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WORKING MEMORY AND EXECUTIVE CONTROL: A TIME-BASED RESOURCE-SHARING ACCOUNT

Pierre BARROUILLET(1) & Valérie CAMOS(2)
(1)*Université de Genève, Switzerland,* (2)*Université de Bourgogne, France &*
(2)*Institut Universitaire de France*

In this article, we address the question of the relationships between executive control and working memory. Through a review of several studies conducted within the theoretical framework provided by our Time-Based Resource-Sharing model, we argue that most of the fractionations of working memory assumed by Baddeley's standard multi-component model tend to disappear when temporal factors are carefully controlled, and that the system known as the central executive is in charge of both functions of processing and storage. However, this does not mean that the concepts of working memory and executive control are coextensive. As suggested by our recent investigation of verbal working memory, central domain-general and peripheral domain-specific mechanisms operate jointly to maintain information active, extending working memory structure and functioning beyond the boundaries of the central executive.

Cognitive psychology considers working memory as the central mechanism in charge of the maintenance of those items of knowledge and environmental information needed to perform the task at hand. Providing a pivotal interface between perception, attention, memory, and action, working memory is thought to be involved in all of our goal-directed activities and controlled behaviour. Thus, at a theoretical level, its relationships with the mechanisms involved in executive control are necessarily close. Nonetheless, theories of working memory have proposed a variety of solutions to account for these relations. We will set aside here the approaches that regard working memory as an executive function among others (see for example Ardila, 2008; Diamond, 2006), to concentrate on those theories that consider executive functions as mechanisms involved in working memory functioning and executive control as one of its functions. Undoubtedly, the best example of this approach was provided by the standard model of working memory put forward by Baddeley and Hitch (1974; see also Baddeley, 1986) who pro-

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Pierre Barrouillet is affiliated with Université de Genève. Valérie Camos is affiliated with Université de Bourgogne and Institut Universitaire de France.

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Correspondence concerning this article should be addressed to Pierre Barrouillet, Université de Genève, Faculté de Psychologie et des Sciences de l'Éducation, 40 bd du Pont D'arve, 1211 Genève 4, Switzerland. E-mail: Pierre.Barrouillet@unige.ch

posed a structural distinction between subcomponents devoted to mnemonic purposes, while a separate entity was in charge of the executive control of cognition. As we will see, this popular conception leads to undesirable assumptions contradicted by facts. Though prominent alternative conceptions of working memory have been proposed, such as Engle's and Cowan's models (Cowan, 2005; Engle & Kane, 2004), they surprisingly inherited from their predecessor the strong assumption of some separate central executive in charge of controlling working memory functioning. Through a review of the main results gathered during the last years within the theoretical framework provided by the Time-Based Resource-Sharing (TBRS) model (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet & Camos, 2007), the aim of this article is to propose a conception of the relationships between working memory and executive control within the TBRS model.

Executive control within the standard model of working memory

With the aim of testing the hypothesis that short-term memory, as described by Atkinson and Shiffrin (1968), could be a plausible candidate for the role of a working memory, Baddeley and Hitch (1974) asked participants to perform a demanding reasoning task, while they maintained near-span series of digits. They reasoned that if Atkinson and Shiffrin's short-term store acted as a working memory in charge of both processing and storage, processing should then be dramatically impaired when the capacity of this short-term memory is exhausted by maintenance requirements. Surprisingly, Baddeley and Hitch (1974) observed that this was not the case, and suggested that processing and storage are in many respects independent and supported by distinct structures and mechanisms. Slave systems would be in charge of storage, with a phonological loop for verbal information and a visual scratchpad for visuo-spatial information, while a central executive would coordinate their functioning, select appropriate strategies, and control processing. Although in the first version of this multi-component model, the central executive was also credited with a capacity of storage when slave systems were overloaded, this assumption was subsequently abandoned and the central executive was thought of as exclusively devoted to processing and its control (Baddeley, 1986). Thus, the multi-component model, that rapidly became the dominant conception of working memory, delineated a clear distinction between the structures and mechanisms devoted to executive control and those committed to the maintenance of information in the short term. On the one hand, an assembly of executive functions was assumed to be in charge of the control of thought by temporarily activating items of knowledge from long term memory, focusing attention to attend selectively to one stream of information while discarding others, dividing this attention in dual tasks or switching it from one task to another. On the other hand, domain-specific buffers and their dedicated mechanisms of rehearsal were assumed to be in charge of the storage and maintenance of relevant information. This structural and functional distinction between a central executive system and peripheral stores was reinforced by neuroimaging studies that revealed distinct cerebral substrates for each subcomponent (Smith & Jonides, 1999). In some sense, the multi-component model had resolved the question of the relationships between working memory and executive control by clearly separating *working* from *memory* in working memory.

