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Is the cognitive system much more robust than anticipated?

Dual-task costs and residuals in working memory

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Running head: Dual task costs and residuals in working memory

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Abstract

Several working memory (WM) theories assume a resource sharing between the maintenance of information and its processing, whereas other theories suppose that these two functions of WM rely on different pools of resources. Studies that addressed this question by examining whether dual-task costs occur in tasks combining processing and storage have led to mixed results. Whereas some of them reported symmetric dual-task costs, others found no or negligible effects, while still others found a reduction in performance in memory but not in processing. In the present experiment, we tested whether these discrepancies in results might be due to participants strategically prioritizing one component of the task over the other. Thus, we asked participants to perform at their maximum level (i.e. span level) in one component of the dual task and assessed performance on the other. In line with resource-sharing views, results indicated that performing at span on one task strongly degraded performance on the other, with symmetric costs. However, important residuals in both processing and storage suggested an unexpected resilience of the cognitive system that any resource-sharing theory must take into account.

Keywords: Working Memory; Resource sharing; Prioritization; Dual task; Attention

Working memory (WM) is the cognitive system devoted to the temporary maintenance and processing of a small amount of information during ongoing cognition (Baddeley, 2007). This dual function of storage and processing has been diversely theorized since the seminal studies by Baddeley and Hitch (1974). Following these studies, several WM theories have assumed that the two functions of WM are supported by distinct cognitive systems and fueled by different resource pools. This is the case of the multi-component model (MCM) proposed by Baddeley (1986; Baddeley & Logie, 1999) and its revised version by Logie (2011, 2018; Logie, Belletier, & Doherty, 2021). According to this view, increasing the cognitive demand of one of the two functions (either processing or storage) should have a negligible or no impact at all on the other function, a prediction that received empirical support (e.g., Duff & Logie, 1999, 2001). This means that when maintaining memory items for further recall (e.g., letters), performing a concurrent task such as solving addition problems should not involve any dual-task cost. Nonetheless, it is assumed that a dual-task cost could occur when demands in one or both of the two functions exceed individual's capacity (Doherty & Logie, 2016).

By contrast, other models assume that processing and storage share a capacity-limited resource most often conceptualized as attention. For example, Cowan's embedded processes (EP) model includes a domain-general attentional controller of limited capacity that supervises covert processes but also maintains representations in memory by counteracting temporal decay (Chen & Cowan, 2009; Cowan, 1999, 2005, 2008; Cowan & Morey, 2007). In a similar way, the Time-Based Resource-Sharing (TBRS) model postulates that both processing and storage rely on a common and limited attentional resource (Barrouillet & Camos, 2015). However, contrary to the EP model, the TBRS model assumes that only one operation can take place at a time with attention switching between tasks. Therefore, when attention is occupied by processing, it is no longer available to counteract the natural decay of

the memory traces, and when attention focuses on memory maintenance, concurrent processing activities must be postponed. Thus, though for different reasons, these two models predict dual-task costs between processing and storage, any increase in demand of storage having a deleterious effect on processing and *vice versa*, a prediction that has also received empirical support (e.g., Barrouillet, Bernardin, & Camos, 2004; Chen & Cowan, 2009; Vergauwe, Camos, & Barrouillet, 2014).

Considering the extant discrepancy in results in the literature, the question of the potential occurrence of dual-task costs between processing and storage in WM has been recently addressed by Doherty et al. (2019). In this study, participants retained series of letters for further serial recall while verifying additions presented successively on screen during a 10-seconds retention interval. The two tasks were performed either in isolation (single-task condition) or together (dual-task condition). Importantly, in order to adapt the cognitive demands of the tasks to individual's capacities (see Doherty & Logie, 2016), each participant performed the memory and the arithmetic tasks at span. For this purpose, the experimental trials were preceded by a titration procedure in which was measured the maximum number of letters each participant was able to recall in correct order after an empty delay of 10 s, and the maximum number of additions he or she was able to verify within an interval of the same duration. Potential dual-task costs were assessed by comparing performance in the single and dual-task conditions for both memory and processing. The pattern of results did not perfectly fit any of the predictions made either by the MCM or the EP and TBRS models. Indeed, whereas a dual-task cost affected memory performance, arithmetic performance remained unaffected by concurrently maintaining a list of letters at span. Doherty et al. (2019) suggested that this surprising asymmetry could be due to the fact that participants prioritized the arithmetic task over the memory task. Accordingly, when studying the possibility of perfect time sharing in dual-task performance, Schumacher et al.

(2001) have observed that manipulating priorities affects performance. In Doherty et al.'s study, the rapid succession of the additions on screen and the requirement to produce immediate responses while the recall of the letters was delayed at the end of the trial might have led participants to neglect the memory task and focus on the arithmetic task.

The potential effect of prioritization was assessed by Rhodes et al. (2019) who presented the same memory and arithmetic tasks as Doherty et al. (2019), but in young and older adults, and manipulated the incentives to perform one task over the other. The results largely replicated Doherty et al. with a dual-task cost affecting memory, but not processing. Moreover, the effects of prioritization remained moderate in magnitude. A decrease in the number of points allocated to the processing task from 90 to 10 (out of 100, the remaining points being allocated to memory) resulted in an overall decline in performance of only 7% in the arithmetic task. These findings might suggest that whatever the priority given to the memory component of the task, processing performance remains largely unaffected while participants maintained a memory load at span. This preserved arithmetic performance might be taken either as the signature of a separate component in charge of processing in WM, or, if the resource-sharing hypothesis was retained, as evidence for a considerable residual processing performance.

