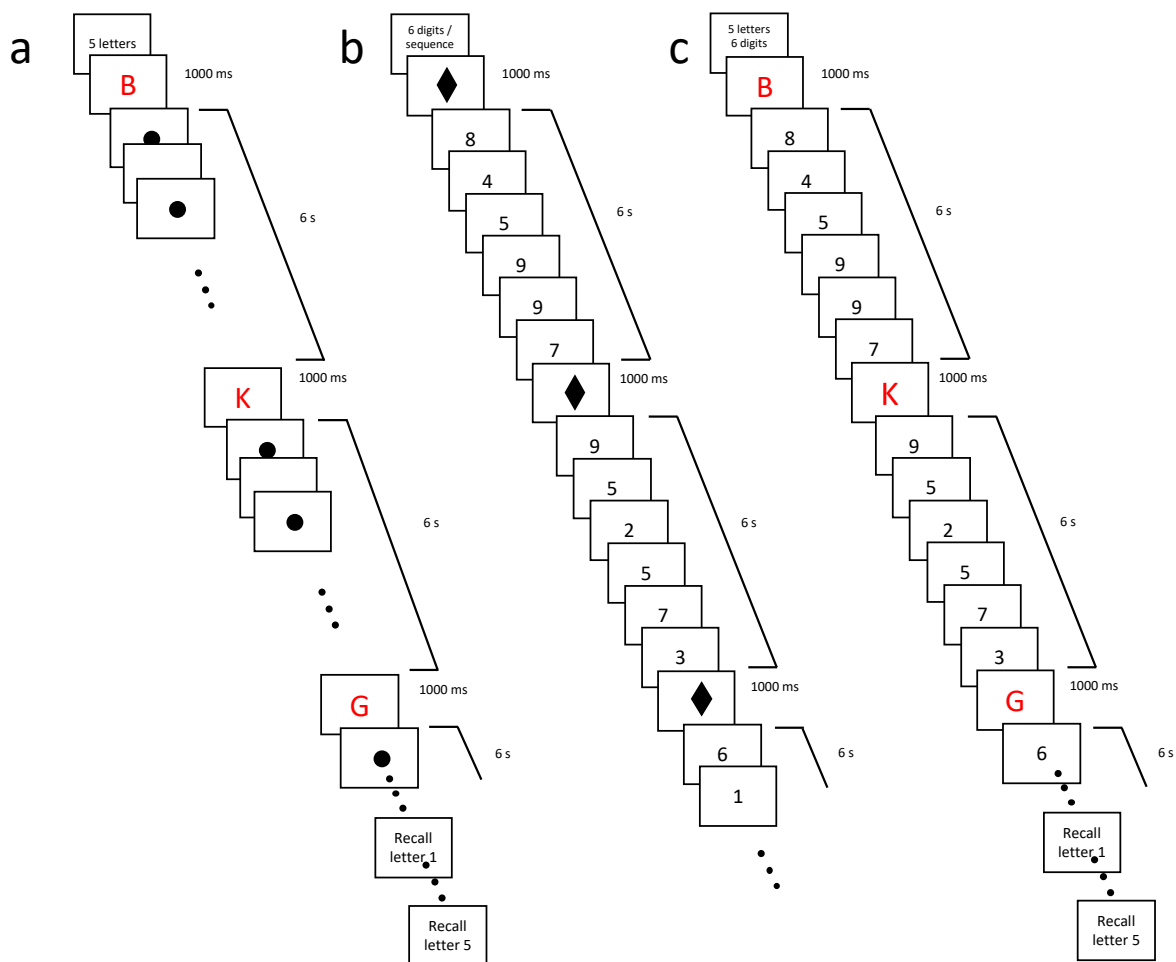


Figure 1

Illustration of the procedure of the single tasks for memory (panel a) and processing (panel b) and of the dual task (panel c). The number of letters to memorize as well as the number of digits presented per sequence were set at span. The black dots appearing on screen on panel a illustrate the flickering point that participants had to fixate during 6 s after each letter in the titration and the single task for memory. See text for details.

During this period, participants were asked to fixate the circle to avoid mnemonic visual strategies using the computer keyboard. At the end of the series, they were asked to recall the letters in correct order by typing them on the keyboard. For the memory titration and all the other tasks, the recall phase followed the same procedure. “Recall letter 1” appeared and remained on screen until participant’s key press that made appear the typed letter for 500 ms

before presentation of the next screen displaying “Recall letter 2”, and so on until the last letter of the series, in such a way that the letters already recalled did not remain on screen. Participants were informed that they could enter the letter “O” when they had forgotten a letter.

After this first step, and for each of the eight steps of the titration procedure, if the average performance (scored as recall in correct position) on the two trials was superior or equal to 90% correct, the number of letters to memorize in the following step was increased of one unit, and otherwise decreased of one unit. In order to guarantee that the measured span corresponded to the highest possible participant’s performance, if memory performance on the eighth step was the best performance achieved (i.e., the highest number of letters for which the 90% criterion was reached), the procedure of two-trial steps continued until the participants failed to achieve the 90% criterion. The memory span was defined as the number of letters involved in the highest step for which the 90% criterion was reached. The titration was preceded by three training trials with three letters.

Titration on processing

The processing titration followed the same procedure of at least eight steps involving two trials each. As already explained, in each trial, participants were presented with a number of processing sequences equal to their memory span previously measured. Each sequence had a duration of 6 seconds. For example, a participant with a memory span of four letters was presented with four processing sequences of 6 seconds each separated by a diamond-shaped placeholder that appeared on screen for 1000 ms (see Figure 1b for the timeline of the events). In the first step, participants had to judge the parity of four digits (from 1 to 9 picked up randomly with replacement) per sequence by pressing, for the even and odd responses, either the right or the left arrow key on which were stuck green and yellow stickers, respectively. In

case of success (90% of correct responses³), one digit was added per processing sequence in the next step, and otherwise removed. The inter-stimulus interval (ISI) between two successive digits being fixed to 250 ms, the duration in ms of their presentation on screen was equal to $(6 - (n \times 250)) / n$ where n is the number of digits to be presented in the 6-second intervals. As in the memory titration, if the last step corresponded to the best score achieved (the highest number of digits for which the 90% criterion was reached), the procedure was continued until the participant failed to reach the 90% criterion. The processing span was defined as the number of digits per sequence involved in the highest step for which the 90% success criterion was reached.

Single tasks

The procedure was similar to the titrations with a few exceptions. First, the number of letters to memorize in each series for the single memory task and the number of sequences in the processing task were equal to the individual memory span as determined by the memory titration. Second, the number of digits to be judged in the single processing task was equal to the individual processing span determined in the processing titration procedure. Participants performed five trials in each single task preceded by three training trials (with three letters for the memory task and three 6-second sequences of three digits in the processing task).

Dual tasks

The two dual tasks consisted in combining the two single tasks. For each trial, participants had to remember a number of letters equal to their memory span. Each letter was followed by a 6-second processing sequence of parity judgment in which a number of digits equal to their individual processing span were presented successively on screen. This interval duration of 6 seconds was chosen long enough to allow the presentation of a substantial

³ Following our example of an individual with a memory span of 4, the titration procedure beginning with four digits per sequence resulted in the judgment of $4 \times 4 = 16$ digits per trial. The criterion of an average of 90% correct over the two trials of the step means that at least 29 out of 32 responses might be correct.

number of digits while avoiding too long trials when memory span was high (i.e., 7 or 8). At the end of the trial, participants were asked to recall the letters in correct order. During the first dual task, they had 20 attempts to realize five “perfect trials” on memory. To be “perfect”, the memory performance in the trial in terms of items recalled in correct position has to be equal or superior to the participant’s average performance on the single memory task. Only this criterion ensured that participants strictly followed the prioritization instructions. However, they were urged to perform well at the same time on the parity judgment task through the following instructions (here translated from French) displayed on screen: “In this part of the experiment, your objective is to succeed in carrying out 5 trials for which you will remember all the letters perfectly, i.e., as well as when you had only the letters to memorize. Remember that you have to both remember the letters and correctly judge the numbers, but keep in mind that your goal is to complete 5 trials with a perfect letter recall (or 5 trials with perfect parity judgments). Press space to start”. After each trial, they were informed that “You have succeeded in perfectly recalling the letters in x trials out of the 5 required. You have x attempts left to get the 5 perfect trials”. In the second dual task, participants had 20 attempts to realize five “perfect trials” on processing (i.e., with the processing performance in terms of correctly processed items being equal or superior to the participant’s average performance on the single processing task), while still performing well on the memory task.

Both dual tasks were interrupted once a fifth “perfect trial” was completed. Three training trials without any instructions of prioritization including three letters and three digits in the processing sequences preceded the dual tasks.

Transparency and openness

In this and the following experiments, we report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. All data are available at

<https://osf.io/q3efr/>. Data were analyzed using JASP (0.16.3; JASP Team, 2022). The design and the statistical analyses were not pre-registered.

Results

We removed from the analyses four participants who did not reach the criterion of five “perfect trials” in both dual tasks, but we nevertheless kept the performance of one participant who fell short at reaching this criterion and completed five “perfect trials” in the dual task with memory prioritization, but only four in the dual task with processing prioritization (see Appendix A for the performance of the participants removed from this and the following experiments). The sample for this experiment thus included 20 participants.

In each experiment of this study, accuracy on memory and processing was scored as the percentage of correct responses, i.e., the percentage of letters recalled in their correct serial position, and the percentage of digits correctly judged during the 6 second intervals for processing. The number of letters and digits presented during the single and dual tasks were adapted to each participant thanks to the titration procedure. However, in these tasks, the memory and processing scores were corrected for guessing using the formula proposed by Diamond and Evan (1973):

$$p_{corr} = p_{raw} - (p_{errors}/(k-1))$$

where p_{corr} is the percentage corrected for guessing, p_{raw} the raw percentage of correct responses, p_{errors} the percentage of incorrect responses (without omissions) and k the number of possible responses (2 for the processing task and 18 for the memory task; all the consonants of the alphabet excluding w and z).

Titration.

On average, participants achieved a memory span of 5.95 letters (95% CI [5.45, 6.45]) and a processing span of 6.70 digits (95% CI [6.32, 7.08]) per 6 second intervals.

Comparison between single tasks and perfect trials in dual tasks.

A series of Bayesian paired sample t-tests were performed on accuracy in the memory and processing tasks. These analyses compared the performance in memory and in processing for each of the three conditions: single task, dual task with priority on memory and dual task with priority on processing. For the dual-task analyses, only performance during the “perfect trials” (i.e., trials in which the participant performed better than or equal to his or her average performance on the corresponding single task) was considered. The mean number of trials needed by the participants to reach the criterion of five “perfect trials” was 9.00 (95% CI [7.52, 10.48]) in the dual task with priority on memory, and 12.80 (95% CI [10.96, 14.64]) in the dual task with priority on processing.

Concerning the accuracy on memory, participants performed better in the dual task with priority set on memory ($M = .97$, 95% CI [.93, 1]) than in the single task ($M = .86$, 95% CI [.80, .92]), $BF_{10} = 1.04 \times 10^3$. This result is not surprising considering that only performance during the perfect trials was taken into account for the dual task. However, more interestingly for the purpose of the study, performance on memory in the dual task with priority set on processing ($M = .24$, 95% CI [.11, .37]) was much lower than in the single memory task ($M = .86$), $BF_{10} = 6.48 \times 10^5$. Not surprisingly, memory performance differed between the two dual tasks $BF_{10} = 1.04 \times 10^7$. In terms of letters recalled in correct position in the dual task with priority set on processing, what we called the memory residual, participants were able to recall on average 1.30 letters (95% CI [0.61, 1.99]; Figure 2 and Table 1), whereas they recalled 5.07 letters when the memory task was performed alone, which constitutes a mean decrease in performance of 73 %⁴.

Concerning the accuracy on processing, and for the same reason as with memory, participants performed better in the dual task with priority set on processing ($M = .92$, 95% CI [.90, .94]) than in the single processing task ($M = .84$, 95% CI [.81, .87]), $BF_{10} = 4.65 \times 10^6$

⁴ Note that this percentage is the mean percentage of decrease across participants, and not the decrease calculated from the mean number of digits recalled in the single and dual tasks, which would be slightly different.

(Figure 2). More interestingly, performance on processing was lower in the dual task with priority set on memory ($M = .63$, 95% CI [.54, .70]) than in the single processing task, $BF_{10} = 2.18 \times 10^3$. Participants in the dual task with priority set on memory were able to correctly judge, on average, 4.25 digits per 6-second intervals (95% CI [3.76, 4.74]), whereas their performance was of 5.64 digits in the parity task performed in isolation. Thus, participants preserved 75% of their processing performance that can be compared with the preservation of only 27% of their memory performance (Table 1).