As noted by Vergauwe, Barrouillet, and Camos (2009), it is possible to distinguish at least two different versions of this separation, a strong and a weaker version. According to the strong version, the peripheral systems are literally stores. Exclusively responsible for the storage of domain-specific information, they would never be involved in any processing activity, which all resort to the central executive that, in turn, is never involved in storage. This conception was illustrated by Duff and Logie (2001), who observed no interference between processing and storage demands in dual tasks within the verbal domain (e.g., maintaining words while reading sentences). Such a strong version involves a clear demarcation between processing and storage, with the two functions of working memory fuelled by separate and independent pools of resources, and rejects any idea of a trade-off between processing and storage in working memory functioning. By contrast, the weak version allows for some interference between processing and storage because it describes the peripheral systems as “specialized for the processing and temporary maintenance of material within a particular domain” (Baddeley & Logie, 1999, p. 29). Thus, interference could be observed at a peripheral level when both processing and storage generate representations that would be maintained and processed by the same domain-specific system. However, whatever the version retained, the multi-component view of working memory excludes central interference by which activities involving two distinct domains (e.g., verbal and spatial or auditory and visual) would interfere with each other. There is no doubt that the prominence of the multi-component view of working memory owes greatly to the evidence provided over the past 40 years by the selective interference paradigm, demonstrating that interference occurs in dual tasks when both tasks involve representations pertaining to the same domain (e.g., when both tasks involve verbal information), but not (or to a very little extent) when the two tasks involve representations pertaining to different domains (e.g., when one task involves verbal representations and the other visuo-spatial representations, see for example Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002).

In summary, the multi-component view of working memory developed by Baddeley proposed a structural distinction between the two functions of working memory that led to assign processing activities to a central executive exclusively dedicated to this purpose, and conceived as functionally and structurally distinct from peripheral systems devoted to storage activities. As we noted, one of the consequences of this approach is that the model only allows some specific patterns of interference, depending on the version of the theory that one favours. As we will see, these predictions are contradicted by facts. However, most of the phenomena revealing central interference remain unnoticed as long as temporal parameters of the tasks are not strictly controlled for, explaining why the selective interference paradigm, which does not impose any time constraints in its standard form, repeatedly confirmed the main assumptions of the multi-component model. Indeed, the empirical evidence that we will review in the following sections were, for the most part, obtained within the TBRS framework that puts a special emphasis on the impact of time on working memory functioning. Before going into this, we will briefly expose the main tenets and assumptions on which the TBRS model is based.

The role of time in working memory: the TBRS model

An overview of the model

The main idea on which the TBRS model is based is that the two functions of working memory, processing and storage, share a unique and limited resource which is attention. The involvement of attention in processing does not constitute a controversial issue in current cognitive psychology. Processing most often requires the selection, activation, and maintenance of some goals and sub-goals, the selection of relevant information, the retrieval from long-term memory of related items of knowledge, the planning and monitoring of adapted strategies, and response selection, all activities known as requiring attention. The idea that attention is needed in storage and maintenance activities is less immediate. For example, the maintenance of verbal information through its recirculation in a phonological loop as described by Baddeley (1986) is known to require little attention, only needed in the first steps of verbal rehearsal. However, other models have suggested that maintenance operations require attention. For example, Cowan (2005) assumed that items of knowledge receive activation for the purpose of maintenance through attentional focusing, an activation that decreases with time as soon as these items leave the focus of attention. Nonetheless, these memories could be reactivated before they are completely lost by redirecting the focus of attention to them. If we assume that attention can only select one item at a time for cognitive operation (Garavan, 1998; Oberauer, 2003) or that there exists a central bottleneck (Pashler, 1998), the idea of a time-related decay that can be counteracted by attentional focusing leads to the TBRS model. Indeed, because working memory is a system in charge of maintaining active the information needed for current processing, this information suffers from an inescapable decline when attention is occupied by processing activities. The only way to avoid a complete loss of the information, which would compromise the achievement of the goal at hand, is to take advantage of short pauses that can be freed between two processing steps to switch attention to memory items and reactivate them.