However, it might be noted that there is no way in the procedure used by Rhodes et al. (2019) to make sure that the priority manipulation is effective. It remains possible that participants were unable to the fine-grained calibration of priorities (decreased by progressive steps of 20) stipulated in the instructions they received, and that the affordances from the arithmetic task still strongly induced its immediate execution to the detriment of the memory component of the task. Another method is hence needed in order to properly assess to what extent both components of the task suffer from dual-task costs, and to measure the residual performance in each component when the participants perform at their maximum in the other.

To what extent are individuals still able to perform a concurrent task while soliciting their short-term memory at its maximum capacity? Are there some remaining items in their WM at the end of a retention interval filled with a concurrent task performed at the highest level they can achieve? These questions are the focus of the current study.

A possible way to control for the effects of prioritization when studying dual-task costs is to assess processing performance during perfect trials in memory and *vice versa*. For example, Vergauwe, Camos, and Barrouillet (2014; see also Camos, et al., 2019) studied the effect of memory load on concurrent processing in a task in which participants had to maintain series of letters of increasing length while performing a parity task in digits occurring successively on screen during a 12-seconds retention interval. They observed that an effect of memory load on processing efficiency was revealed only when trials in which recall performance was perfect were taken into account. In order to achieve a better assessment of the dual-task costs between memory and processing and of the respective residuals than in Doherty et al. (2019) and Rhodes et al. (2019), the present study used a procedure inspired from these studies, but with the requirement of perfect performance in one of the two components of the task as Vergauwe et al. (2014) did.

Experiment 1

In this first experiment, participants maintained a series of letters for further recall, and performed a parity judgment task on digits presented successively on screen during an interval of 10 seconds. After having assessed the span of each of them in both components through a titration procedure, participants were invited to perform the memory and the processing tasks in isolation with a number of letters to be remembered and a number of digits to process that corresponded to their own spans. Then, they performed both tasks in a dual-task procedure with the parity judgment task inserted within the retention interval of the memory task. However, they were asked in this dual-task condition to prioritize either the

memory or the processing component to achieve a minimum of five trials in which their performance in the prioritized component was at the level of their previous performance in the corresponding single task condition. To the best of our knowledge, such a procedure has never been used in the analysis of the relationships between processing and storage in WM. The hypothesis of a resource-sharing between both functions predicts symmetric dual-task costs, memory disrupting processing as processing disrupts memory, while the separate component assumption will expect no or negligible dual-task costs. Beyond these predictions, assessing the residual observed in one component when the other is performed at its optimal level should provide us with an assessment on how the cognitive system is resilient when facing the constraints of dual-tasking, with valuable insights about the structure and functioning of WM.

Method

The two experiments presented in this paper were approved by the ethic committee of the university of Fribourg.

Participants

Participants were 24 undergraduate students (7 males; age: $M=22.25$, $SD=2.03$) at the University of Fribourg and received course credits or cinema vouchers for their participation. All had normal or corrected-to-normal vision.

Material and general procedure

The task was run using the software PsychoPy (Peirce, 2007), and the experimenter stayed in the experimental cubicle (sitting next to the participant) during the entire experiment. The participants began with two titration procedures, one assessing their level on memory (visually presented letters to memorize), the other assessing their level on processing (parity judgement task). They then performed five trials of the memory task alone (single task) and five trials of the processing task alone (single task), both tasks being individually

adapted based on the results of the titration procedure. After the two single tasks, participants did two dual tasks, one with the priority set on memory, and the other one with the priority set on processing. Half of the participants began by the memory tasks, resulting in the following order: memory titration, processing titration, memory single task, processing single task, memory dual task, processing dual task. The other half began by the processing tasks, resulting in the following order: processing titration, memory titration, processing single task, memory single task, processing dual task, memory dual task.

Titration on memory

Participants' span was assessed using a staircase procedure. In the first two trials, five letters were presented sequentially on the center of screen for 250ms each, with an inter-stimulus-interval (ISI) of 750ms. Participants had to remember the letters for a duration of 10 seconds during which a blinking circle was displayed in the center of the screen. Participants were then asked to recall the letters in correct order by using the keyboard. If the average performance of the two trials was superior or equal to 90% correct, the two next trials included one additional stimulus, in this case six letters. If the averaged performance was below 90%, the two next trials would include one less stimulus, in this case four letters. This procedure was repeated for eight groups of two trials. If the last group of two trials was the best score achieved (the highest number of letters remembered), additional pairs of trials were presented until the participants failed to achieve the 90% criterion. The memory span was defined as the highest number of letters remembered at 90% performance. Three training trials with four letters were presented at the beginning of the task.

Titration on processing

The titration on processing followed the same procedure. In the two first trials, participants saw five placeholders (diamond shapes) that appeared for 250ms with an ISI of 750ms and then judged the parity of five digits (from 1 to 9 picked up at random) in 10

seconds by pressing a yellow key (left arrow on keyboard) with the left hand if the digit was even, and a blue key (right arrow on keyboard) with the right hand if the digit was odd. If the 90% criterion was reached on the pair of trials, participants would have to judge one supplementary digit in 10s, and one less if the criterion was not reached. The processing titration also contained eight pairs of trials. If the last group of two trials was the best score achieved (the highest number of digits for which parity was correctly judged), additional pairs of trials were presented until the participants failed to reach the 90% criterion. The processing span was defined as the highest number of digits judged in 10s at a 90% success rate. Three training trials with four digits were added at the beginning of the task.