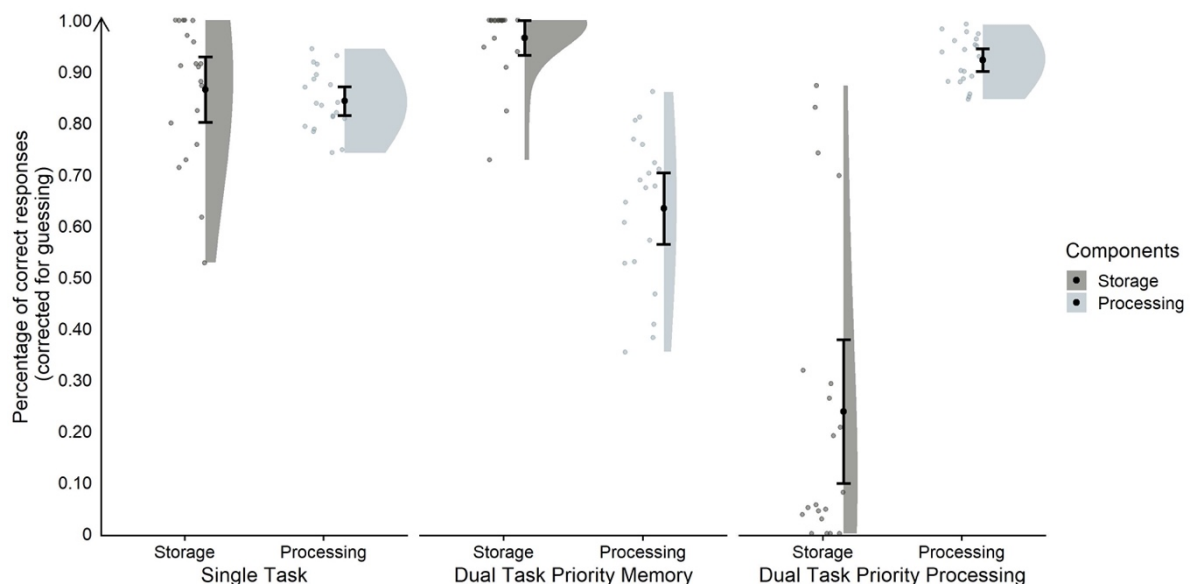


Figure 2

Mean accuracy on memory and processing for Experiment 1 as a function of the type of task (single vs. dual) and priority (set on memory vs. processing). Error bars represent 95% confidence intervals.

Discussion

Experiment 1 aimed at testing the reciprocal dual-task costs of storage and processing and at providing a new assessment of the memory and processing residuals by using a task more appropriate to assess WM capacity than the Brown-Peterson paradigm used by Belletier et al. (2021). We surmised that the task implemented in Belletier et al. (2021) study could

favor some strategic grouping or chunking of the letters, which should have led to overestimate the memory residual. In the present study, the use of complex span tasks in which letters were interleaved with processing episodes should reduce the opportunities of chunking and lead to smaller residuals. Three main findings were observed.

First, in accordance with Belletier et al.'s findings, we observed that the accuracy on both memory and processing was reduced when participants maintained a high level of performance on the other component of the dual task, suggesting a trade-off between the two functions. These results reinforce the pattern of reciprocal dual-task costs reported by Belletier et al. (2021), and also show that the detrimental effect of concurrent processing on memory and *vice versa* was not dependent on the paradigm they used. This pattern of results is in line with several models of WM, such as Cowan's embedded-processes model (2005; Cowan et al., 2021) and Barrouillet and Camos' (2015, 2021) TBRS model, that suggest a sharing of attentional resources between processing and storage in WM. By contrast, it is at odds with models assuming distinct and separate pools of resource for processing and storage (e.g., Baddeley & Logie, 1999; Doherty & Logie, 2016).

Second, as we expected, the residual performance in memory while maintaining the performance on processing at the same level as in the single task proved far lower in the present experiment than in Belletier et al. (2021). While, in the Brown-Peterson task with priority on processing used by these authors, participants were able to correctly recall 50% of their span, this percentage dropped to 24% in the present experiment. It should be noted that our participants were achieving rather similarly on the titration as those tested by Belletier et al. (2021) with memory spans of 5.95 and 6.54, respectively. By contrast, while participants were still able to recall 3.27 letters (95% CI [2.75, 3.79]) in the Brown-Peterson task, their performance dropped to 1.30 letters in the complex span task used in the present experiment

(95% CI [0.61, 1.99]). We are not aware of any experiment using a complex span task in which recall performance dropped to such a low level.

As mentioned in the introduction, the Brown-Peterson task facilitates the grouping or chunking of letters, because memoranda are presented one after the other in immediate succession. Thus, this way of presenting information could make easier to “glue” memory items together and form the perceptual object described by Jones and Macken (2018) in their approach of short-term memory as object-oriented action. By contrast, the presentation of memoranda interspersed with processing episodes in complex span tasks makes more difficult the construction of the series to be recalled. Moreover, the Brown-Peterson task involves shorter delays of retention (e.g., 10 seconds in Belletier et al., 2021) than the complex span task in which the first items presented must be maintained several tens of second before recall (e.g., in the present experiment, for a span of 6 letters, recall occurred more than 40 seconds after the first letter had disappeared from screen). It should also be noted that memory traces could suffer more interference from the digits of the parity task in the complex span task paradigm in which a series of digits is processed after each letter. Thus, in the extreme conditions in which the demands of the processing component impeded the active maintenance of information in WM, the shorter delays of retention and the lower level of interference in the Brown-Peterson paradigm could make easier to retrieve memory traces from episodic long-term memory (LTM).

Third, and contrary to what was observed with the memory residual, processing residuals were approximately the same in Belletier et al. (2021) and in the present experiment (62% and 63%, respectively). The two processing spans being very close to each other (1.24 and 1.12 digits per second, respectively), so were the residuals (0.78 and 0.71 digits per second, respectively). Thus, the present experiment reveals a strong asymmetry between processing and memory residuals (63% vs. 24% of span, respectively) that did not appear

with the Brown-Peterson procedure. The cognitive system appears to be more robust in its processing than short-term storage function. Before discussing this finding in the general discussion, let us return to some characteristics of the memory residual observed.

Considering the small size of the memory residual, we wondered about the serial position of the rare letters recalled. It appeared that recall performance was characterized by a primacy effect with no recency effect (Figure 3), the two first presented letters being better recalled than the two last letters (.31 and .19 of correct responses, respectively), $BF_{10} = 5.27$. However, this was not due to a higher accessibility at recall of the first over the last letters presented. In fact, when considering free recall scoring (i.e., whether an item was recalled at all, regardless whether it was in correct position), recall rate did not strongly vary from the first to the last serial positions (.46 and .41 for the two first and the two last letters, respectively), but the rate of error positions increased as the rate of recall in correct position decreased (Figure 4). Thus, the primacy effect observed in the rate of recall in correct position was not due to some decrease in the strength of letter encoding across input serial position, as suggested by several models of serial recall (Farrell & Lewandowsky, 2002; Lewandowsky, 1999; Page & Norris, 1998), but to a progressive loss of the serial position of the accessible letters. These findings reveal that the number of letters still accessible from memory at the end of the trials in the complex span task was higher than the 1.30 letters reported above when only considering recall in correct serial position, but was of 2.52 ($SD = 1.67$).

Such a performance pattern could be due to the requirement of a strict forward serial recall in which participants were asked to type each letter in turn up to the last letter of the series. This could have induced output interference effects that are known to contribute to the primacy effect in immediate serial recall (ISR; Cowan, Saults, Elliott, & Moreno, 2002; Oberauer, 2003; Tan & Ward, 2007). Cowan et al. (2002) showed that when input and output order are dissociated, for example by asking participants to recall only a portion of the series

under study and to begin their serial recall by another item than the first presented, recency effects occurred. However, because the series of items they used were probably supra-span for many participants (nine digits), their maintenance in WM is uncertain and at least some of the recalled items were probably retrieved from episodic LTM. In order to explore the potential effect of these output interference that could have distorted the size and nature of the WM residual, we adopted a strategy slightly different from Cowan et al. (2002). The following experiment used the same procedure as in Experiment 1, but we asked participants to recall only three letters from the series presented, still in their order of presentation, but at three unpredictable positions within the presented series, these three positions changing from one trial to the other. This procedure of partial recall should have a strong impact on recall. As we suggested in introduction, the primacy effect observed in the present experiment might be due to the strategic maintenance of a subset of memory items, namely the first presented. If this is the case, a partial recall at unpredictable serial positions should discourage this strategy and reduce the primacy effect. Moreover, the accessibility of the items being approximately the same whatever their serial position (see the panel “All” in Figure 4), a partial recall reducing output interference could abolish the primacy effect and possibly give rise to a recency effect as observed in Cowan et al. (2002).

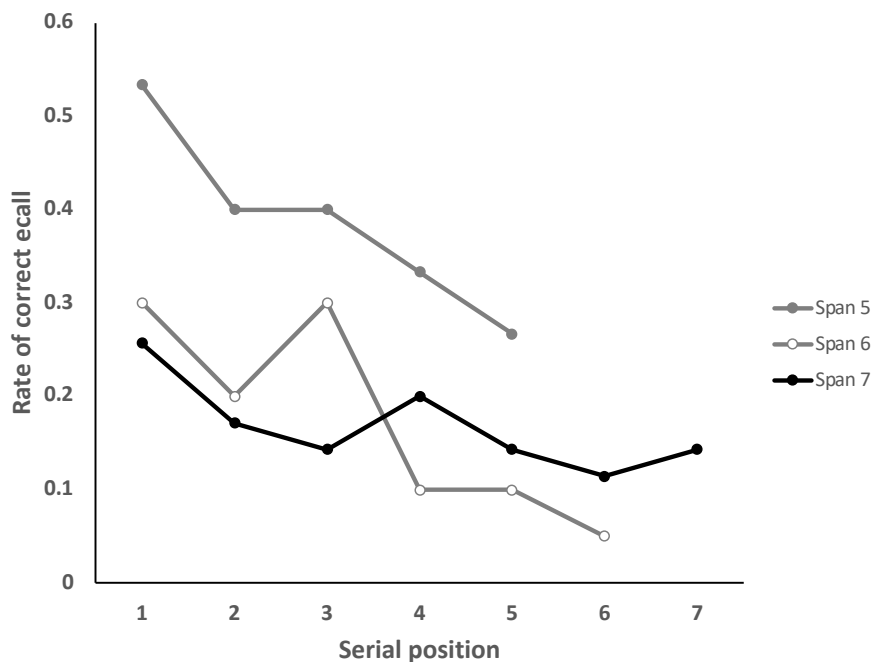


Figure 3

Rates of recall in correct position as a function of serial position for participant with a memory span of 5 ($n = 7$), 6 ($n = 4$) and 7 ($n = 7$) letters in Experiment 1.

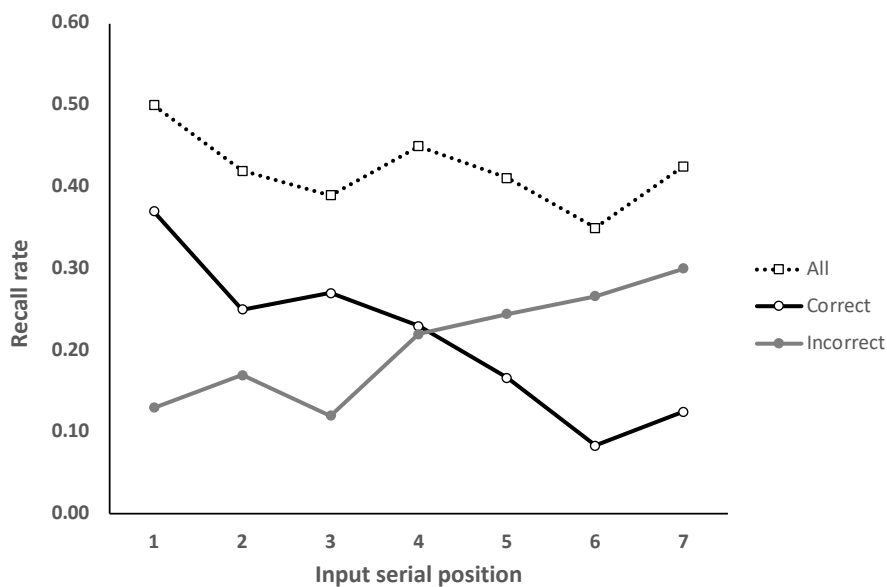


Figure 4

Rates of recall in correct and incorrect position, and their sum (All), as a function of the input serial position of the letters in Experiment 1. Note that serial position 8 has not been reported in the figure, only one participant having been presented with 8 letters (this eighth letter was never recalled in correct position and in incorrect position at a rate of .20).

Experiment 2

This experiment investigated the size and nature of the WM residual when participants had to maintain series of letters set at span while performing at their best in the processing component of a complex span task, but were probed at recall on only some (i.e., three) of the serial input positions. By reducing output interference and discouraging strategies of maintenance of only some items, the procedure of partial recall should result in a better recall of the last items than in Experiment 1, the results of which having shown that these last items, although rarely recalled in correct position, were nonetheless accessible from memory. Partial recall at unpredictable positions could also reduce or abolish primacy effects. Although reciprocal dual-task costs should be observed, this manipulation was not expected to affect the processing residual that was far higher than the memory residual in Experiment 1.

Method

Participants

Participants were 24 undergraduate students (24 females; age ranging from 18 to 22 years) at the University of Clermont Auvergne (France) who received course credits for their participation. All had normal or corrected-to-normal vision. None of them participated to the previous experiment.

Material and general procedure

The material and procedure were the same as in Experiment 1 with a single change concerning the recall phase of the memory titration task, the single memory task and the dual tasks. Instead of the series of screens “Recall letter 1”, “Recall letter 2”, etc., a single screen displayed a number of lined up dashes corresponding to the number of letters to be remembered, with three dashes replaced by question marks at the to-be-recalled serial positions. For example, for a series of seven letters, the recall screen could take the following form: “- - ? - ? ? -”, asking for the recall of the third, fifth, and sixth serial positions.

Participants were asked to type the three requested letters in their order of presentation. Each typed letter appeared on screen below the line of dashes for 500 ms and disappeared in such a way that participants never saw the entire set of recalled letters. After entering the third letter, the line of dashes disappeared and participants pressed a key for the next trial.

Before each task requiring recall, the experimental trials were preceded by three training trials involving three letters. For these trials, two and not three dashes were replaced by question marks.