Thus, the TBRS assumes that information is maintained by rapid switching from processing to storage that permits an attentional refreshing of memory traces. This refreshing, which could take the form of the covert retrieval process described by Cowan (Cowan, 1992; Cowan, Keller, Hulme, Roodenrys, McDougall, & Rack, 1994), has been described by Raye, Johnson, Mitchell, Greene, and Johnson (2007) as a minimal executive function that involves left dorsolateral PFC and can be neurally distinguished from articulatory rehearsal. Another main idea of the TBRS model is that processing activities differ from each other on the amount of attention they leave available for refreshing: those activities that continuously occupy attention would greatly hinder refreshing and hence allow for the concurrent maintenance of only some items, whereas other activities would be less attention demanding and permit the frequent refreshment of several items.

This leads to a new conception of cognitive load. The cognitive load that a given task involves, that is, the extent to which it impedes other activities to take place at the same time, should correspond to the proportion of time during which it occupies attention. Actually, one of the key predictions of this model is that the amount of information that can be maintained while processing is concurrently running would strongly depend on the temporal constraints of the task. The cognitive load of a given task, defined as the amount of work to be done, would depend on the time allowed to perform it. If there is less time, the same amount of work would result in a more continuous occupation of attention and thus in rarer and shorter slots during which attention could be diverted. It can be seen that, contrary to the strong version of the multi-component model described above, the TBRS model predicts interference between processing and storage, and even predicts a perfect trade-off between the two functions. Indeed, the amount of information that can be kept active during processing would depend entirely on the cognitive load of the processing activity, which is the proportion of time it occupies attention and impedes the refreshing of memory traces. We will begin by reviewing some of the empirical evidence we gathered in favour of the TBRS model concerning the trade-off between processing and storage.

Interference between processing and storage

As the seminal work of Baddeley and Hitch (1974) made clear, the tasks requiring simultaneous processing and storage are especially suited for working memory enquiry. This is the case in complex span tasks, where a series of digits, letters, or words have to be maintained while performing some demanding activity such as reading sentences for comprehension or problem solving. If performance on these tasks has proved to be so predictive of high level cognition and fluid intelligence (Kane, Hambrick, Tuholski, Wilhelm, Payne, & Engle, 2004), it is probably because they quite perfectly mimic the natural functioning of a working memory alternating between processing and maintenance requirements. Thus, we tested the predictions of the TBRS in complex span tasks. Because our main hypotheses concern the role of time, and contrary to the most frequently used working memory span tasks such as the reading span or the operation span tasks that are self-paced, we designed computer-paced tasks that allow for a strict control of temporal parameters.