Single tasks

The procedure for memory and processing in the single-task conditions was similar to the titrations with two exceptions. First, the number of letters in each sequence for the memory task and the number of digits to judge for the processing task were equal to the individual span level as determined in the titration procedure. Second, participants realized five trials in each single task. Three training trials with four items were presented at the beginning of each of the single tasks

Dual tasks

The two dual tasks were the combination of the two single tasks, with similar timings. Participants 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 10 seconds. Finally, they were asked to recall the letters. During the first dual task, participants were given 20 attempts to produce five “perfect trials” on memory (i.e. with a performance on memory equal or superior to the average performance on the single task on memory). The instructions also emphasized that participants should nonetheless try to perform well on the secondary (processing) task. The

second dual task was similar, but participants were asked to produce five “perfect trials” on processing. The task was interrupted once the five “perfect trials” completed. Three training trials without instructions about the priority and including four letters and four digits were presented at the beginning of the first of the two dual tasks.

Results

Accuracy on memory and processing was assessed as the percentage of letters recalled in correct position and the percentage of digits the parity of which was correctly judged, respectively, the number of letters and digits presented having been fixed for each participant through the titration procedure. However, for the single- and dual-task conditions, both the memory and the processing scores were corrected for guessing with the formula proposed by Diamond and Evans (1973): where p_{corr} is the percentage corrected for guessing, p the raw percentage of correct responses, p_{errors} the percentage of incorrect responses (without the omissions) and k the number of possible responses (2 in the case of the processing task, and 18 in the case of the memory task).

Titration

On average, participants achieved a memory span of 6.54 letters recalled (CI95%=[6.20;6.89]), and a processing span of 12.38 digits judged in 10 seconds (CI95%=[11.45;13.30]).

Perfect trials

A series of Bayesian paired samples t-tests was conducted on accuracy in the memory task, and on accuracy and reaction times in the processing task to compare the performance in each of the three conditions: single task, dual task with a priority on memory, and dual task with a priority on processing. For the dual-task conditions, these analyses focused on the performance during the “perfect trials”, namely the trials of the dual tasks for which participants reached the same (or a better) level in performance than during the corresponding

single task. A mean number of 8.83 (SD = 3.87) and 8.96 (SD = 3.42) trials were necessary in the dual tasks with priority on memory and on processing, respectively, for reaching the criterion of five “perfect trials”.

Concerning the accuracy in memory, participants performed better in the dual task with a priority on memory ($M = .96$, $CI_{95\%} = [.94;.99]$) than in the single task ($M = .84$, $CI_{95\%} = [.77;.90]$), $BF_{10} = 1433$, something due to the fact that were only taken into account in the dual task those trials in which the memory score was equal or higher than in the single task. More interestingly, memory accuracy was better in the single task than in the dual task with a priority on processing ($M = .50$, $CI_{95\%} = [.42;.58]$), $BF_{10} = 787247$ (Figure 1). The accuracy on memory during the two dual tasks also significantly differed, $BF_{10} = 1.37 \times 10^8$.

Concerning processing accuracy, and for the same reason as with memory, participants performed better in the dual task with a priority on processing ($M = .97$, $CI_{95\%} = [.95;.98]$) than in the single task ($M = .85$, $CI_{95\%} = [.82;.88]$), $BF_{10} = 1.82 \times 10^8$. However, and more importantly, their performance on the single processing task was better than in the dual task with a priority on memory ($M = .63$, $CI_{95\%} = [.56;.71]$), $BF_{10} = 6993$ (Figure 1). The accuracy on processing significantly differed between the two dual tasks, $BF_{10} = 9.88 \times 10^8$.

Finally, concerning reaction times on processing, participants were faster in the single task ($M = 472$ ms, $CI_{95\%} = [454;491]$) than in both dual tasks, with a priority on memory ($M = 510$ ms, $CI_{95\%} = [481;538]$), $BF_{10} = 48.51$, and with a priority on processing ($M = 490$ ms, $CI_{95\%} = [474;.506]$), $BF_{10} = 15.69$. The two dual tasks did not seem to differ from each other, but with only little evidence against the existence of an effect $BF_{01} = .88$.

Discussion.

When investigating the relationships between the two WM functions of processing and storage, Doherty et al. (2019) as well as Rhodes et al. (2019) observed an asymmetry in dual-task costs, with processing having a detrimental effect on concurrent memory maintenance,

whereas memory maintenance did not have any detectable effect on concurrent processing. A first aim of this first experiment was to verify whether this asymmetry remains when the effects related to the prioritization of one task over the other are controlled by measuring performance in one component in those trials in which performance was perfect (i.e. at the optimal individual's level) in the other. Our results are particularly clear. In those trials in which participants maintained their level of performance at span in one component of the dual task, their performance in the other component degraded. These results are in line with the expectations of those WM models that assume a resource sharing between the two functions (e.g., Cowan's EP or Barrouillet and Camos's TBRS models). Individuals are unable to reach their highest level of performance in two tasks performed concurrently. Concerning the second aim of our experiment, namely to assess the level of performance participants reached in the non-prioritized component of the dual-task conditions, it becomes clear that the resource-sharing hypothesis is far from exhausting the question. Whereas performance in both dual-task conditions was almost perfect in the prioritized condition (Figure 1), participants were still able to correctly process 63% of the digits and to recall 50% of the letters presented, corresponding respectively to a mean of 7.86 digits processed in 10 seconds and 3.27 letters recalled, revealing important residuals even when the other component of the dual task was at span. Where do these residuals come from?