Results

As in the previous experiment, we used the percentage of correct responses to measure participant's accuracy on processing and memory. Both memory and processing scores in the single and dual tasks were corrected for guessing in the same way as in the previous experiment. Data from five participants were removed from the analyses because they did not reach the criterion of five "perfect trials" in both dual tasks, but as in Experiment 1, the performance of two participants was kept because they completed five "perfect trials" in the dual task with memory prioritization, but only four in the dual task with processing prioritization (see Appendix A for the performance of removed participants). The sample for this experiment thus included 19 participants.

Titration.

On average, participants achieved a memory span of 6.42 letters (CI95% = [5.85;6.99]) and a processing span of 6.00 digits (CI95% = [5.63;6.37]) correctly judged per 6-second interval. Note that the average memory span (6.42 letters) was not lower, and even slightly higher, than in Experiment 1 (5.95 letters), indicating that the partial recall procedure used in the present experiment did not strongly impact the assessment of memory capacities.

Perfect trials.

Analyses were the same as in the previous experiment. For this second experiment, participants needed a mean number of 6.2 trials (CI95% = [5.7;6.7]) to validate the criterion of five “perfect trials” in the dual-task with priority on memory. In the dual-task with priority on processing, a mean number of 11.9 trials (CI95% = [10;13.8]) were necessary for participants to reach the same criterion.

Concerning accuracy on processing and for the same reasons as noted above for accuracy on memory, participants performed better on the dual task with priority set on processing ($M = .94$, CI95% = [.92;.96]) than on the single-task on processing ($M = .87$, CI95% = [.85;.89]), $BF_{10} = 9.98 \times 10^6$. According to our expectations and in line with Experiment 1, participants accuracy on processing was better in the single task ($M = .87$) than in the dual-task with priority set on memory ($M = .64$, CI95% = [.59;.69]), $BF_{10} = 855030.17$.

Participants in the dual-task with priority set on memory were able to correctly judge, on average, 3.82 digits per 6 second interval. This performance was significantly lower than in the dual-task with priority set on processing, $BF_{10} = 2.00 \times 10^7$.

Concerning the accuracy on memory, participants performed better on the dual-task with priority set on memory ($M = .90$, CI95% = [.84;.96]) than on the single-task on memory ($M = .83$, CI95% = [.77;.89]), $BF_{10} = 8.54$. This result is not surprising considering the explanations given previously in Experiment 1 section. As in this previous experiment, memory performance was better in the single memory task ($M = .83$) than in the dual task with priority set on processing ($M = .27$, CI95% = [.13;.41]), $BF_{10} = 19581.45$ (Figure 5 and Table 1).

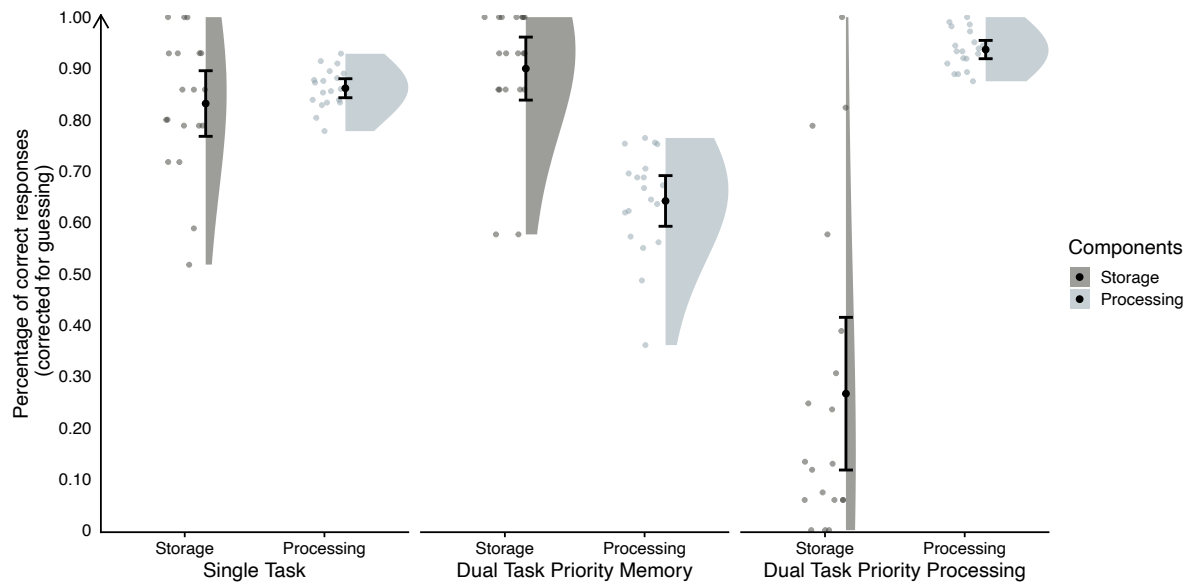


Figure 5

Mean accuracy on memory and processing for Experiment 2 as a function of the type of task (single vs. dual) and priority (set on memory vs. processing). Error bars represent 95% confidence intervals

In terms of memory residual, which was the focus of the present experiment, the three letters probed in each trial constituted a sounding of the memory set accessible in WM at recall. The mean rate of .27 of correct recall corresponds to 0.80 letters among the three letters probed. Assuming that the proportion of letters correctly recalled among the three probed letters reflected what the participants remembered from the series they studied, it was possible to estimate, for each participant, the numbers of letters in correct position still present in WM at recall by multiplying this proportion by participant's span. This resulted in a mean memory residual of 1.65 letters (CI95% = [0.83;2.47]).

Note that this residual was higher than in Experiment 1 in which a full serial recall was required (1.30). This is due to the fact the mean memory span in this experiment was higher than in Experiment 1 (6.42 vs. 5.95, Table 1), but also that letters in the last serial positions were, when probed, better recalled than in Experiment 1. Whereas the two first letters were better recalled than the two last letters in Experiment 1 (.31 and .19 of correct

responses, respectively), this difference disappeared in the present experiment (.34 and .33, respectively). For sake of comparison, Figure 6 displays the serial position curves for the two most frequent memory spans (i.e., 6 and 7) in Experiment 2, while Figure 7 displays the rate of correct recall for the seven first serial positions in the two experiments (in which data for all the participants are involved). Whereas full serial recall in Experiment 1 was characterized by a primacy effect without recency effect, it appears that partial recall in Experiment 2 resulted, as we expected, in a recency effect, but did not abolish, as it could have been expected, the primacy effect. The analysis of recall rate variations as a function of serial positions contrasting the beginning, the middle, and the end of the series⁵ in participants with memory spans of 6 and 7 revealed a significant quadratic trend, $t(26) = 2.96$, $p = .007$ (.35, .18, and .35 for beginning, middle and end, respectively).

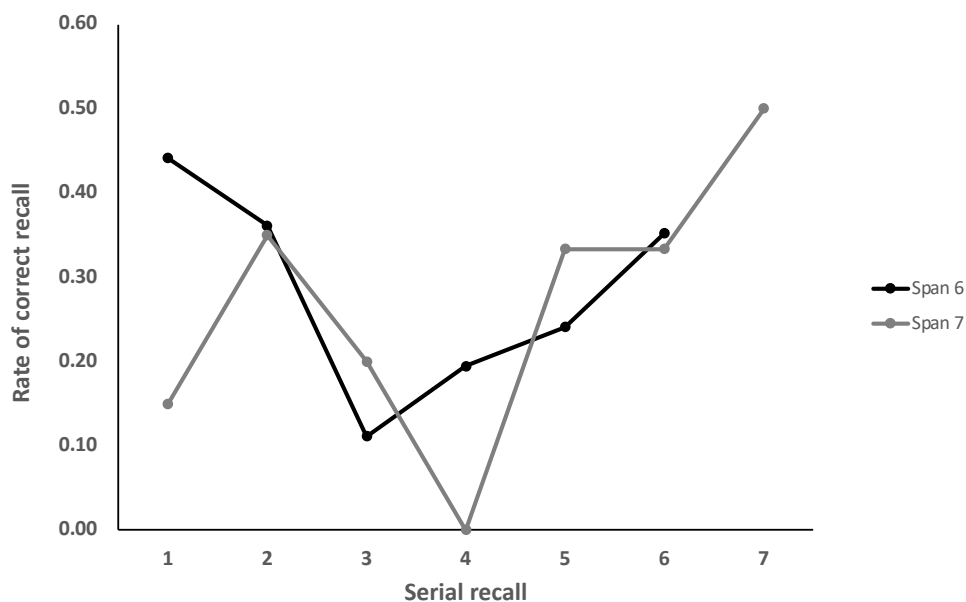


Figure 6

⁵ Recall rates for the beginning and the end were calculated by averaging recall rates of the two first and the two last serial positions, respectively, while the middle corresponded to the mean of the third and fourth positions for individuals with memory span of 6, and the third, fourth, and fifth positions for individuals with memory span of 7.

Rates of recall in correct position as a function of serial position for participant with a memory span of 6 ($n = 9$), and 7 ($n = 5$) letters in Experiment 2

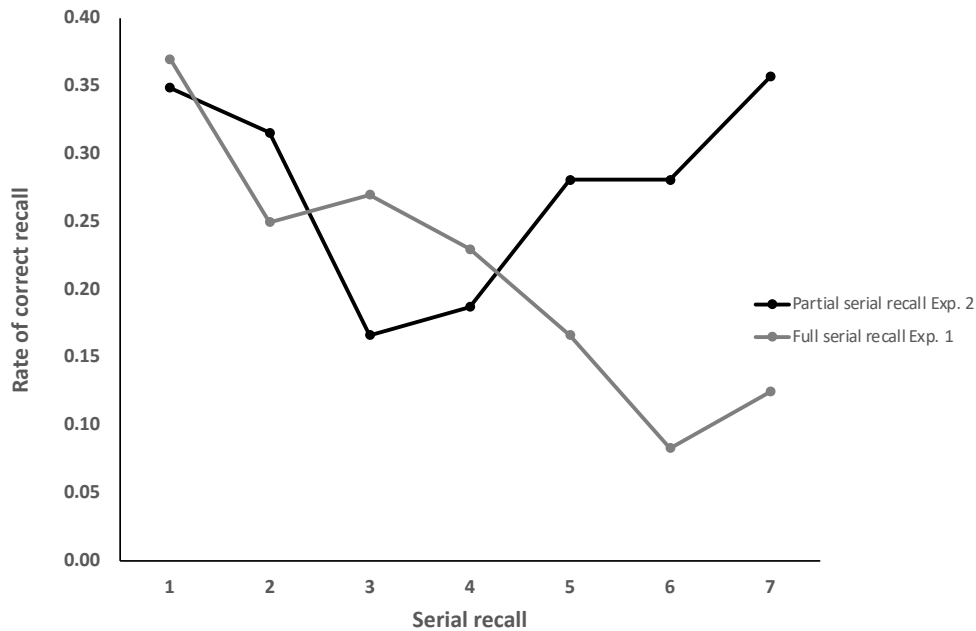


Figure 7

Rate of recall in correct position as a function of serial position in Experiment 2 when position probed (partial serial recall) and in Experiment 1 (full serial recall, identical to “Correct” in Figure 4). Note that for Experiment 2 the rates of recall for positions 8 (.25, $n = 3$) and 9 (0, $n = 1$) were not reported

Discussion

The present experiment replicated Experiment 1 by demonstrating that pushing at its maximum the demand of the processing component of a complex span task has devastating effects on recall performance even when the recall procedure reduces output interference (24% of memory span in Experiment 1, and 27% in the present experiment). By contrast, the processing residual was far higher and close to what was observed in Experiment 1 (64% and 63% of the processing residual, respectively). This replicates one of the main findings of Experiment 1 indicating that, when the demand of one of the two components of the complex

span task is maximized, a dual-task cost occurs for both memory and processing, but it is larger for memory.

The analysis of recall as a function of the serial position of the letters within the series to be recalled in Experiment 1 suggested that the primacy effect and the absence of recency effect observed in WM residuals was not due to the mere forgetting of the last items presented that were often recalled in incorrect positions, but to output interference by which recall of the first presented items degrades the memory traces of the subsequent items (Cowan et al., 2002; Oberauer, 2003). The recall procedure used in the present experiment revealed that when only some items are probed, WM residual is slightly more important. This procedure did not abolish the primacy effect, but a recency effect occurred, evoking the serial position curves observed in free recall in which both primacy and recency effects occur (Tan & Ward, 2007). Recall that the analyses in Experiment 1 revealed that, when serial position was no longer taken into account, the rate of recall of the letters presented did not strongly vary according to their input position (between .40 and .50, see Figure 4, panel “All”). What the serial position curves in the present experiment suggest is that, when informed of the serial positions to be recalled, participants were more accurate in identifying the corresponding letters when these positions were close to the edges of the series than located in its middle.

Before drawing conclusions about the origin of this WM residual, a further control is needed. Although this residual was particularly low in the two first experiments, it could have benefited from articulatory rehearsal. It has been argued that maintenance in verbal WM is achieved through two distinct and independent mechanisms, attentional refreshing and articulatory rehearsal (Barrouillet et al., 2021; Camos, 2017; Camos, Lagner, & Barrouillet, 2009). However, the concurrent parity judgment task only hindered the former, leaving participants free to articulate the to-be-remembered letters. Thus, in order to analyze WM

residuals when this latter mechanism is no longer available, the following experiment introduced a concurrent articulation.

Experiment 3

The aim of this third experiment was to introduce a concurrent articulation to prevent the use of articulatory rehearsal as a means to maintain letters in WM. We used the same rationale and tasks as in the previous experiments, except that all the tasks were performed under concurrent articulation. Because titrations were also performed under concurrent articulation, we expected lower spans than in the previous experiments and consequently shorter series of memory items. Thus, we opted for a serial recall procedure as in Experiment 1, the short series of to-be-remembered letters being less appropriate for the partial recall procedure used in Experiment 2.