The TBRS model predicts that variations in the cognitive load involved by processing activities would have a direct impact on the concurrent maintenance of information, with higher cognitive load having a more disruptive effect on maintenance. We tested this prediction in a series of studies in which adult participants were presented with series of letters for further recall, each letter being followed by a series of digits to be read that appeared successively on screen at a regular rhythm (Barrouillet et al., 2004). Because cognitive load corresponds to the proportion of time during which the task occupies attention, there are two ways of increasing this load, that is, either by increasing the amount of work to be done in a fixed period of time, or by reducing the time allowed to do a given amount of work. This was done by increasing the number of digits to be read within a fixed interletter interval, and by decreasing the duration of this interval while keeping constant the number of digits to be read, respectively. In the first case, either 6 or 10 digits were displayed over a total period of 6 s after each letter (Barrouillet et al., 2004, Exp. 4). Using a span procedure, the length of the series of letters to be recalled was progressively increased from 1 to 7 until the participants failed to recall all the series of a given length (there were three series of each length). Each correctly recalled series counted as one third, and the total number of thirds was added up to provide a span score. In line with our prediction, increasing the cognitive load of the processing component of the task resulted in poorer recall, the 10-digit condition resulting in lower span than the 6-digit condition (2.77 and 4.28 respectively). Interestingly, reducing the time allowed to read a given number of digits had a comparable effect. In a following experiment, we increased the cognitive load of the task by reducing the time available to read each digit from 1 s to 600 ms (there were either 5, 6, or 7 digits after each letter in both conditions). As we predicted, the faster pace of the reading task resulted in poorer recall (mean span of 3.01 compared to 4.67 with the slow pace). The same results were extended to a different task in which the processing component consisted in solving arithmetic problems instead of reading digits. After each letter, a one-digit operand was displayed on screen for 1 s, followed by a series of sign-operand pairs drawn at random from 4 possible pairs (i.e., + 1, + 2, - 1, - 2). Participants were asked to perform the operations aloud. For example, for the string 4 / + 1 / - 2 / + 1, the expected answer was “four, plus one, five, minus two, three, plus one, four”. This task was named the *continuous operation span* task. The critical variable was the time allowed to process each operand-pair that was either 1.2 s or 2.0 s. As predicted by the TBRS, reducing the time allowed to perform each operation increased the cognitive load of the continuous operation and resulted in lower span (mean spans of 2.88 and 1.80 respectively for the 2.0 s and 1.2 s conditions respectively).

In a final experiment, we investigated the nature of the trade-off function between processing and storage. For this purpose, the reading digit span task was used in which the cognitive load of the reading task was systematically varied by manipulating simultaneously the number of digits to be read after each letter (either 4, 8, or 12) and the total time allowed to read them (6 s, 8 s, or 10 s), resulting in 9 different values of cognitive load. The results revealed that increasing the cognitive load, expressed as the number of digits read per second, resulted in a smooth decline of recall performance following a linear trend (Figure 1).

We interpreted this result as demonstrating that the retrieval from long-term memory involved in reading digits, or in solving very simple arithmetic operations, is sufficient to capture attention and to impede the refreshment of memory traces. As such, these results clearly indicate that processing and storage interfere in working memory and, therefore, they rule out a strong version of the multi-component model assuming a sharp distinction between executive control and storage. However, a weak version could accommodate such findings by assuming that processing and storage interfere when they involve representations pertaining to the same domain. For example, in all the studies evoked above, both the processing and the storage components of the tasks involved verbal material that could create peripheral interference. Of course, we demonstrated that the effects of processing on storage went beyond what could be expected from the mere concurrent articulation resulting from processing verbal material. For example, solving the operations of the continuous operation span had a far more detrimental effect on the concurrent maintenance of letters than simply reading these operations and their answers (Barrouillet et al., 2004, Exp. 2). Nonetheless, the observation of central interference occurring between domains is needed to ascertain the

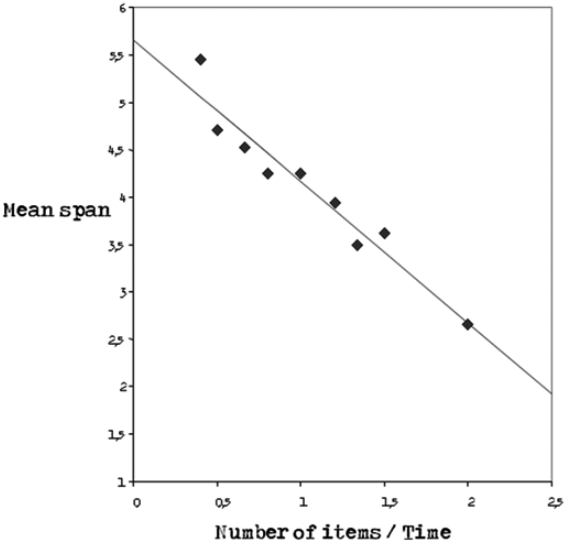

Figure 1
Mean working memory spans as a function of the cognitive load of the processing task expressed as the number of digits to be read per second in Barrouillet, Bernardin, and Camos (2004, p. 83-100) © APA, adapted with permission

existence of an involvement of executive control in storage activities. The following section will address this question.