Concerning memory, it might be assumed that even if the common resource shared by memory and processing was exhausted by the parity task performed at span, other memory-specific resources could come into play. For example, it is possible that a phonological loop, as assumed by Baddeley's (1986) model as well as by the MCM (Logie, 2018) and the TBRS (Barrouillet & Camos, 2015) models, held about three letters through articulatory rehearsal without any involvement of the resource needed to perform the parity task. Baddeley and Hitch (1974) had already observed that individuals were able to maintain up to three letters

without any impact on a concurrent reasoning task. It might also be assumed that the mnemonic residual is retrieved from some secondary long-term memory, while the parity judgment task could be carried out by a primary memory that can be assimilated with the focus of attention (Unsworth & Engle, 2007). This is congruent with evidence showing that WM models must assume some long-term memory involvement to account for performance in WM tasks (Cowan, Rouders, Blume, & Saults, 2012). Finally, it is worth noticing that a secondary task involving motor responses such as the one we used in this study should never lead to a floor result in memory performance, at least if one considers a time-based sharing of attention. Indeed, producing a motor response involves its programming and execution, with only the first step capturing attention (Fisher, 1997). Consequently, during motor response execution, the attention can be directed back to refreshing of the memory traces. In other words, designing a task capturing attention during 100% of time (in other words, a cognitive load of 1) poses probably insuperable problems and therefore attentional refreshing is never completely prevented. In summary, articulatory rehearsal, retrieval from secondary memory and some remaining refreshing could account for the fact that people can perform a processing task at their highest possible level of efficiency while still being able to concurrently maintain a substantial amount of verbal information.

Explaining the large residual in the processing task seems more complex. Even though there are domain-specific systems for verbal memory, the dual-task cost observed when priority was given to processing suggests that WM storage relies at least in part on a domain-general resource also shared by processing. Because the memory task was performed at span when prioritized, it might be assumed that memory used this domain-general resource at its maximum capacity. Under this hypothesis, the residual performance in the parity judgement task should rely on some domain-specific resource that cannot be used for storing memory items. According to Dehaene et al. (1993), information about parity could be accessed from

the Arabic visual representation of numbers. Thus, parity judgement could rely on some visual-specific resource such as the visuospatial sketchpad hypothesized by the multicomponent model (Baddeley, 1986; Logie, 2018). However, it has been argued that such a domain-specific system does not exist in WM for visuospatial information (Barrouillet & Camos, 2015; Morey, 2018). Moreover, Vergauwe et al. (2014) observed that even the maintenance of a single letter disrupted parity judgments, suggesting that there is no domain-specific resource for parity that verbal memory could not use. But if the parity judgment task can only rely on a resource that memory can also use, how it was possible for our participants to process so many digits while maintaining a memory set at span?

Another possibility might be that the maintenance of a list of letters at span level requires attention, but does not continuously mobilize the total amount of attentional resources. It has been suggested that two separate systems contribute to verbal maintenance in WM, verbal rehearsal and attentional refreshing (Camos, 2015, 2017; Camos, Lagner, & Barrouillet, 2009). It could be imagined that maintaining a list of memory items at span level involves a subtle interplay between the two systems that does not totally exhaust their respective capacity if, for example, relying on verbal rehearsal is more efficient than attentionally maintaining some verbal items, freeing attentional resources for other purpose (Barrouillet, Gorin, & Camos, *in press*).

Thus, both the memory and the processing residuals might be partly due to the existence of a dual system for verbal WM, verbal maintenance relying on articulatory rehearsal when the processing tasks performed at span captures most of the available attention, and the processing task benefiting from some residual attention due to the use of articulatory rehearsal in maintenance. Thus, although deciphering the puzzle of the sources of these residuals will probably require extended investigations, as a first step in this direction, we ran a second experiment that aimed at impeding verbal rehearsal while making the

processing task as constantly attention-demanding as possible, and hence blocking its availability for maintenance.

Experiment 2

Participants were presented with the same combination of memory and processing tasks after a titration procedure as in Experiment 1 with two exceptions. First, all the tasks were performed under concurrent articulation to prevent articulatory rehearsal. Second, in order to prevent attention to shift toward maintenance purpose during the motor component of the parity task, the to-be-processed digits were presented in such a way that it was possible to prepare and anticipate the response to the next digit while responding to the current one. For this purpose, instead of appearing successively on screen at key press, five digits were always simultaneously present on screen, the current digit to be processed and the four forthcoming digits (Figure 2).

Verbal rehearsal being hindered by concurrent articulation, memory maintenance should mainly rely on attention and have a strong impact on concurrent processing. Moreover, the new way of presenting digits was expected to capture attention at its maximum due to the possibility to judge the parity of the forthcoming digit while responding to the current one. In the other way around, due to the increased attentional demand of the parity judgment task, processing it at span should have a dramatic effect on concurrent maintenance when memory items can no longer be articulatorily rehearsed. Thus, beyond the replication of the symmetric dual-task costs observed in Experiment 1, we expected reduced residuals for both components of the dual task.

Method

Participants

Twenty-four undergraduate students aged from 18 to 28 (3 males) at the University of Fribourg received course credits or cinema vouchers for their participation. All had normal or corrected-to-normal vision.

Material and general procedure

The procedure was the same as in Experiment 1 with the following changes. First, the two titrations and all the experimental conditions were performed under articulatory suppression. At the beginning of the trial, when the ready signal was presented on screen (i.e., before the first memory letter or placeholder), participants started uttering the three syllables *ba bi bou* aloud until the end of the trial. For the memory single task and dual-task conditions, articulatory suppression stopped when the signal for aloud recall appeared on screen. Second, processing task was modified in order to make appear not only the digit to be judged, but also the four forthcoming digits. Thus, five digits were always displayed on screen, the target digit in a box on the center of the screen, and a string of four digits on its right (Figure 2).

Results

As in Experiment 1, for the single- and dual-task conditions, both memory and processing accuracy scores were corrected for guessing.

Titration

On average, participants reached a memory span of 3.54 letters (CI95%= [3.23;3.85]), and a processing span of 11.71 digits judged in 10 seconds (CI95%= [10.25;13.17]). **It can be noted that the titrated processing spans, and consequently the number of digits to be processed in the experimental conditions were lower in Experiment 2 than in Experiment 1 (11.71 and 12.38 digits processed, respectively). These lower titrated spans could result from the fact that the titration of the parity judgment task was performed under articulatory**

suppression in the present experiment, due to the involvement of verbal code in the parity judgment task.