Articulatory rehearsal being impeded by concurrent articulation, WM maintenance should only rely on attention, the availability of which was strongly reduced by the parity task performed at span in the dual task with priority set on processing. Thus, WM models assuming a resource sharing between processing and storage such as the TBRS model (Barrouillet & Camos, 2021) would predict the disappearance of any memory trace in WM and a memory residual virtually null. However, in line with Cowan et al. (2012) estimates of a LTM component in recall performance, a residual of a maximum of one item could be observed.

Concerning processing residual, we have seen that our complex span task with prioritization on memory had a significant but less important impact on parity judgment performance. Although it has been argued that information about parity is associated with a visual Arabic, and not verbal, code for numbers (Dehaene, Bossini, & Giraux, 1993), it is also possible that a concurrent articulation would have a detrimental impact on the parity judgement task. Indeed, the TBRS model (Barrouillet & Camos, 2015) assumes that there is,

in complex span tasks, a rapid switching between processing and storage, and it has been shown that concurrent articulation could slow down switching processes (Saeki & Saito, 2004). This greater difficulty in switching could reduce the number of digits processed within the 6-second intervals. However, the detrimental effect on processing of the concurrent maintenance of a memory load at span should not strongly differ from what was observed in the previous experiments. Indeed, according to the TBRS model (Barrouillet & Camos, 2021), this effect is due to the attentional capture involved by the refreshing of memory traces, and participants were presented with a memory load corresponding only to the letters they were able to maintain through attention. Thus, the attentional demand for maintaining memoranda by refreshing should remain the same as in previous experiments, and hence the effect of this maintenance on processing.

Method

Participants

Participants were 24 undergraduate students (23 females and 1 male; age ranging from 18 to 22 years) at the University of Clermont Auvergne (France) who received course credits for their participation. All had normal or corrected-to-normal vision. None of them participated in the previous experiments.

Material and general procedure

The material and procedure were the same as in Experiment 1, except that articulatory suppression was introduced in all the phases of Experiment 3. Participants had to repeat out loud the syllables “ba-bi-bou” during all the tasks. Before each task, in order to familiarize participants with the expected rhythm of articulation (one syllable per second), they were invited to press a key for hearing this rhythm (series of beeps played by the computer) as long as they wanted. For the tasks involving serial recall (memory titration, single memory task and dual tasks), participants were asked to initiate their articulation when hearing a single

beep presented before the first letter and to continue articulating “ba-bi-bou” until the recall screen. For the processing titration and the single processing task, this beep occurred before the first diamond and participants articulated “ba-bi-bou” until the end of the trial. The experimenter who was sitting in the experimental cubicle for the entire duration of the experiment (as in the previous experiments) monitored the compliance of this procedure by ensuring that participants kept doing articulatory suppression at the expected rhythm during the entire trials. If a participant failed in a trial to comply with this instruction, the experimenter gave a reminder at the end of this trial.

Results

The same analysis on memory and processing accuracy were performed as in the previous experiments, with the same correction for guessing. As in the previous experiments, data from four participants were removed from the analyses because they did not reach the criterion of five “perfect trials” in both dual tasks, but the performance of one participant was kept because she completed five “perfect trials” in the dual task with processing prioritization, but only four in the dual task with memory prioritization (see Appendix A for performance of the removed participants). The sample for this experiment thus included 20 participants.

Titration.

On average, participants achieved a memory span of 3.00 letters (95% CI [2.51, 3.49]) and a processing span of 5.55 digits (95% CI [4.98, 6.07]) correctly judged per 6-second interval. As we expected, the mean memory span was far lower than in Experiment 1 (5.95 letters) showing that the concurrent articulation impaired the maintenance of letters. The mean processing span was also slightly lower than in the two previous experiments (6.70 and 6.00 digits for Experiments 1 and 2, respectively, Table 1), indicating that articulatory suppression had also a detrimental effect on parity judgment that could involve some verbal dimension.

Comparison between single tasks and perfect trials in dual tasks.

In this third experiment, the mean number of trials needed to reach the criterion of five “perfect trials” was of 10.4 (95% CI [8.3, 12.5]) in the dual task with priority on memory, and of 9.4 (95% CI [8.2, 10.6]) in the dual task with priority on processing.

Concerning accuracy on memory and for the same reasons as in Experiment 1, participants performed better in the dual task with priority on memory ($M = .99$, 95% CI [.98, 1]) than in the single task ($M = .89$, 95% CI [.84, .90]), $BF_{10} = 1.17 \times 10^2$. According to our expectations, accuracy on memory was better in single task ($M = .89$) than on the dual task with priority on processing ($M = .28$, 95% CI [.17, .39]), $BF_{10} = 5.12 \times 10^7$. In terms of numbers of letters recalled in correct position when priority was given to processing, this performance corresponded to a mean memory residual 0.66 letters (95% CI [0.43, .89], Figure 8 and Table 1). This low rate of correct recall makes the analysis of serial positions hazardous. Figure 9 displays serial position curves for recall in correct position or not as a function of input position in participants with a span of 3, which was the most frequent among our sample ($n = 10$). Contrary to what was observed in Experiment 1, there was no clear primacy effect and the difference between recall in correct position and simple recall was less pronounced. Whereas the rate of letters recalled in correct position among those that were recalled was only .44 in Experiment 1, it increased to .72 in the present experiment. This was probably due to the fact that, the series to be recalled being shorter, it was easier to identify the position at which the letters retrieved had been presented and the probability of a correct positioning by chance was higher.

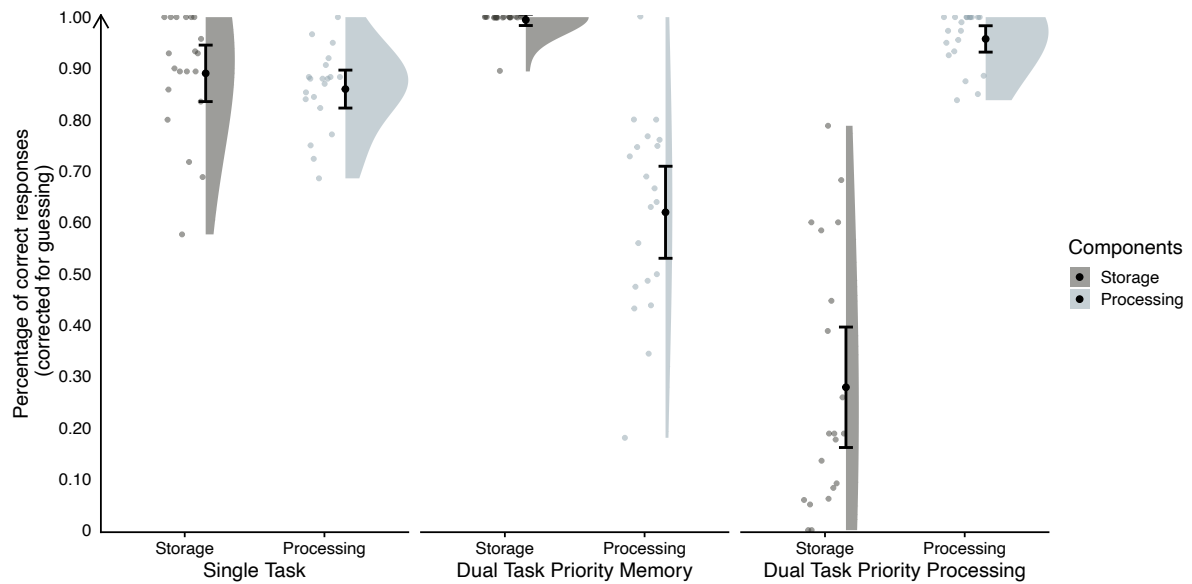


Figure 8

Mean accuracy on memory and processing for Experiment 3 as a function of the type of task (single vs. dual) and priority (set on memory vs. processing). Error bars represent 95% confidence intervals

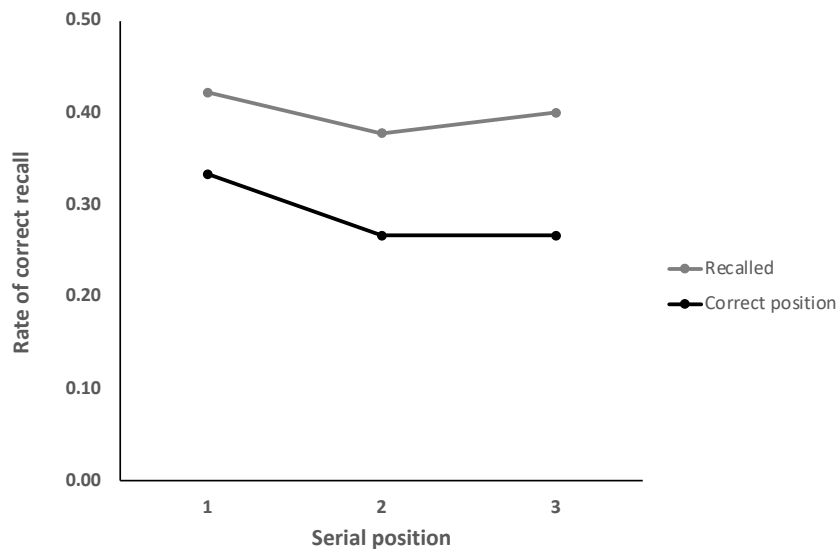


Figure 9

Rate of recall at any position (Recalled) and in correct position (Correct position) as a function of serial position in Experiment 3 for participants with a memory span of 3 ($n = 10$)

Concerning accuracy on processing, participants performed better in the dual task with priority set on processing ($M = .96$, 95% CI [.94, .98]) than in the single processing task ($M = .86$, 95% CI [.83, .89]), $BF_{10} = 7.28 \times 10^6$. More interestingly, and according to our

expectations, participants accuracy on processing was better in this single task ($M = .86$) than in the dual task with priority set on memory ($M = .62$, 95% CI [.54, .70]), $BF_{10} = 2.70 \times 10^4$. Participants were, in this latter task, able to correctly judge, on average, 3.31 digits (95% CI [2.96, 3.66]) per 6-second intervals. This performance was significantly lower than in the dual task with priority set on processing (5.26), $BF_{10} = 6.58 \times 10^5$.

Discussion

Whereas, under articulatory suppression, the processing residual remained relatively high (3.31 digits processed in 6 seconds) and unchanged compared with the previous experiments (63%, 64%, and 62% of the span in Experiments 1, 2, and 3, respectively), memory residual, which was only 1.30 and 1.62 letters in Experiments 1 and 2, respectively, dropped in the present experiment below 1 (0.66, Table 1). This was not a null residual, but it should be noted that in 30% of the trials, participants did not recall any of the presented letters, even in an incorrect serial position, and in half of the trials they did not recall any letter in correct position. Only 5 out of the 20 participants had a mean of correct recall higher than 1 when prioritizing processing (max = 1.8). This indicates that impeding any strategy of active maintenance, either through attention or articulatory rehearsal, had a devastating effect on memory. The mechanisms by which forgetting occurs in short-term or WM has been the subject of intense and continuing debates. While some studies led to the conclusion that short-term memory decays with time when maintenance activities are prevented (e.g., Brown, 1958; Peterson, & Peterson, 1959; Reitman, 1974), others called this conclusion into question (e.g., Reitman, 1971; Roediger, Knight, & Kantowitz, 1977; Shiffrin, 1973) and attributed forgetting, when observed, to interference. This question is not yet settled, with authors assuming that decay is, along with interference, a source of forgetting in the short term (e.g., Barrouillet, Uittenhove, Lucidi, & Langerock, 2018; Cowan & Aubuchon, 2008; Lucidi et al., 2016), while others deny any role of time per, favoring an interference-only hypothesis (e.g.,

Berman, Jonides, & Lewis, 2009; Lewandowsky, Oberauer, & Brown, 2009; Oberauer, Farrell, Jarrold, & Lewandowsky, 2016). Whatever its source, the present results indicate that this forgetting is dramatic when a concurrent task is performed at individual's maximum capacity and rehearsal prevented by concurrent articulation.

This memory residual of 0.66 letter can be compared to the 2.34 letters obtained by Belletier et al. (2021) using a Brown-Peterson paradigm. The transition from the Brown-Peterson to the complex span paradigm has resulted in a reduction of 72% of the memory residual. There is no reason to suppose that this Brown-Peterson paradigm, which used the same intervening parity judgment task and the same concurrent articulation as we used here, offered greater opportunities than the complex span task for the active maintenance of memory traces in WM. Thus, it must be concluded, as we suggested, that most of the memory residual observed by Belletier et al. (2021) came from mnemonic systems outside of WM. The origin of this small residual and the remarkable robustness of the processing component in face of storage demands will be addressed in following general discussion. However, before drawing firm conclusions from these results, we conducted a last test of our hypotheses.

Experiment 4

The aim of this fourth experiment was twofold. First, it aimed at replicating the results of Experiment 3, and more precisely that memory residual almost vanishes under articulatory suppression. Though providing clear results concerning the asymmetry between processing and memory residuals, the sample size we used in the previous experiment could be judged as modest; replicating these results in a larger sample should strengthen our conclusions. Second, although the size of the memory residual was, as we predicted, smaller with a complex span task than a Brown-Peterson task paradigm, this contrast relies on a between-experiment comparison. A safer way to assess the difference between memory residuals

measured through the two paradigms is to compare them in a single experiment. For this purpose, Experiment 4 compared the processing and memory residuals produced by the titration and perfect-trials procedure applied to both the complex span paradigm used in the present study and the Brown-Peterson paradigm adapted from Belletier et al. (2021) in a between-subject design involving a larger sample of participants, all the tasks being performed under articulatory suppression. As far as the complex span paradigm is concerned, we expected the same asymmetry between processing and memory residuals we observed in Experiment 3, with a memory residual lower than 1 item. Moreover, we expected that this memory residual should be smaller than that observed when using the Brown-Peterson paradigm as it was the case when comparing Experiment 3 with the results of Experiment 2 in Belletier et al. (2021), thus confirming that different memory systems are at play in the two paradigms.