Central interference in working memory

As we have seen above, one of the main tenets of the multi-component model of working memory is that processing and storage functions involve distinct structures and processes fuelled by distinct pools of resources. Thus, the two functions could interfere with each other when involving representations pertaining to the same domain, but processing a given type of information would not disrupt, or only to a very little extent, the maintenance of representations pertaining to another domain. This conception delineates a clear distinction between storage activities on the one hand and executive control on the other, with a central executive exclusively devoted to processing activities. Though a host of studies using the selective interference paradigm have provided seemingly strong evidence in favour of this thesis, many findings indicate that processing and storage actually interfere with each other in a predictable way.

According to the TBRS model, temporal constraints are one of the main characteristics of central processes. Thus, the implication of executive control in maintenance activities and the resulting central interference between processing and storage cannot be observed without a careful control of the temporal aspects of the tasks. This is what we did in recent studies investigating between-domain interferences in complex span task settings. A first illustration will be given with interference between the visual and the spatial domains of working memory.

Central interference between visual and spatial working memory

To characterise the peripheral slave systems of working memory, studies using the selective interference paradigm led to distinguish between verbal and visuo-spatial domains, but also to a further fractionation of this latter system into a visual and a spatial component (Baddeley, 2007; Baddeley & Logie, 1999; Logie, 1995). For example, viewing irrelevant pictures appeared to selectively interfere with visual but not spatial memory, whereas concurrent movements selectively interfered with spatial memory (Logie & Marchetti, 1991), a pattern found in many studies (e.g., Darling, Della Salla, & Logie, 2007; Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Hecker & Mapperson, 1997). It could be argued that most of these studies were inappropriate to test the hypothesis of an involvement of executive control in storage activities because they mainly involved passive tasks that do not solicit attentional control (e.g., viewing irrelevant pictures). However, Klauer and Zhao (2004) reported the selective interference pattern when combining visual and spatial storage (memory for Chinese ideograph and locations of dots respectively) with attention demanding visual and spatial tasks (i.e., the judgment of colours as “more red than blue” or “more blue than red”, and the search for a stationary target within a display of 11 moving objects respectively). In the same way, Duff and Logie (1999) combined a spatial tracking task with the storage of visual forms and found maintenance unaffected. Thus, studies based on the selective interference paradigm clearly supported the fractionation between visual and spatial systems, a fractionation that also received confirmation from neurophysiological investigations (e.g., Ungerleider & Haxby, 1994).

While this consensus seems impressive, it could be noted that, in all of these studies, participants performed the tasks at their own pace, whereas, as we noted above, careful control of time is probably needed to reveal any involvement of executive control. We filled this gap in a recent study in which we combined visual and spatial processing with visual and spatial storage in computer-paced working memory span tasks (Vergauwe et al., 2009). Participants were required to memorise series of ball movements or visual patterns as spatial and visual memoranda respectively. Each item to be memorised was followed by a processing phase during which participants performed either a spatial or a visual task on a series of stimuli successively displayed at a fixed rhythm. The spatial tasks involved judgments about the symmetry of geometrical patterns or the spatial fit of a line between two dots (Figure 2), whereas the visual task required a colour discrimination (i.e., “more red than blue” or “more blue than red”?).

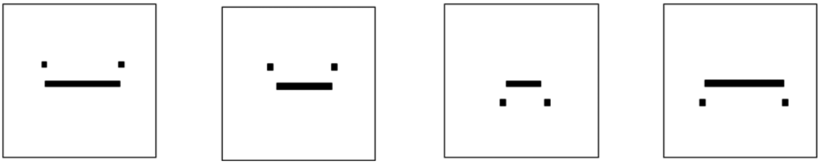

Figure 2
Examples of stimuli used in the spatial fit task in Vergauwe, Barrouillet, and Camos (2009, p. 1012-1028) © APA, adapted with permission

We reasoned that central interference would be revealed by a trade-off between processing and storage, not only within, but between domains. For this purpose, we manipulated the cognitive load involved by the processing tasks by varying the number of items to be processed within a processing phase of fixed duration (i.e., 3, 5, or 7 items within a delay of 8,500 ms). The TBRS model assumes that recall performance depends on the cognitive load of the concurrent task, that is, the proportion of time during which it occupies attention. Within this framework, the duration of the attentional capture during which memory traces suffer from a time-related decay is more important than the exact nature of the process that causes this capture. Thus, above and beyond peripheral interference that could occur when both activities involve the same type of representation (i.e., when both processing and storage involve visual or spatial material), we predicted that variations in the cognitive load involved by spatial and visual processing tasks would have an isomorphic detrimental effect on spatial recall performance, the same going for visual recall performance.