Perfect trials

The same analyses as in Experiment 1 were performed. To reach the criterion of five “perfect trials” in the dual-task conditions, participants needed a mean number of 8.79 trials (SD = 2.89) for memory and 7.79 trials (SD = 2.17) for processing.

Replicating the results of Experiment 1, recall performance was higher when the memory task was performed concurrently with a priority on memory ($M = .99$, $CI_{95\%} = [.97;1.00]$) than when performed in isolation ($M = .87$, $CI_{95\%} = [.82;.91]$), $BF_{10} = 5498$. Moreover, the accuracy on memory was lower when the memory task was performed concurrently with a prioritized processing ($M = .66$, $CI_{95\%} = [.59;.73]$) than when performed in isolation, $BF_{10} = 882.18$. Not surprisingly, when comparing the two dual-task conditions, prioritizing processing led to poorer recall performance than prioritizing memory, $BF_{10} = 2.7 \times 10^6$ (Figure 3). It is worth noting that the memory residual, when expressed in percent of correct responses, was higher in this experiment than in Experiment 1 (66% and 50%, respectively). However, because titration was made under articulatory suppression in the present experiment, the number of letters presented in the single- and dual-task conditions was lower (3.54 instead of 6.54). Thus, the raw number of letters participants were still able to recall while performing the processing component at span was lower in this experiment than in Experiment 1 (2.34 compared to 3.27).

Regarding the results on processing, participants performed better when asked to prioritize the processing ($M = .98$, $CI_{95\%} = [.97;1.00]$) than in the single task ($M = .91$, $CI_{95\%} = [.88;.93]$), $BF_{10} = 143247$. Moreover, they were less accurate when prioritizing the concurrent memory task ($M = .78$, $CI_{95\%} = [.72;.83]$) than when performing the parity judgment task in isolation, $BF_{10} = 235.92$, or when prioritizing it over memory, $BF_{10} =$

410136.08. It can be noted that the rate of correct responses on processing was higher in Experiment 2 than in Experiment 1 **in all conditions**. Overall, the raw processing residual when priority was given to memory was higher in the present experiment (9.13 digits correctly judged, 78% of 11.71) than in Experiment 1 (7.86 digits, 63% of 12.38). **We do not have any explanation for this unexpected finding.**

Finally, the patterns of reaction times were similar to those in Experiment 1. Participants were faster in the single task ($M = 367$ ms, $CI_{95\%} = [310;425]$) than in the dual tasks with a priority on memory ($M = 445$ ms, $CI_{95\%} = [378;511]$) $BF_{10} = 385.73$, or on processing ($M = 406$ ms, $CI_{95\%} = [340;473]$) $BF_{10} = 20.20$. The two dual tasks also differed from each other, $BF_{10} = 16.67$, **contrary to what we observed in Experiment 1 in which this difference was smaller and not significant**. It can be noted that, in all the experimental conditions, participants were faster in Experiment 2 than in Experiment 1.

Discussion

Altogether, the results of this experiment replicated those of Experiment 1. When combining a memory and a processing task, prioritizing one of the tasks deteriorated the performance on the other. This dual-task effect seems therefore to be symmetric, as predicted by WM theories that postulate a sharing of resources between memory and processing (e.g., Barrouillet & Camos, 2015; Cowan, 2005). Nonetheless, even under the very demanding conditions of this experiment, we still observed residuals in performance of the non-prioritized tasks that were far from null.

In our first experiment, we observed a mean memory residual of 3.27 letters when participants were presented with series of letters at span while prioritizing concurrent processing. In this second experiment, we examined whether this residual would be lesser when the memory task is performed under articulatory suppression, and when the processing task is made more demanding. Under these conditions, the memory residual indeed dropped

to 2.34 letters, indicating that part of the memory residual in Experiment 1 was probably due to the availability of the articulatory loop. Nonetheless, even in the very difficult conditions created in this second experiment, recall performance did not drop to zero. Given that the parity judgment task was performed at span, probably inducing a high attentional cost, and given that the task was performed under articulatory suppression, one should assume that this memory residual is sustained by a mechanism that would not, or at least minimally, rely on attentional or articulatory resources. We will discuss this point further in the general discussion.

Concerning the residual on processing, we designed a task supposed to induce a more continuous attentional demand than in Experiment 1 by allowing participants to anticipate forthcoming judgments. Our rationale was that as soon as participants had made a decision on an item, they would shift their attention to the forthcoming digit. Such a preparation that allowed participants to a more proactive processing was expected to increase the number of digits processed within the 10 s interval. Contrary to this expectation, the maximum number of digits participants were able to process in 10 s during the titration procedure remained almost unchanged. Hence, it seems that the maximum number of digits participants were able to judge in 10 s in Experiment 1 constitutes some sort of limit than cannot easily be overcome. Of course, the concurrent articulation also performed during processing could have restricted the expected improvement. Nonetheless, the findings in Experiment 2 confirmed those from Experiment 1. Participants maintaining a memory set at their maximum individual capacity were still able to process 9.13 digits in 10 s, which is a remarkable residual.

To summarize, Experiment 2 replicated the symmetric dual-task costs evidenced in Experiment 1. It also supported the hypothesis that memory residual relied at least in part on

articulatory rehearsal. However, articulatory suppression did not result on any reduction in processing residual.