Method

Participants

Participants were 96 undergraduate students at the University of Fribourg (Switzerland) who received course credits for their participation. They were randomly affected to the complex span (46 females and 2 males; age ranging from 18 to 26 years) and the Brown-Peterson paradigm (42 females and 6 males; age ranging from 18 to 26 years). All participants had normal or corrected-to-normal vision. None of them participated in the previous experiments. Ethic approval for this experiment was obtained from the institutional review board of University of Fribourg (Switzerland).

Material and general procedure

For the complex span paradigm, the material and procedure were the same as in Experiment 3 of the present study. For the Brown-Peterson paradigm, material and procedure were adapted from Experiment 2 in Belletier et al. (2021). First, participants' memory and

processing spans were assessed through a titration procedure following the same rationale as in the present study (i.e., staircase procedure with two trials per length and a 90% correct criterion). For memory, the first two trials involved four letters presented sequentially on the center of the screen for 1000ms each. Participants had to remember the letters for a duration of 12s during which a blinking circle was displayed in the center of the screen, the number of which was arbitrarily fixed to ten (950 ms on and 250 ms off). For processing, participants saw a number of placeholders (diamond shapes) equal to their memory span that appeared for 900 ms with an ISI of 100 ms followed by a processing phase of 12s during which digits (from 1 to 9 picked up at random) appeared successively on screen for parity judgment. The titration began by two trials with eight digits. The ISI between digits was set to 250 ms and the duration of each digit equal to $(12 - (n \times 250)) / n$ where n is the number of digits to be presented in the 12-second retention interval. Both titration tasks were performed under articulatory suppression. At the beginning of each trial, a ready signal appeared before the first letter or placeholder, and participants were instructed to start uttering the three syllables “*ba bi bou*” aloud until the end of the trial. As in Experiment 3, participants had been previously familiarized with the rhythm of articulation (one syllable every 1000 ms) and trained to follow it. For memory tasks, articulatory suppression stopped when a signal for recall appeared on screen at the end of the processing phase. The titration tasks were preceded by three training trials each with three letters for memory and six digits for processing. For sake of comparison, the order of the task was the same as in the complex span paradigm and the titration on memory was systematically performed first (see Exp. 1).

The titration phase was followed by two single tasks for memory and processing, each involving five trials set at span. Each task was preceded by three training trials with three letters and six digits. Then, in the same way as for the complex span task, participants performed two dual-tasks, one with prioritization on memory and the other on processing.

They first saw the letters to memorize, with the number of letters presented equal to their individual span in memory. They then had to judge a number of digits equal to their individual processing span for a period of 12s. Finally, they were asked to recall the letters. For both tasks, participants had 20 attempts to produce “five perfect trials” as in the other experiments of the present study. The dual tasks were preceded by three training trials (with three letters followed by six digits) without any prioritization instruction.

Results

As for the previous experiments, performance in the complex span and Brown-Peterson tasks from participants who did not reach the criterion of five “perfect trials” in both dual-task conditions was discarded from analysis (i.e., 3 and 5 participants for complex span and Brown-Peterson task, respectively), but performance of those participants who fell short at reaching this criterion and completed five “perfect trials” in the dual task with memory prioritization, but only four in the dual task with processing prioritization was kept (one and two participants, respectively). Similarly, performance of one participant who achieved five “perfect trials” in the processing prioritization condition for the complex span task, but only four in the memory prioritization was also included in the analysis. Hence, data from 45 participants in complex span task and 43 in Brown-Peterson task were involved in the following analysis (see Appendix A for performance of the removed participants).

To reach the criterion of five “perfect trials”, the mean number of trials needed by the participants was 10.82 (95% CI [9.72, 11.92]) and 10.05 (95% CI [8.92, 11.18]) in the dual task with priority on memory for the complex span and Brown-Peterson tasks, respectively, and 11.07 (95% CI [9.91, 12.23]) and 10.26 (95% CI [9.10, 11.42]) in the dual task with priority on processing for the two tasks, respectively.

Titration.

On average, participants achieved a memory span of 4.16 letters (95% CI [3.73, 4.59]) and a processing span of 6.20 digits (95% CI [5.86, 6.54]) per 6 second intervals for the complex span task. For the Brown-Peterson task, they achieved a memory span of 3.72 letters (95% CI [3.48, 3.96]) and a processing span of 12.42 digits (95% CI [11.61, 13.23]) for the 12 second retention interval (Table 1).

Comparison between single tasks and perfect trials in dual tasks.

The first aim of this final experiment was to replicate the results of Experiment 3, especially the almost disappearance of a memory residual in complex span task under articulatory suppression. To this aim, and as in our previous experiments, a series of Bayesian paired sample t-tests was performed on accuracy in the memory and processing tasks to compare the performance in memory and in processing between single- and dual-task conditions.

As far as the complex span task is concerned, results replicated what was observed in Experiment 3 (Figure 10). Memory accuracy was higher in the dual task when priority was given to memory ($M = .99$, 95% CI [.98, 1]) than in the single task ($M = .87$, 95% CI [.84, .91]), $BF_{10} = 8.032 \times 10^6$, while it was largely lower than in the single task when priority was given to processing ($M = .16$, 95% CI [.10, .21]), $BF_{10} = 7.666e +25$. This led to a difference in memory accuracy between the two dual-task conditions, $BF_{10} = 4.522 \times 10^{28}$. Similarly for processing accuracy, it was higher in the dual task when priority was given to processing ($M = .93$, 95% CI [.92, .95]) than in the single task ($M = .84$, 95% CI [.81, .86]), $BF_{10} = 3.444 \times 10^{15}$, while it was smaller than in the single task when priority was given to memory ($M = .52$, 95% CI [.47, .57]), $BF_{10} = 3.189 \times 10^{13}$. The two dual-task conditions differed on processing accuracy, $BF_{10} = 4.625 \times 10^{17}$. This finding confirmed the drastic reduction of the memory accuracy under articulatory suppression when priority was given to processing, as well as the

asymmetry between memory and processing residuals, processing being more resistant when priority is given to memory than *vice versa*.

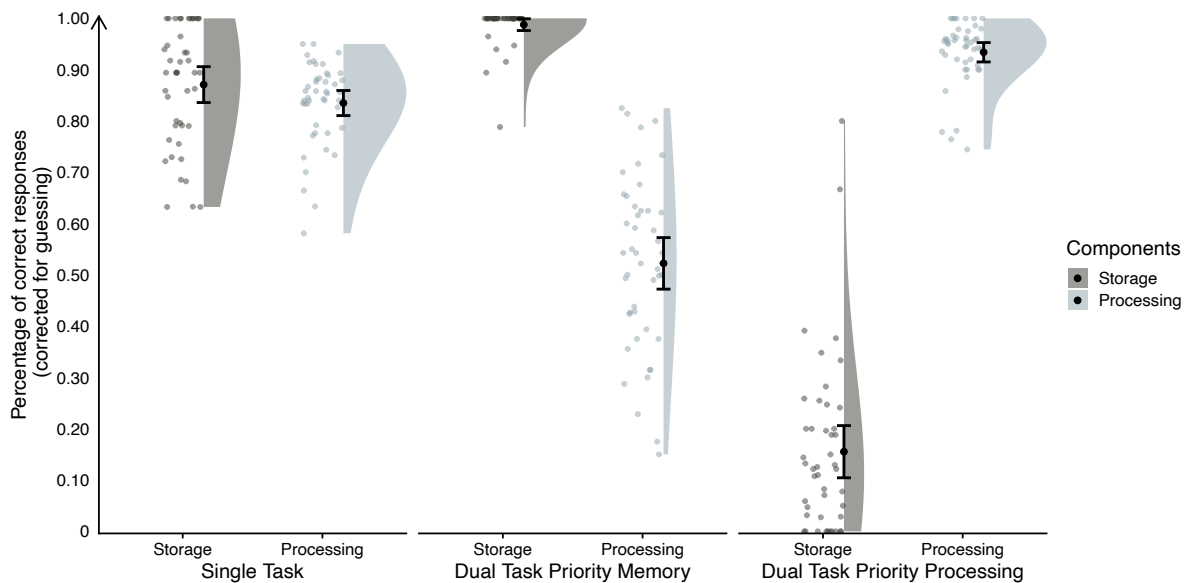


Figure 10

Mean accuracy on memory and processing for the complex span paradigm in Experiment 4 as a function of the type of task (single vs. dual) and priority (set on memory vs. processing). Error bars represent 95% confidence intervals

The same analyses were performed in the Brown-Peterson task, replicating Belletier et al.'s (2021) findings (Figure 11). Memory accuracy was higher in the dual task when priority was given to memory ($M = .97$, 95% CI [.95, .99]) than in the single task ($M = .86$, 95% CI [.82, .90]), $BF_{10} = 2.094 \times 10^8$, while it was lower than in the single task when priority was given to processing ($M = .50$, 95% CI [.43, .57]), $BF_{10} = 1.108 \times 10^{11}$. This led to a difference in memory accuracy between the two dual-task conditions, $BF_{10} = 4.724 \times 10^{14}$. Similarly for processing accuracy, it was higher in the dual task when priority was given to processing ($M = .96$, 95% CI [.93, .98]) than in the single task ($M = .85$, 95% CI [.82, .88]), $BF_{10} = 3.191e + 10$, while it was smaller than in the single task when priority was given to memory ($M = .66$, 95% CI [.61, .71]), $BF_{10} = 2.992 \times 10^7$. Thus, the two dual-task conditions differed on processing accuracy, $BF_{10} = 2.484 \times 10^{12}$. This finding confirmed in the Brown-Peterson task

both the reduction of memory accuracy when priority was given to processing and the asymmetry between memory and processing residuals.

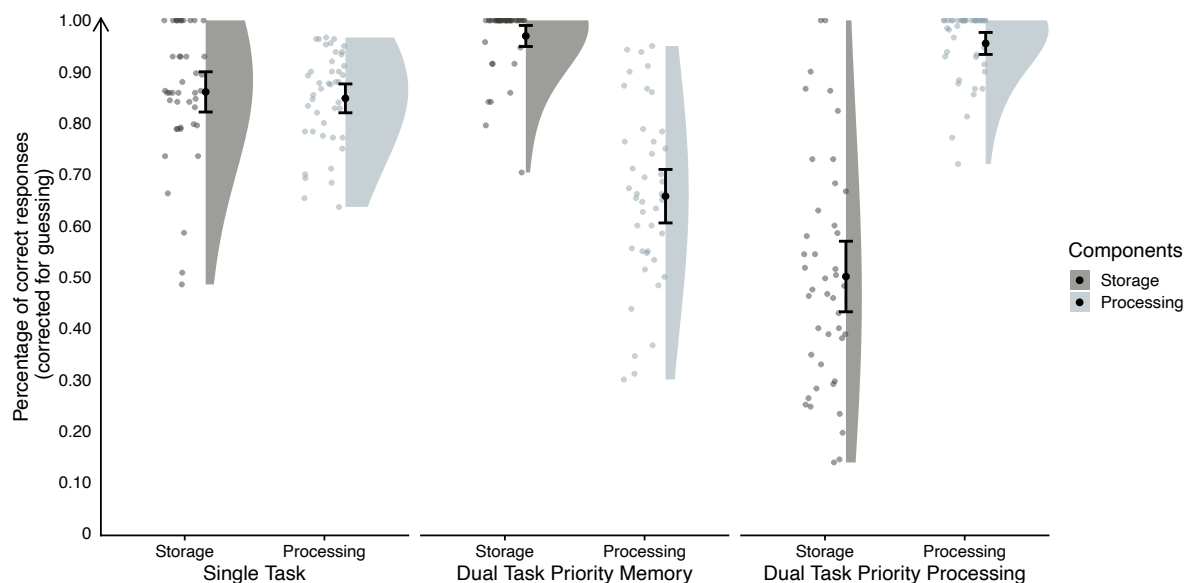


Figure 11

Mean accuracy on memory and processing for the Brown-Peterson paradigm in Experiment 4 as a function of the type of task (single vs. dual) and priority (set on memory vs. processing). Error bars represent 95% confidence intervals

Comparison between complex span and Brown-Peterson tasks.

The second aim of this experiment was to compare the complex span and the Brown-Peterson tasks on their memory and processing residuals. Despite expecting an asymmetry among the residuals for the two tasks, we expected that the complex span task would lead to a smaller memory residual than the Brown-Peterson task, because we assumed that the two tasks do not rely on the same memory systems. Our results fully confirmed these predictions.

In a Bayesian ANOVA performance in the dual task conditions with prioritization on memory vs. on processing (within-subject factor) was compared between complex span and Brown-Peterson tasks (between-subject factor) with default settings for the priors. The full model that includes the main effect of tasks and conditions and their interaction was the best model, $BF_{10} = 9.94 \times 10^{24}$. This model was more than 700 times better in accounting for the

data than the second-best model that included only the main effects, $BF_{10} = 1.40 \times 10^{22}$.

Residuals were larger in the Brown-Peterson than in the complex span task, and in both tasks, the residual was larger in processing than memory, confirming the asymmetry already observed ($BF_{10} = 7.58 \times 10^{12}$, for complex span, and $BF_{10} = 112.39$, for Brown-Peterson). However, difference between residuals was larger in the complex span task (Figure 12). As we predicted, the memory residual was lower in the complex span than the Brown-Peterson task, $BF_{10} = 2.796 \times 10^9$, though remaining greater than zero, $BF_{10} = 7.50 \times 10^4$. In terms of letters recalled in correct serial position, the mean memory residual in the Brown-Peterson paradigm was 1.80 (95% CI [1.57, 2.03]), whereas it was only 0.56 (95% CI [0.41, 0.71]).