The results perfectly confirmed our expectations. Increasing the cognitive load involved by both the visual and the spatial tasks by increasing the number of items to be processed disrupted spatial memory, and the two tasks did not differ from each other in their effect. The same occurred for visual recall performance that was disrupted to the same extent by increasing the difficulty of both the visual and the spatial tasks (Figure 3).

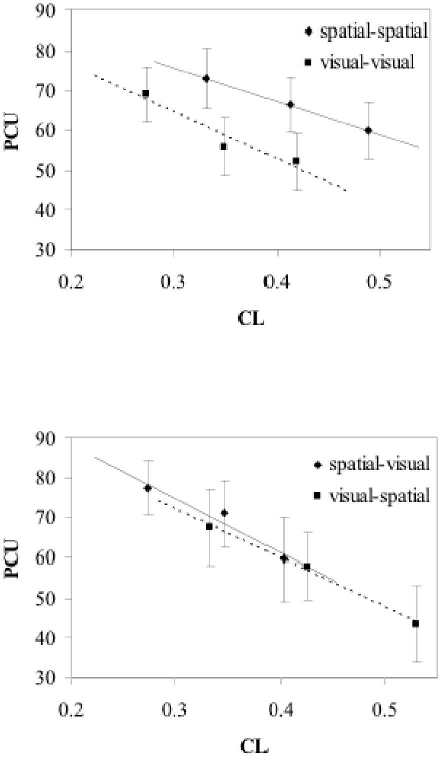

Figure 3

Mean recall performance expressed as Partial-Credit Units (PCU, Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005) as a function of the cognitive load involved by the processing component in the visuo-spatial working memory span tasks studied by Vergauwe et al. (2009). The top panel refers to within-domain conditions in which both storage and processing components involved either visual or spatial representations. The bottom panel refers to between domain conditions with spatial storage associated with visual processing (spatial-visual) and visual storage associated with spatial processing (visual-spatial)
(Vergauwe et al., 2009, p. 1012-1028) © APA, reprinted with permission

Thus, a careful control of the time allowed to perform the memory tasks, along with a manipulation of the attentional demand involved by their processing components led to a pattern of results completely different from what is usually observed through the selective interference paradigm. A trade-off occurred between processing and storage, suggesting that both activities rely on the same resource or supply and, more importantly, this effect occurred within but also between domains, demonstrating that this resource or supply is domain-general, contradicting the multi-component view of working memory. As the title of Vergauwe et al.'s (2009) article claimed, visual and spatial working memory are not that dissociated after all. However, it could also be acknowledged that visual and spatial systems can be merged into a unique system without abandoning the idea of a working memory fractionation, for example by assuming a clear distinction between verbal and visuo-spatial systems. In fact, there is no doubt that the evidence for a disruptive effect of processing on storage between the verbal and the visuo-spatial domains would constitute a more stringent criterion for the existence of central interference.

Central interference between verbal and visuo-spatial working memory

In a recent study, we extended our investigation of central interference in working memory by the combination of verbal and visuo-spatial activities (Vergauwe, Barrouillet, & Camos, 2010). Using approximately the same design of complex span tasks, we combined verbal and visuo-spatial storage (i.e., maintenance of series of 3 to 6 consonants and of locations within 4 x 4 matrices respectively) with verbal and visuo-spatial processing. The processing tasks were both two-choice reaction time tasks, requiring semantic categorisation for the verbal task (judging whether words were animal nouns or not) and spatial fit judgment for the visuo-spatial task (see Figure 2). As in the previous study, cognitive load was manipulated by varying both the duration of the processing phases and the number of stimuli to be processed. Low, medium, and high load conditions were created by presenting 4 items in 8,000 ms, 4 items in 5,172 ms, and 8 items in 8,000 ms respectively. When considering visuo-spatial recall performance, the same pattern of results as in the previous study emerged. Increasing the cognitive load of both the verbal and the visuo-spatial tasks had a detrimental effect on recall, and there was no effect of processing domain. The fact that visuo-spatial maintenance was disrupted to the same extent by verbal and visuo-spatial concurrent processing strongly suggests that the locus of the interference concerns central processes shared by storage and processing activities. Additionally it shows that peripheral interference resulting from similarity in the representations maintained and processed plays a minor role in working memory forgetting, at least when using visuo-spatial memoranda in a complex span paradigm (Figure 4).