General discussion

A classical approach to explore the structure and functioning of WM is to examine changes in behavior resulting from the combination of memory and processing requirements (Baddeley & Hitch, 1974; Barrouillet, Bernardin, & Camos, 2004; Daneman & Carpenter, 1980; Doherty et al., 2019; Duff & Logie, 2001; Turner & Engle, 1989). The lack of an (or a small) effect of a processing component on memory performance or *vice versa* is often seen as a proof that processing and memory do not rely on the same mechanisms or resources (e.g., Duff & Logie, 2001). However, the question of prioritizing is often underestimated in this approach. The absence of an effect might simply be due to participants spontaneously or strategically focusing on one task on the detriment of the other. For example, participants might choose to prioritize the processing task merely because they have it under their eyes, letting the processing task unaffected by the neglected memory task (e.g., Belletier et al., in revision).

In the present study, we assessed dual-task costs on memory and processing in two experiments in which we manipulated the prioritization of one task over the other. Participants' spans were evaluated during a titration phase using a scale procedure on a serial recall of letter sequences and on a parity judgment task. Participants then performed the same tasks either in isolation (single task) or in combination in a Brown-Peterson paradigm (dual task) at their individual span level. The prioritization was manipulated during the dual-task condition by asking participants to achieve "perfect trials" on either recall or parity judgment without ignoring the other task. The two experiments showed a similar pattern of results. Clear and symmetric dual-task costs were observed on both memory and processing when the other component was prioritized. These results are difficult to reconcile with the idea of

independent components for memory and processing (e.g., Baddeley & Logie, 1999; Logie, 2011) and are more in line with a sharing of resources as assumed by Cowan's (2005) EP model or Barrouillet and Camos' (2015) TBRS models.

However, neither the memory nor the processing residuals dropped to (or even approached) zero, even in the most difficult conditions (Experiment 2). Concerning memory, the residual was of 2.34 letters when the participants had to perform at span a dual task under articulatory suppression with a priority on processing. In this condition, the capacity of both the attentional and phonological maintenance mechanisms, as assumed by the TBRS model (Barrouillet & Camos, 2015), is supposed to be exhausted, and one can wonder how these two letters are maintained. A first possibility is to assume a supporting role of long-term memory (Hitch, Halliday, & Littler, 1989; Unsworth & Engle, 2007). More specifically, the context relevant information not maintained in WM would be retrieved from long-term memory by using a controlled search process based on retrieval cues (Unsworth, Brewer & Spillers, 2013). If this is true, our results indicate that individuals are able to recall about 2 letters by using this retrieval process. It is worth noticing that we used a Brown Peterson paradigm in these experiments, meaning that all the letters were presented first, then followed by the processing task. It might be that this presentation helped participants to rely on long-term memory storage, because they had the opportunity to link the letters by forming acronyms for example. Other types of presentation, such as in complex span tasks, may lead to a smaller residual. However, it should be noted that previous experiments using complex span task did not reveal WM spans dropping below 2 letters, even under high cognitive load and concurrent articulation (Barrouillet et al., 2004, Exp. 7). Another possibility might be that, when confronted with a task exceeding their capacities, participants strategically reduce the difficulty by jettisoning a part of this task and focusing only on some letters (Belletier et al., in revision). If one assumes that the articulatory suppression and the attentional capture of

the secondary task did not perfectly drain all the resources used for maintenance, these letters could be maintained in WM. Let us exemplify this idea with the notion of refreshing. Let us assume that the secondary task captures the attention needed to refresh the information in working memory during a large part (but not all) of the time. In other words, the attention is rarely free to go back to the memoranda in order to refresh them and counteract their decay. If the participant tries to maintain five letters, these few episodes of refreshing might need to be scattered between all the letters, which may result in a huge loss of information. On the contrary, if the participant strategically focuses on only two letters, each of these letters might benefit from longer episodes of refreshing. A similar reasoning can be made concerning the maintenance in the articulatory loop. Just rehearsing four letters proves more beneficial than trying to rehearse six or seven letters (Barrouillet et al., in press). Another way to put it is that, according to this account, each supplementary memorandum to maintain does not *linearly* increase the strain in working memory because it also impairs the maintenance of all the items already maintained in working memory. Therefore, when less resources are at their disposal, participants might focus on a limited number of memoranda that are easier to *maintain simultaneously*. In other words, according to this view, the residual might merely be what the participants estimate being capable of memorizing given the resources left at their disposal. More research is therefore needed to confirm that the memory residual is indeed the reflection of a retrieval process in long-term memory rather than the use of a reduction strategy.

Our results on processing are more puzzling. A first thing to note is that the percentages reported in both experiments were corrected for guessing. This is important because the processing tasks were two-choice decision tasks done under time-pressure. One might surmise that participants do a lot of guessing under these circumstances. But even when correcting for guessing, our participants were able to judge accurately the parity of a non-

negligible number of digits in 10 seconds while prioritizing the memory task (7.80 digits in Experiment 1 and 9.13 digits in Experiment 2). In other words, they were able at the same time to judge the parity of a number every 1100 to 1200 ms and to perform the memory task at the same level as when it was done in isolation. Thus, although the observed dual-task costs contradict WM theories postulating separate components and resources for maintenance and processing (Baddeley's or Logie's models), the substantial processing residuals question the theories postulating a resource sharing (Cowan's EP or Barrouillet-& Camos's TBRS models).