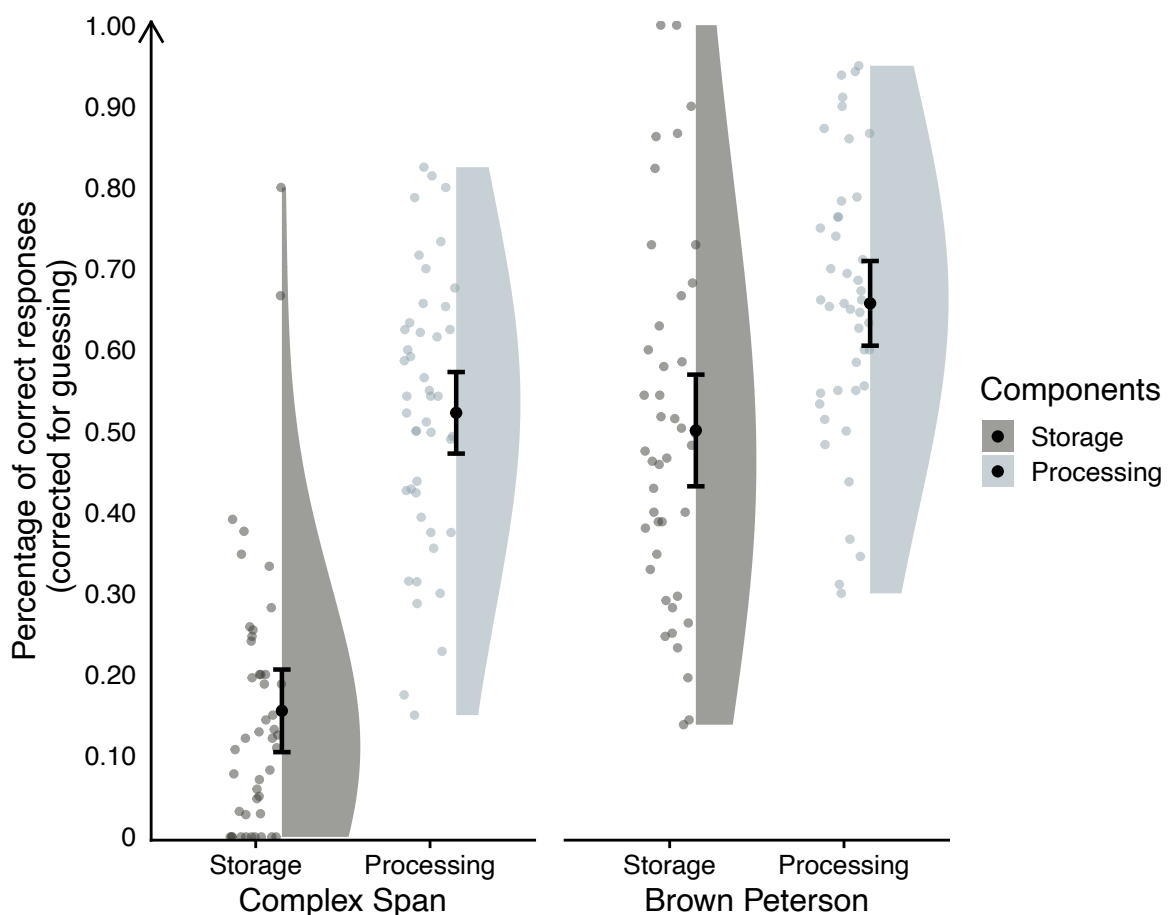


Figure 12

Comparison of the memory and processing residuals observed in the complex span and Brown-Peterson paradigms in Experiment 4. Error bars represent 95% confidence intervals

Discussion

This final experiment aimed at replicating the results observed in Experiment 3 with a complex span task paradigm under articulatory suppression, and at comparing the observed residuals with those issued from a Brown-Peterson paradigm as we used in Belletier et al. (2021). The present experiment confirmed the asymmetry between processing and memory residuals. When using a perfect-trial procedure, the processing component turns out to be less affected by memory prioritization than this latter component is when priority is given to processing. As we predicted, this was true with the complex span, but also with the Brown-Peterson paradigm. In terms of residuals, the memory residual in the complex span task was once more very small, and even smaller than in Experiment 3 (0.66 and 0.56 letters recalled in correct position in Exp. 3 and 4, respectively). This confirms that, when priority is given to processing, participants have great difficulties maintaining a single letter along with its serial position. It is worth noting that, when serial position was not taken into account at recall (free recall scoring), the residual was of course higher, but did not exceed a single letter (0.98). This one-letter memory residual could correspond to the item retrieved from long-term memory that Cowan et al. (2012) found necessary for verbal WM models to work. It can also be noted that, with memory lists of about 4 items in average (the mean span was 4.16, Table 1), the chance level for correctly positioning this residual letter is about .25, which is not so far from the memory residual of 0.56 letter recalled in correct position we observed. As we already observed in Experiment 3, prioritizing processing in a complex span task almost abolishes memory traces when articulatory rehearsal is prevented by articulatory suppression.

Interestingly, and as we expected, this residual is larger when WM functioning is assessed through a Brown-Peterson paradigm. The processing-storage asymmetry is still

there, but memory performance while prioritizing processing reached half of the memory span. This residual of 1.80 letters recalled in correct position increases to 2.26 with a free recall scoring. As we already suggested, this higher resistance of the memory component in the Brown-Peterson paradigm might be due to the peculiarities of this paradigm. The presentation of memory items in immediate succession could facilitate their grouping into sequences of two or three letters at the start or the end of the series, as recently suggested by Ward (2022). Such sequences could be retrieved from episodic memory, even after a demanding intervening 12-second processing episode.

By contrast, though there was a difference between the two paradigms in terms of processing residual, this difference was less pronounced than for memory (.66 and .52 for processing residuals in Brown-Peterson and complex span task, respectively, compared with .50 and .16, respectively, for memory). This suggests, as we surmised, that the peculiarity of the Brown-Peterson paradigm facilitates storage, possibly because other mnemonic systems than WM come into play. In the same way, it has been reported that using a Brown-Peterson task can abolish the cognitive load effect observed in complex span task on visuo-spatial material (Ricker & Vergauwe, 2020, 2022). Nonetheless, despite this relative facilitation of the memory component, the processing-storage asymmetry remains with the Brown-Peterson task. It is on this asymmetry that the following general discussion focuses.

General discussion

The aim of the present study was to shed light on how our cognitive system resolves the challenge of maintaining information active while carrying out concurrent activities, and of achieving decent performance in demanding tasks while maintaining directly accessible the information needed for their resolution. The conception of a system devoted to this dual function, a WM which would be the seat of the maintenance of information and its processing, soon appeared fraught of difficulties. The seminal investigations by Baddeley and

Hitch (1974) suggested that the register at short term of the modal model of Atkinson and Shiffrin (1968), which was assumed to fulfill this dual function, was unsuitable for this role. Maintaining a memory load at span, which should have depleted the capacity of the short-term register, had only a negligible effect on complex and demanding activities like reasoning. Baddeley and Hitch (1974) and subsequently Baddeley (1986; Baddeley & Logie, 1999) or Logie (Logie et al., 2021) concluded that the two functions are probably fulfilled by distinct systems. At the same time, other studies (e.g., Barrouillet et al., 2004; Vergauwe et al., 2014), and more recently carefully controlled investigations (Belletier et al., 2021) contradicted this claim by demonstrating reciprocal dual-task costs between processing and storage.

The present study confirmed this latter observation. In four successive experiments, maintaining a memory load at span degraded the performance on a concurrent parity judgment task on digits, and sustaining in this task a level of performance at least equal to that achieved when performed in isolation resulted in a dramatic decrease of memory performance, with less than one letter recalled in correct position in the most extreme case (i.e., with a complex span task performed under articulatory suppression). However, pushing the difficulty of one of the two components at its maximum did not result, even in the complex span task, in a complete collapse of the other. We could say, as Baddeley did, that we ‘found the cognitive system to be much more robust than anticipated’ (Baddeley 1986, p. 69). Nonetheless, this robustness proved asymmetric and mainly concerned processing. Whereas participants preserved more than 60% of their processing span when loading their short-term memory at span, performing at their best in the parity task only left accessible less than 30% of their memory capacity. Such an asymmetry, though less pronounced, was also observed with a Brown-Peterson paradigm. This asymmetry suggests that, although there is certainly a resource-sharing between processing and storage in WM, it might be more

complex than the mere sharing of a single resource, or mental space, that could be flexibly and indifferently allocated to both functions. In the following, we shall address in turn the questions about WM resources that are raised by the asymmetric residuals we observed, the origin of the small memory residual, and the putative reasons for the asymmetric limitations of memory and processing in WM.

The robustness of the cognitive system and the question of resources

One of the main findings of the present series of experiments is that the resource sharing revealed by the dual-task costs observed does not correspond to the sharing of a common resource that can be flexibly and indifferently allocated to processing or storage in its totality. This constrains WM models that must account for a resource sharing, but bounded in nature. We have already noted that the resource-sharing phenomenon rules out models assuming distinct and independent resources for processing on the one hand and storage on the other (Baddeley, 1986; Baddeley & Logie, 1999; Logie, 2011; Logie et al., 2021). However, it should be noted that our results are not at odds with the seminal proposals of Baddeley and Hitch (1974).

Having observed that maintaining one or two digits had no effect on a concurrent reasoning task, and that the maintenance of six digits had only an effect on speed, but not on reasoning efficiency, Baddeley and Hitch (1974) reasoned that processing and storage were probably underpinned by distinct systems, namely a central executive devoted to processing and a phonemic loop devoted to verbal storage. However, the small effect of storage on processing when six digits had to be maintained suggested that the independence between the two functions is relative. Baddeley and Hitch surmised that, when the phonemic loop is overloaded, the capacity of which was estimated at three or four items, some workspace within the central executive could be allocated to the storage of the supernumerary items. It is worth noting that this initial conception of a subpart of the central executive that could be

recruited for storage purpose, a conception subsequently abandoned by Baddeley (1986), could account for the asymmetry we observed between processing and storage residuals. If only a part of the central executive workspace can be diverted from processing to storage purpose, for example when maintaining a memory load at span, a large part of this workspace remains available for processing, hence the large processing residual we observed. By contrast, when the cognitive demand of processing increases, this small part of the workspace usable for storage would be recruited for processing, hence the small memory residual we observed, a residual virtually null (less than one item) when storage in the phonemic loop was prevented by articulatory suppression in a complex span task (Experiments 3 and 4).

However, Baddeley and Hitch's (1974) proposal can only account for the large processing residual and the small memory residual if one assumes that only a part of the resources available for processing can be used for storage. In fact, the other models of resource sharing should adopt the same restriction to account for our results. For example, Case (1985) assumed that a total processing space is shared between a short-term storage space and an operation space. Accounting for the dissymmetry between residuals would require fixing some limit to the space that the short-term storage can occupy, while the operation space could be stretched to the limits of the total processing space. A similar assumption should be added to the TBRS model (Barrouillet & Camos, 2015, 2021) we evoked in introduction. Accounting for a large processing residual obliges to assume that the maintenance of items in WM, even at span, does not continuously occupy attention, the remaining free time being available for processing. By contrast, it must be assumed that such a limit does not exist for processing, the optimal performance necessitating an almost continuous allocation of attention that reduces memory residual to less than one item.

Although Cowan's (1988, 2010; Cowan et al., 2021) embedded process model or Unsworth and Engle's (2007) model do not mainly focus on the interplay between processing

and storage or resource-sharing, a similar restriction might be introduced. In both models, processing and storage draw upon the same capacity-limited attention system. In the embedded process model, attention-demanding activities trade-off with the storage of information within the focus of attention. This focus is assumed to hold up to four chunks, explaining the limitations of WM capacity (Cowan, 2001). If maintaining a memory load at span requires the continuous occupation of the four slots of the focus of attention, this would prevent any concurrent attention-demanding activity to take place and the processing residual should be virtually null, contrary to what we observed. However, introducing the temporal dimension proper to the TBRS model could correct this drawback. It could be imagined that even when maintaining a memory load at span and when the four slots of the focus of attention are occupied, attention could be diverted for processing purpose. In this case, the memory items would be temporarily displaced into the activated part of LTM, from which they could be safely retrieved if processing episodes are sufficiently short to avoid their complete decay, hence a substantial processing residual. By contrast, the continuous occupation of the focus of attention by demanding activities would prevent any storage of memory items, hence the small memory residual that would be reduced to the few items retrieved from LTM. In Unsworth and Engle's model that distinguishes between primary and secondary memory, the primary memory would play the same role as the focus of attention in Cowan's model, maintaining up to four items (Unsworth & Engle, 2007). In complex span task, the concurrent processing is assumed to displace memory items toward the secondary memory from which they can be retrieved. The same introduction of a temporal dimension as we suggested for Cowan's model would explain why it remains possible to achieve decent performance in a concurrent task while maintaining a memory load at span. Note that in this case, the two models would not strongly differ from the TBRS model.