The results concerning verbal storage were slightly different, and even more interesting. As for visuo-spatial memory, both the visuo-spatial and the verbal processing tasks had a disruptive effect on verbal memory, as the effect of cognitive load testified, which was significant for both tasks without any interaction with processing domain. However, and contrary to

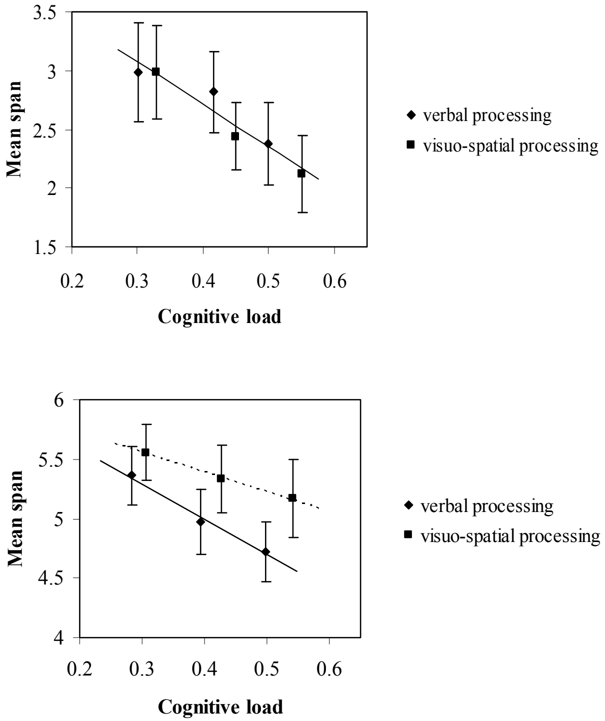

Figure 4
Mean working memory spans as a function of the cognitive load involved by the processing component in the working memory span tasks studied by Vergauwe, Barrouillet, and Camos (2010). The top and bottom panels refer to visuo-spatial and verbal storage respectively

visuo-spatial memory, there was a significant effect of processing domain, the verbal task having a more disruptive effect on verbal memory than the visuo-spatial task (Figure 4). This latter result suggests that, over and above the domain-general central interference occurring when verbal memory was combined with the visuo-spatial processing task, there was a domain-specific peripheral interference within the verbal domain that was not observed when the two components of the task involved visuo-spatial representations. This pattern of results suggested that, as recent studies have shown, verbal information is maintained in working memory by two different and independent mechanisms, attentional refreshing and articulatory rehearsal (Camos, Lagner, & Barrouillet, 2009; Hudjetz & Oberauer, 2007). By contrast, the visuo-spatial domain seems to lack a specialised mechanism of rehearsal, so that maintenance of visuo-spatial information has to rely entirely on attentional refreshing. Thus, verbal processing would interfere with both mechanisms, whereas visuo-spatial processing would only impede attentional refreshing, explaining the pattern of results we observed.