Though accounting for the large processing residual will probably require a long and complex inquiry, we would like to propose some explanatory factors at two different levels, the parity judgment task itself on the one hand, and the cognitive architecture on the other. Concerning the task, it might be that it became less and less demanding over the trials due to its automatization. When entering the dual task with prioritization on memory, participants had already made about 30 parity judgments on each digit. Following the instance theory of automaticity (Logan, 1988), it might be assumed that the occurrence of each digit on screen triggered the obligatory retrieval of many memory traces containing the response previously given. This kind of automatization has been proved to strongly reduce the interference between tasks and allow a smooth proceeding while performing other activities (Klapp, Boches, Trabert, & Logan, 1991; Logan & Klapp, 1991). Moreover, the possibility to preview the forthcoming digits in Experiment 2 could have induced a change in the way the task is performed by allowing some planning on the successive key presses permitting to anticipate perseverations or switches in responses. This would also lead to reduce the attentional demand of the task and could explain why residual was even larger in Experiment 2 than in Experiment 1. At the architectural level, it might be assumed some parallelism in cognitive processes, as in Meyer and Kieras' (1997) EPIC model. For example, Meyer and

Kieras suggest that the transformation of sensory inputs to symbolic perceptual outputs, i.e., WM representations, might proceed in parallel with other cognitive processes. In the parity judgment task, this would mean that the identification of digits susceptible to trigger the obligatory retrievals evoked above might run in parallel with the response selection on the previous digit. Other parallelisms could occur with the operations of maintenance of memory traces, leading to the observed sizeable residuals. This does not necessarily mean, as the EPIC model assumes, that there is no bottleneck at all at the central level of cognition, but a limited number of cognitive processes restricted by a central bottleneck along with some processes running in parallel could account for the coexistence of dual-task costs and residuals in WM. **What our results and the perfect-trial method suggest is that findings issued from the dual-task procedure should be cautiously interpreted. Sizeable residuals show that the cognitive system is much more robust than anticipated, but they do not mean that this system can be reduced to a collection of independent system working in parallel, as the symmetrical dual-task costs testify. Models of cognition, and in particular working memory models, should integrate this complexity and be less committed with Manichean oppositions.**

As we noted above, the strong symmetric dual-task costs support the resource-sharing models, while the existence of large residuals points towards the independence of, at least, some processes. Thus, it seems that the main models of WM need some adaptations. On the one hand, WM models based on resource-sharing at the central level (e.g., Barrouillet & Camos, 2015; Cowan, 2015) might benefit from a closer analysis of the systems and mechanisms underpinning processing and memory in order to tease apart those cognitive steps or mechanisms necessarily shared at the central level from those susceptible to run in parallel. Concerning multicomponent models (Baddeley, 2007; Logie, 2011), they should evolve in order to consider the symmetric sharing between memory and processing. A possibility might be that the performance observed at the individual span level is in fact the

reflection of numerous mechanisms, some of them being also recruited during processing. Some recent proposal might be a step in this direction (Logie, Belletier & Doherty, 2021).

To conclude, we showed in these two experiments how important the prioritization is when one aims to study WM by examining the constraints imposed by a dual tasking. The method of the “perfect trials” (Camos, et al., 2019; Vergauwe, et al., 2014) proved once again insightful, because it allows to study the impact of prioritization when it is actually achieved. The use of this method revealed strong and symmetric dual-task costs that can not be neglected. This finding makes clear that, contrary to models assuming separate resources fuelling independent components for storage and processing (Baddeley & Logie, 1999; Logie, 2011), theorizing must necessarily include some resource sharing. However, WM proved more resilient than expected. The substantial residuals we observed suggest that models assuming a unique resource and a central bottleneck can not account for all the WM phenomena. Our findings call for a close scrutiny of the underlying mechanisms or systems that support these residuals.

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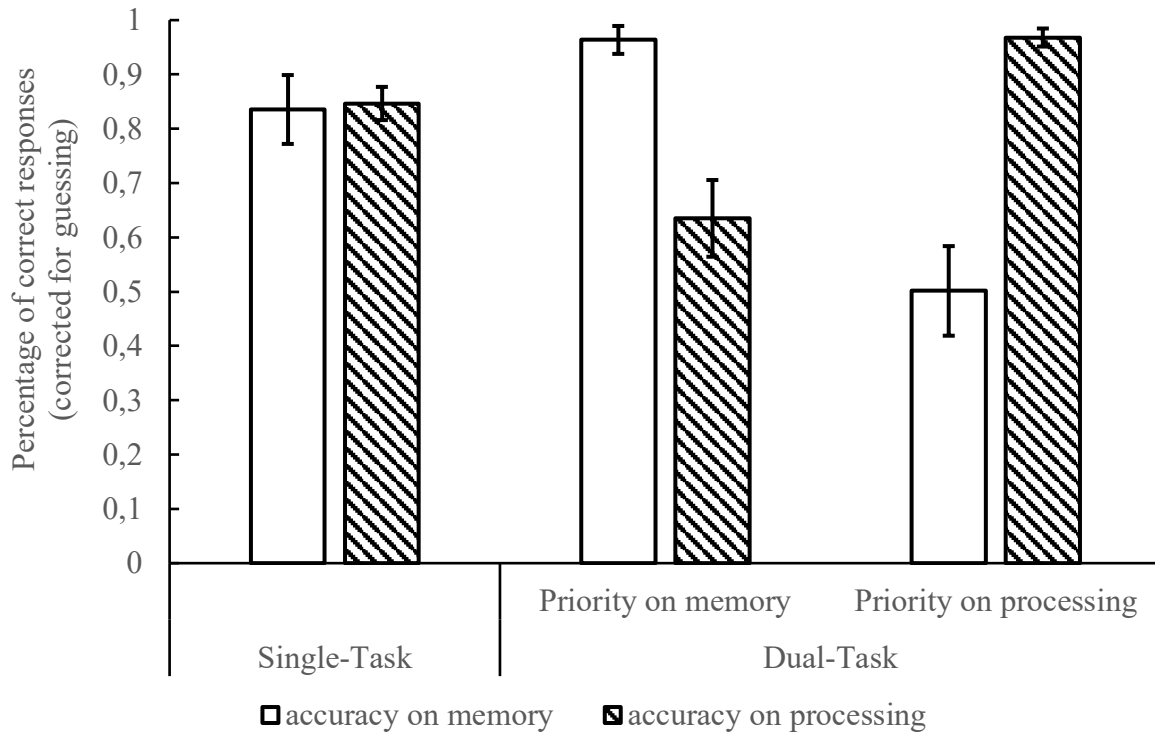


Figure 1. Accuracy on memory and processing in Experiment 1 as a function of the type of task (single vs. dual) and the priority (on memory vs. on processing) in the dual-task conditions. Only “perfect trials” were taken into account in the dual-task conditions (see text). The number of items presented during the memory and the processing tasks were individually titrated. Error bars represent confidence intervals at 95%.