Thus, whatever the nature of the resource shared between processing and storage, accounting for the asymmetry between the two residuals requires to assume that processing can benefit from the allocation of this resource up to its limit, whereas the optimal memory performance (i.e., span performance) can be achieved without this resource being depleted. For the models using the spatial metaphor of a workspace (Baddeley & Hitch, 1974; Case, 1985), it must be imagined that storage can only occupy a limited part of it. For the models envisioning the shared resource as some energy supply like attention (Cowan, 2010; Cowan et al., 2021; Unsworth & Engle, 2007), it seems that the introduction of the temporal dimension at the heart of the TBRS model (Barrouillet & Camos, 2015, 2021) is needed for understanding the phenomenon. We will discuss later possible explanations for the fact that storage does not deplete WM resources.

The origin of the memory residual

When the demand of the parity task was pushed at the limits of the participants' capacities, recall performance fell down but some memory residual remained. In Experiments 1 and 2, an average of 1.30 and 1.65 letters, respectively, was still recalled in correct position, a number that fell down to 0.66 under articulatory suppression in Experiment 3, and to 0.56 in Experiment 4. From which memory system do these recalled letters come from? The serial position curves in Experiment 1, with a primacy effect and no or negligible recency effect, evoke what is usually observed in immediate serial recall (ISR). As such, this pattern would suggest an active maintenance of items in WM (Jahnke, 1963; Madigan, 1971; Lewandowsky, 1999), with the restriction that the primacy effect was attenuated when compared with an ISR task, the rates of recall of the first letters being very low (.37 and .25 for the two first letters). However, we believe that it is not warranted that the recalled letters had been actively maintained and retrieved from WM, at least for two reasons.

First, an active maintenance, either by attentional refreshing or articulatory rehearsal, would have mainly benefited the first letters for which there are more opportunities of refreshing or rehearsal in a complex span task paradigm. However, all the letters were as accessible as each other at recall, whatever their input serial position (see Figure 4), suggesting that there was no active maintenance. The refreshing mechanism might have been entirely prevented by the high rate at which the parity task had to be performed, and the articulatory rehearsal could have been avoided by many participants because it hindered parity judgments, as suggested by the lower processing span under concurrent articulation in Experiments 3 and 4.

Second, the recency effect that appeared with the partial serial recall used in Experiment 2 has often been associated in the literature with the passive maintenance of short lists of items. For example, Palladino and Jarrold (2008) as well as Bunting, Cowan and Saults (2006) observed that in running span tasks in which participants wait passively for the end of the list before trying to recall items, recall exhibit a pronounced recency effect. Moreover, the pattern of recall observed in Experiment 2 echoes what is observed in free recall of lists that exceed WM capacity (Crowder & Greene, 2000). For example, Tan and Ward (2007, Exp. 1) visually presented participants with lists of eight words for either a forward or a free output order at recall, participants being informed of this output order either before (precued condition) or after (postcued condition) encoding. In both conditions, the forward output order resulted in the typical serial position curve of ISR with strong primacy and small recency effects, but a recency effect occurred with the free output order. Moreover, Tan and Ward observed that, with free output order, participants began by recalling the last presented words. The partial serial recall of our Experiment 2 was not a free recall, but it is possible that when informed of the three serial positions probed at the end of the trial, and when one of these positions was close to the edges of the series, the resulting increased

distinctiveness facilitated the retrieval of the letter associated with this position (Bjork & Whitten, 1969; Johnson, 1991). This is all the more possible as this process most often concerned only a single letter (the number of letters recalled among the three positions probed was only 0.80, 74% of the participants recalling in average one letter or less). When one of the last positions was probed, retrieving the corresponding letter and keeping it in mind until filling the probed position involves a retrieval process akin to that probably used in the postcued free recall procedure of Tan and Ward's study. Of course, when one of the first positions was probed, its proximity with the beginning of the list made the corresponding letter more salient and facilitated its retrieval. In the same way as it is unlikely that Tan and Ward's participants actively maintained eight words in WM (word span in adults is about five), the few letters constituting the memory residuals in our study could have been retrieved from secondary or LTM, their position at the edges of the series facilitating retrieval.

The collapsing of the memory residual in Experiments 3 and 4 (on average, 0.66 and 0.56 letter recalled, respectively) corroborates the hypothesis of no item actively maintained through attentional refreshing when the demand of the processing component was pushed at its maximum. Assuming, as Cowan et al. (2012) did, that recall in WM tasks involves a LTM component of about one chunk, it is possible that the memory residual in Experiments 3 and 4 was drawn from this LTM component and that it contributed to the residuals observed in the previous experiments. Of course, we do not have incontrovertible evidence that memory residuals were entirely drawn from LTM and that a processing at span prevents any active maintenance in WM. However, the small size of these residuals, especially when articulatory rehearsal was prevented, indicates at least that it is almost impossible to hold information in WM while reaching an optimal performance in a concurrent activity.

On the asymmetric limitations of working memory functions

Whereas prioritizing processing reduced the memory residual to less than one item, more than 70% of the performance achieved in the single processing task was preserved while maintaining a memory load at span. This means that prioritizing processing depletes the available resources and strongly limits concurrent storage, but prioritizing storage does not. The robustness of the cognitive system Baddeley (1986) noticed only holds for processing, but not for storage. At a first glance, it seems surprising that the storage function leaves unused a large part of WM resources, while, aside from the phonological loop, they can be almost entirely recruited for processing. What is the purpose of leaving a part of the available resources unused when targeting an optimal performance in a given activity?

A potential answer to this question could be that an adaptive system that has evolved for the maintenance and processing of information must remain able to fulfill its dual function even in the most extreme conditions. It must remain able to register and keep some incoming information while carrying out intense cognitive operations, and to maintain a minimal level of activity while keeping in mind a high memory load. Assuming that the cognitive structure we call WM has evolved for the temporary maintenance and processing of a small amount of information during ongoing cognition (Baddeley, 2007), one of the properties that such a structure must have is to avoid that maintaining the required information decisively hinders its processing. If WM resources could be depleted by the activity of maintenance, this maintenance would become of no purpose as making impossible the processing of the maintained information. Such a WM would be dysfunctional. Note that the converse is not true and that the totality of WM resources must be able to be allocated to processing when it concerns information that remains permanently accessible in the environment and, thus, has not to be maintained in short-term memory. This is for example the case of the quality control tasks in manufacturing when units have to be tested at a high rate while avoiding misses and

false alarms. These tasks require an almost continuous allocation of attention but do not involve concurrent maintenance.

Several ways can be envisioned to attain the requested asymmetry between processing and storage. A first would be to have distinct and separate resources for the two functions. However, the large dual-task costs systematically observed in the present and previous studies demonstrate that this is not the case. A second way is to imagine a proper resource for processing along with a resource available for storage that could be entirely recruited by processing when needed, plus an additional system for verbal storage based on articulatory rehearsal. Such a solution corresponds to Baddeley and Hitch's (1974) idea of a part of the central executive that could be occasionally used for storage when the phonemic loop is overloaded. It could also be formulated as a tripartite system, with a component exclusively devoted to verbal storage, the phonological loop, an equivalent component exclusively devoted to processing, and a third multifunction system that can be indifferently used for processing or storage. In both cases, we have to imagine, among the resources available for processing, a subpart of a special nature appropriate for storage while the remaining could be used for processing only. Considering that a specific system like the phonological loop does exist for verbal storage (Barrouillet, Gorin, & Camos, 2021), there is *prima facie* no reason to reject an equivalent system for processing, along with a multifunction resource. The difficulty here is to understand why storage could use a part, but not the totality, of the resources that can be used for processing. It must be noted that the solution initially envisioned by Baddeley and Hitch (1974) of a subpart of the central executive that could be used for storage purpose was subsequently abandoned by Baddeley (1986; Baddeley & Logie, 1999). Thus, although this solution cannot be rejected, its abandonment by its very instigators suggests that it involves insurmountable theoretical difficulties.

A third solution would be to move away from the notion of resource sharing as we have considered it so far to adopt the idea of a resource that fuels both processing and storage, but that recovers over time⁶, as suggested by the source of activation confusion model of memory (SAC; Popov & Reder, 2020). According to this model, the same resource is used for encoding memory and processing items, this encoding depleting a certain proportion of the resource pool. The initial strength of memory traces depends on the resource available at their encoding and, as in the TBRS model, memory traces decay over time, but the resource recovers over time in between item presentations. Due to the temporal dynamics of the complex span task, this mechanism of recovery could be at the source of the asymmetry we observed between processing and storage. While prioritizing memory, participants could use all the available resource when each memory item appears. However, because the time needed for a full recovery has been estimated to about 5 seconds by Popov and Reder, a certain amount of resource would become available anew to process some of the items appearing during the 6-second interval following each letter, ensuring a reasonable though reduced level of performance on processing. By contrast, in the priority-to-processing condition, participants have to process as many digits as they are able to correctly judge in the 6-second intervals, something that would completely deplete their resource. Because each to-be-remembered letter appears immediately after a digit sequence, and because encoding items requires much more resource for memory than processing due to their necessary binding with the corresponding serial position, memory suffers greatly from the near complete depletion of the resource after each processing phase, explaining the larger decrement on the memory than the processing component.

Although the dynamics of the resource recovery coupled with the temporal dynamics of the complex span task could account for the asymmetry between processing and storage,

⁶ We would like to thank Ven Popov for having suggested to us this alternative explanation and its mechanism.

this explanation is not without problems. First, the asymmetry between processing and storage was not only observed with the complex span, but also with the Brown-Peterson paradigm (Exp. 4). In this latter task, encoding memory items does not follow, but precedes the processing phase. If encoding items for memory was much more demanding than for processing due to the necessary binding with serial positions, prioritizing memory should have been especially devastating for processing, which follows the encoding of memory items in the Brown-Peterson paradigm. This effect should have been more important than the effect on memory of prioritizing processing, which cannot have any effect on letter encoding, all the letters being presented before the processing phase. Nonetheless, Experiment 4 established that, even with the Brown-Peterson paradigm, memory suffers more than processing from the prioritization procedure (see also Belletier et al., 2021). Second, the SAC model seems to make additional predictions that are not supported by facts. If encoding an item for storage or processing results in some depletion of the resource, and even if encoding for processing requires less resource than for memory, each digit processed should result in some depletion of the resource. Because, in the complex span tasks, digits followed each other at a fast pace during the 6-second interval (the range of processing spans was 5 to 8 digits), there was no sufficient time for recovery. Consequently, processing digits in rapid succession during a 6-second interval should progressively deplete the resource. This progressive depletion should lead to weaker and weaker encoding and more difficult and longer response selections resulting in a progressive increase of parity judgment times. However, this is not what we observed.

We analyzed the response times (RTs) to the digits presented in the 6-second intervals as a function of their serial position through Bayesian statistical analyses in the complex span tasks of Experiment 1. Because the minimum processing and memory spans were of 5 digits and 4 letters, we limited our analysis to the five first digits presented in the processing phases

that followed the four first letters, every participant having at least processed five digits in four processing phases. The overall mean RTs for the five first digit positions were 639 ms, 536 ms, 526 ms, 527 ms, and 539 ms for the position, 1, 2, 3, 4, and 5, respectively. The longer RTs for the first position have already been observed in previous studies (Camos et al., 2019; Vergauwe et al., 2014) and are usually attributed to the conjunction of the consolidation of memory traces and the switching from storage to processing. Thus, a Bayesian ANOVA was performed on response times to the digits from position 2 to position 5. Because we did not have any available set of data on which to base prior values, we opted for the default settings to avoid introducing non-reliable values of priors. The BF_{10} of the models involving the main effects only (i.e., component prioritized – memory vs. processing, serial position of letters from 1 to 4, serial position of digits from 2 to 5), and then main effects + interaction effects were obtained by their comparison with the null model. We favored the best model when its probability to account for the data was 3 times greater than the second-best model.

This analysis revealed that the null model was the best model, indicating that the serial position of the digit, the serial position of the letter or the component prioritized had no effect on RTs. Accordingly, the $BF_{\text{exclusion}}$ for the serial position of the digits was 17.88, providing strong evidence in favor of the null (Dienes, 2014; Jeffreys, 1961). Thus, the analysis of RTs does not provide any evidence of a phenomenon of resource depletion.

A structural and adaptive limitation of storage capacity

A fourth solution is to assume that the well-known limitations of short-term memory are structural and adaptive in nature, a limited number of items requiring a limited amount of resource for their maintenance, the rest of the resources remaining available for processing. The most recent version of Baddeley's multicomponent model could correspond to such a structure. Baddeley et al. (2021) have suggested to separate out the memory storage function of the central executive from its attentional control function as a separate subsystem, the

episodic buffer. This buffer would store representations integrating information from other stores (the phonological loop, the visuospatial sketchpad, and LTM). Because this component is controlled by the central executive and its content maintained through attentional refreshing, its storage function would draw on the resources available for attention-demanding activities and processing. Importantly, this episodic buffer, akin to the focus of attention in Cowans' model, would have a capacity limited to four episodic chunks. It could be supposed that this limited and small number of chunks would only require a part of the attentional resources of the central executive, a part that could be used for processing when needed. However, within this framework, the mechanism by which refreshing the content of the episodic buffer would only require a part and not the totality of the central executive resources remains to be specified.

The TBRS model (Barrouillet & Camos, 2015, 2021) of WM could account for such a mechanism. This model assumes that both processing and storage are fueled by a unique attentional resource shared on a temporal basis. Due to a central bottleneck, when attention is occupied by processing episodes, it is not available for the encoding and maintenance of memory traces, and vice versa, attention rapidly switching from one activity to the other. However, none of these activities is susceptible to continuously occupy attention, leaving room for some flexibility of the system. In the same way as processing activities, as we suggested above, can leave some periods of time free for maintenance purpose, maintaining a memory load at span could spare periods of time available for processing activities.

Baddeley (1986) surmised that short term memory span corresponds to the number of items that can be reactivated by articulatory rehearsal in the phonological loop during the period of time needed by temporal decay to delete memory traces. In the same way, the TBRS model assumes that memory items are sequentially refreshed by attentional focusing, each item decaying as soon as attention is shifted away, including toward another memory item

(Barrouillet & Camos, 2015, 2021). Within this theoretical framework, it could be imagined that short-term memory span corresponds to the number of items that can be successively refreshed before the first item of the series has decayed to the point it is definitively lost. Note that in this case, the maintenance of a set of items at span would require the continuous occupation of attention for their refreshing. However, our results make clear that this is not the case, because our participants were still able to process a substantial number of digits while maintaining their recall performance at span, even when attentional refreshing was the unique way of maintaining the memoranda (i.e., under articulatory suppression). Thus, memory span is not achieved by a continuous allocation of attention toward storage activities.

To understand why attention does not have to be continuously allocated for maintaining a memory load at span, one has to add to functional constraints like the speed of decay and refreshing (see Camos & Barrouillet, 2018, for a discussion of these factors) some structural constraints (Barrouillet & Camos, 2015, 2021). If, due to structural constraints, WM can only hold a small number of memory items, it can be imagined that the maintenance of these items does not call for a continuous allocation of attention. According to the TBRS model, the number of items that can be maintained and recalled in a WM task corresponds to the numbers of items that can be sufficiently reactivated during the periods of free time in such a way that their level of activation is sufficient for being retrieved and reactivated after distracting episodes during which their activation has decayed (Barrouillet & Camos, 2014)⁷.

⁷ Suppose a situation in which all the distracting episodes have the same duration (e.g., the time needed for a parity judgment), each of them being followed by a constant free time ft during which attention is available for refreshing. If all the memory items have a strength S and that this strength decays of ΔD during a distracting episode, their strength Se at the end of this episode will be $Se = S - \Delta D$. Suppose now that a given item is refreshed during the following free time, its activation being increased of Δri . If Sm is the minimal level at which an item can still be retrieved for refreshing or recall, the value Δri must satisfy the inequality $Se + \Delta ri - \Delta D \geq Sm$ for permitting the memory trace to survive the next distracting episode and being retrieved for refreshing or recall. Considering that $Se \geq Sm$ (if this is not the case, the item can not be retrieved and refreshed), the inequality will be verified each time Δri equals or exceeds ΔD . However, this is not necessarily true for all the items to be maintained. If tr is the time needed by the refreshing mechanism to produce the requested Δri on a single memory trace, and ft the free time available before the next distracting episode, the maximum number of items that can be sufficiently refreshed to survive this next distracting episode is the integer n such as $n = \lfloor ft/tr \rfloor$.

If the number of items that can be maintained is structurally limited to four items, as suggested by Cowan (2001) and as assumed by the TBRS model (Barrouillet & Camos, 2015, 202; Barrouillet et al., 2021), the balance between the time needed for refreshing these four items on the one hand, and the time necessary for their decay and complete loss on the other, can be reached without devoting all the time to refreshing activities. This mechanism would make adaptive the limitation of WM capacity by allowing an optimal maintenance of information without compromising the cognitive processes for which this information has been stored.

Hence, a direct consequence of the structural constraint hypothesized above is that processing should not be dramatically impaired by the concurrent maintenance of information. This was what Baddeley and Hitch (1974) originally observed, drawing the conclusion that processing and storage rely on distinct WM components. The temporal dynamics described by the TBRS model with the assumption of structural limitations of a WM capacity can conciliate the seemingly contradictory findings of a relative robustness of processing in face of storage, and of strong dual-task costs on both processing and storage when jointly performed (Belletier et al., 2021).

It is worth noting that it has often been argued that the limitations of short-term memory are adaptive in nature. From a mathematical analysis, Dirlam (1972) established that optimizing memory search requires to group information into chunks of about three or four items, which corresponds to the capacity of verbal WM when articulatory rehearsal is prevented (Chen & Cowan, 2009). From a mathematical analysis of memory organization and retrieval, MacGregor (1987) came to the same conclusion that the limited capacity of short-term memory can be interpreted as an efficiency of design, four being the capacity limit for an optimal exhaustive search in an unorganized short-term memory. Beyond this limit, it would

Thus, although the attention is not occupied by storage activities during the distracting episodes and can be devoted to other activities (e.g., parity judgment), these n items can be maintained and recalled.

become more efficient to group items into chunks. It has also been assumed, based on connectionist networks training, that language learning benefits from severe short-term memory limitations (Elman, 1993; see also Newport, 1988). Such a limitation might be beneficial not only for language, but for any kind of learning. As Kareev (2000) noted, correlations (i.e., regularities in the environment) underlie all learning, and the probability to encounter a sample in which the correlation is stronger than in the population, and hence to facilitate the detection of regularities, is maximized for small samples of 7 ± 2 items. Thus, Kareev (2000) argued that the cognitive system might have evolved so as to increase the chances for detecting strong and useful correlations in the environment by maintaining WM capacity in restricted limits. More recently, Trapp, Parr, Friston, and Schröger (2021) argued for what they call a predictive brain that predicts its sensory input and minimizes surprise to give rise to perception, memory and action. However, as Trapp et al. demonstrate, predictions must be capacity limited because, as short-term memory capacity increases, benefits on prediction accuracy reach a ceiling beyond which complexity and computational costs increase without benefit. Interestingly, they show that there is an optimum number of discrete events that a short-term memory can hold for representing and predicting a dynamic world, this optimum ranging between four and six.

It might be that all these proposals are not exclusive from each other, even if the numerical estimates they advance slightly vary. In several domains, a limited-capacity WM seems to present adaptive advantages. We believe that, among these advantages, the necessity for a system designed for information processing to remain capable of acting while keeping directly accessible the information to be processed is of paramount importance. Although the mnemonic function of WM has been the main concern of research for decades, WM is a memory for action, as recently stressed by Heuer, Ohl, and Rolfs (2020) in the visual domain.

For being operational, WM must preserve its processing capacities when its memory component is saturated, hence the asymmetry between the two functions.

Conclusion

As we noted in introducing this work, the pioneers of the cognitivist revolution in the middle of the previous century envisioned that conceiving human mind as an information processing system obliged to imagine some buffer able to hold the program to be carried out and the information to be processed (Shannon, 1950; Turing, 1950), what has been called working memory (Miller et al., 1960). They also emphasized that this system has a “very little capacity to carry out elaborate operations” (Turing, 1948). Accordingly, this little capacity has always been a subject of reflection (Cowan, 2001, 2005, Miller, 1956), and despite about 50 years of research on WM, the question on its limitations remains vivid (e.g., Belletier et al., 2021; Doherty et al., 2019; Logie et al., 2021; Rhodes et al., 2019). These limitations have, by now, mainly been envisioned as storage limitations (Barrouillet et al., 2011; Cowan, 2005; Cowan et al., 2012). However, this tradition as well as the contemporary research focus on the storage function of visual WM could lead us to overlook that WM does not maintain information for storage, but for action purpose. Even in the well-known example of memorizing at short term a phone number, the number is not maintained for a mere storage purpose, but for the action of dialing it. When storage and processing are assumed to draw on distinct pools of resources, as in Baddeley’s (1986) model, storage limitations can be understood as resulting from functional limitations. For example, storage capacity would correspond to the number of items that can be sequentially rehearsed before decay when all the available resources are mobilized. However, if the resources used for storage are the same as those needed for processing, depleting this resource for storage only is of no purpose. The resources that can be devoted to storage must be limited to allow WM to still fulfill its function of information processor, even when storage has reached its limits. Hence the

asymmetry between processing and storage that the present study evidenced for the first time. We believe that this limitation is mainly structural because the limitation of attentional capacities around four items, which determines short-term memory spans (Barrouillet et al., 2021; Cowan et al., 2021), has been observed not only in adults (Cowan, 2001), but also in infants in a variety of studies (Cowan, 2007; Feigenson & Carey, 2003, 2005; Feigenson, Carey & Hauser, 2002; Kibbe & Leslie, 2013). Working memory might have evolved as an action-oriented system in which short-term memory capacity is structurally limited to spare the resources needed for processing the information it holds, the human cognitive system privileging processing over short-term storage. The asymmetry evidenced in this study has huge implications in suggesting that even a high mental load does not fully prevent the achievement of other activities, and in understanding multitasking and the circumstances in which it can lead to failures.

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Table 1

Mean (and SD) performance on the storage (number of letters) and processing (number of digits processed in 6 seconds) components of the complex span (CS) task in the four experiments and of the Brown-Peterson task in Experiment 4 (BP). Note that, in this latter case, the processing period was of 12 and not 6 seconds. "Span" refers to the performance on the titration task and "Dual task" refers to the performance with priority set on the other component, what is called "residual". Prop. / Sing and Prop. / Span refer respectively to the mean proportion of the single task performance and of the span the residual constitutes.

Tasks	Experiment	Span	Single task	Dual task (residual)	Prop. / Sing	Prop. / Span
Storage	1 CS	5.95 (1.15)	5.07 (0.97)	1.30 (1.57)	.27 (.33)	.24 (.30)
	2 CS	6.42 (1.26)	5.30 (1.21)	1.65 (1.82)	.31 (.36)	.27 (.31)
	3 CS*	3.00 (1.12)	2.63 (0.97)	0.66 (0.51)	.30 (.26)	.28 (.25)
	4 CS*	4.16 (1.48)	3.61 (1.43)	0.56 (0.52)	.17 (.19)	.16 (.17)
	4 BP*	3.72 (0.80)	3.16 (0.66)	1.80 (0.77)	.58 (.23)	.50 (.22)
Processing	1 CS	6.70 (0.86)	5.64 (0.79)	4.25 (1.12)	.75 (.19)	.63 (.15)
	2 CS	6.00 (0.82)	5.16 (0.64)	3.82 (0.68)	.74 (.12)	.64 (.10)
	3 CS*	5.55 (1.19)	4.69 (0.66)	3.31 (0.80)	.71 (.18)	.62 (.19)
	4 CS*	6.20 (1.18)	5.17 (1.10)	3.20 (1.18)	.63 (.20)	.52 (.17)
	4 BP*	12.42 (2.72)	10.52 (2.49)	8.01 (2.25)	.77 (.18)	.66 (.17)

Note: * indicates tasks performed under articulatory suppression.

Appendix A

Participants who failed to reach five perfect trials in at least one of the two dual-tasks of the complex span paradigm were excluded from the analyses. Nonetheless, they succeeded in making some perfect trials from which residuals could be estimated. For sake of exhaustivity, we report here the results of these participants.

It is worth to note that the discarded participants did not necessarily fail to reach the 5-perfect-trial criterion in both dual tasks. In Exp. 1, two failed to reach the criterion while prioritizing memory, and two others while prioritizing processing. In Exp. 2, the five discarded participants failed to reach the criterion only for processing, whereas, in Exp. 3, two participants failed to reach the criterion in both dual tasks, while one participant did not reach it for memory, and another for processing. Finally, in Exp. 4, three participants failed to reach 5 perfect trials in the complex span task when priority was given to memory

A possible explanation of this failure in reaching the criterion of 5 perfect trials would be that participants who achieved a high performance in one or both of the single tasks encountered difficulties in repeating it in the context of the dual task, even when urged to prioritize the corresponding component. Accordingly, when considering the performance in the single task that preceded the failure to reach the criterion for one of the dual task conditions, this performance was often situated in the first quartile of the distribution of scores of the sample (63% of the participants with memory failure and 60% of the participants with processing failure, when combining the Experiments 1-4). Overall, 17% of the participants whose performance in the single memory task was situated in the first quartile of the distribution failed to reach the memory criterion in the following dual task. This percentage was 20% for processing. Although these percentages are high, it is worth to note that a large majority of participants whose performance was situated in the first quartile for

the single memory or performance task were nonetheless able to perform five perfect trials in the corresponding dual task.

Table 1A

Mean spans, performance on the single tasks and residuals in the complex span paradigm for the participants discarded from the analyses in Experiments 1-4 with the corresponding data for the participants who reached the criterion of 5 perfect trials in both dual-tasks (see text). Mem: memory, Proc.: processing, Single: single tasks, Res.: residual. The memory residuals refer to a number of letters while the processing residuals refer to a number of digits processed in 6 s.

Exp.	Participants	Mem. span	Proc. span	Single Mem.	Single Proc.	Mem. Res.	Proc. Res.
1 (n=4)	Discarded	6.50	6.50	5.49	5.72	0.19	3.73
	Retained	5.95	6.70	5.07	5.64	1.30	4.25
2 (n=5)	Discarded	6.00	6.60	5.35	5.98	0.69	3.51
	Retained	6.00	6.42	5.30	5.16	1.65	3.82
3 (n=4)	Discarded	3.75	7.25	3.64	6.30	0.28	3.40
	Retained	3.00	5.55	2.63	4.69	0.66	3.31
4 (n=3)	Discarded	4.33	6.33	4.13	5.38	1.20	1.42
	Retained	4.16	6.20	3.61	5.17	0.56	3.20

Among the 16 participants who were discarded from the analyses in the four experiments, only two of them did not reach the criterion in both dual tasks. Moreover, failing to reach the criterion does not mean that no perfect trial was produced. Among the 18 failures to reach the criterion in one of the two dual tasks, there were eight total failures (i.e., 0 perfect

trials), but in the remaining cases, at least one perfect trial was carried out, allowing the assessment of a residual. Table 1A reports the mean performance of the discarded participants for both titration tasks, both single tasks and the residuals observed in the dual tasks along with the corresponding means for the participants who satisfied the criterion in both dual tasks and were consequently retained for the analyses. It can be noted that the mean residuals of the discarded participants were systematically lower than those reported in the main text except for processing in Exp. 3 and memory in Exp. 4. This means that the memory and processing residuals we reported in our study are probably slightly overestimated.