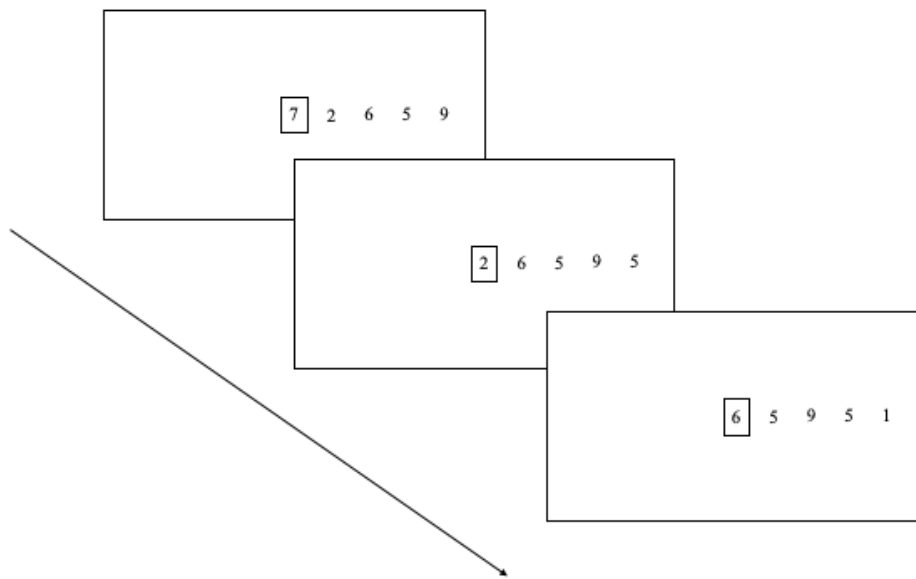


Figure 2. Illustration of the parity judgment task in Experiment 2. Five digits were always displayed on screen, the target digit in a box on the center of the screen, and a string of four digits on its right.

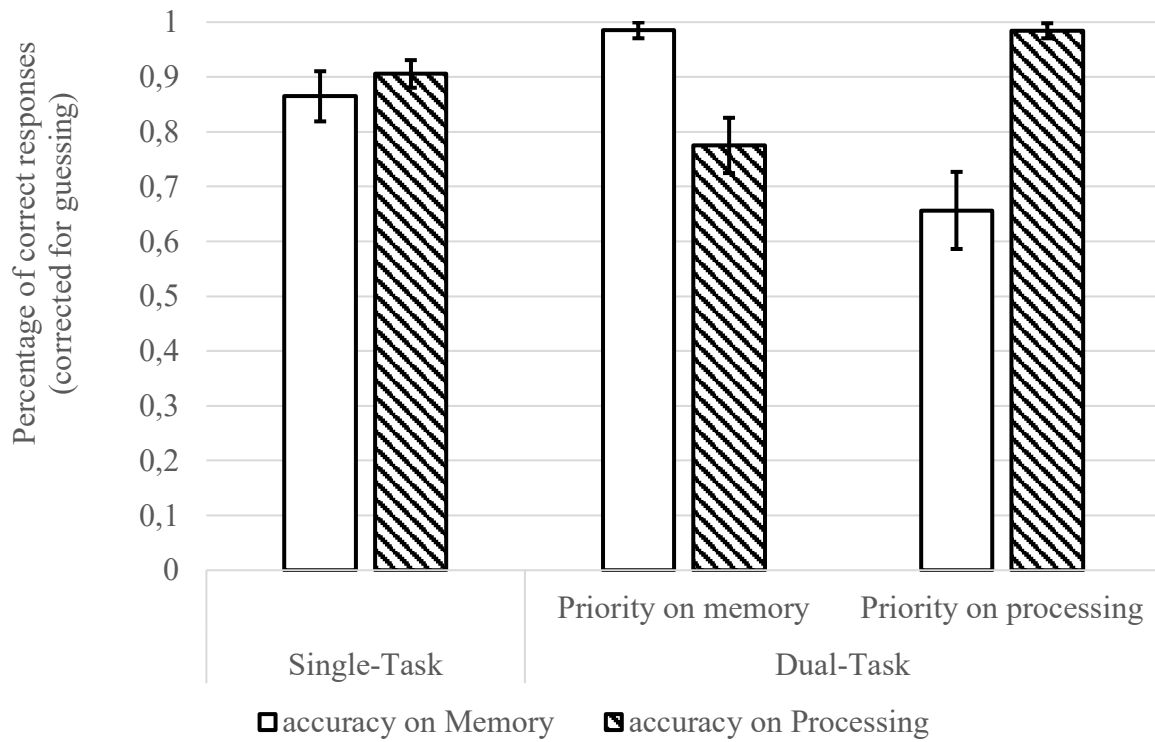


Figure 3. Accuracy on memory and processing in Experiment 2 as a function of the type of task (single vs. dual) and the priority (on memory vs. on processing) in the dual-task conditions. Only perfect trials were taken into account in the dual-task conditions (see text). The number of items presented during the memory and the processing tasks were individually titrated. Error bars represent confidence intervals at 95%.