The fact that variations in the cognitive demand of a visuo-spatial task have a disruptive effect on the concurrent maintenance of verbal information, and that the other way round, increasing the cognitive demand of a verbal task disrupts the concurrent maintenance of visuo-spatial information not only suggests that processing and storage interfere in working memory, but that this interference occurs between domains, ruling out even the weak version of the multi-component model suggested by Baddeley and Logie (1999). These phenomena cannot be accounted for without assuming some central resource or supply implicated in both functions of working memory, whatever the nature of the information involved. Interestingly, other studies reported between-domain interference in a variety of situations, testifying for the generality of these phenomena. For example, Stevanoski and Jolicoeur (2007) observed that a tone-pitch discrimination had a disruptive effect on visual memory for coloured disks. In the other way round, Jolicoeur and Dell'Acqua (1998) observed that maintaining three instead of one letter for further recall systematically elevated the reaction times to the tone-pitch discrimination task. Concurring results were obtained by Chen and Cowan (2009) who reported a conflict between a speeded choice reaction time task on the location of a target (a red square) and the retention of verbal material, such as digits presented either in visual or auditory format. As we will see below, we observed similar results by demonstrating that the variations in the cognitive demand of a visuo-spatial task such as judging the location of a target appearing either on the upper or the lower part of the screen disrupted maintenance of verbal material such as letters (Barrouillet et al., 2007).

All these results suggest some central capacity or system shared by both processing and storage activities, whatever the domains they involve. It is usually assumed that this central capacity is attention, the amount of which would be limited (e.g., Chen & Cowan, 2009). However, as noted by Chen and Cowan (2009), these central inferences could be accounted for by two types of theoretical models that slightly differ from each other. On the one hand, as in Cowan's (1999) model, one could assume that competing activities continuously share a limited amount of resources, with central interference occurring when the need for attentional resource of one activity increases (e.g., processing), drawing more and more attention away from the other activity (e.g., storage), the output of which is thus impaired. On the other hand, central interference would occur when the amount of time spent by one function using those attentional resources increases, thus postponing other activities. Such a postponement could have detrimental effects when the time available to perform the activity is limited, or when what is postponed is the refreshment of decaying memory traces. This latter conception corresponds to the TBRS model.

Though being different, both accounts presume that interference occurs because concurrent activities compete for attention, thus assuming that the locus of interference between processing and storage is the central system in charge of controlling attention. In other words, and contrary to the multi-component view of working memory, the storage function of working memory would require executive control. The extent literature suggests that executive control is involved in at least two processes related to storage. The first process takes place in the earliest steps of encoding in short-term memory and has been named consolidation by Jolicoeur and Dell'Acqua (1998). This process transfers representations produced by perceptual encoding into a more durable form of memory, and there is evidence that this requires central processing mechanisms. Indeed, Jolicoeur and Dell'Acqua (1998; see also Stevanovski & Jolicoeur, 2007) have demonstrated that encoding items for further recall causes interference in concurrent central processes such as response selection, even if the SOA between encoding and response selection varies from 300 ms to 1,600 ms. Interestingly, this phenomenon is not related to the mere perception of these items because interference does not occur when they do not have to be memorised. The second process concerns the maintenance of the durable storage resulting from consolidation. As we noted above, Raye et al. (2007) have identified a mechanism of refreshing that is distinct from verbal rehearsal, and which may be related to the reactivation of memory traces through attentional focusing. They described this mechanism that involves left dorsolateral PFC as a minimal executive function. Thus, contrary to the multi-component view of working memory, the two functions of working memory, processing and storage, cannot be strictly distinguished on the basis of their underlying systems. Instead, both functions appear to require executive control. As a direct test of this hypothesis, we systematically explored the effects on storage of the concurrent involvement of the central executive.

Executive functions and working memory

In the last years, we conducted a series of studies to investigate the relationships between executive functions and working memory, with the hypothesis that working memory maintenance would suffer from the concurrent involvement of executive processes that occupy the central bottleneck, thus preventing the refreshment of decaying memory traces. A corollary assumption was that this damaging effect on storage would depend on the time during which the central bottleneck is occupied, which determines the time during which memory traces decay, and not on the nature of the executive function concurrently involved. Our first studies investigated the damaging effect on working memory of concurrent retrievals from long-term memory, such as those involved in reading digits or performing elementary running counts while maintaining letters (see for example Barrouillet et al., 2004; Lépine, Bernardin, & Barrouillet, 2005). This first approach was further extended to other executive functions such as response selection, task switching, updating, and inhibition. The present section offers a brief overview of these studies.

Response selection

We explored the effect of response selection on concurrent maintenance in Barrouillet et al. (2007). As in most of our previous studies, we used a computer-paced working memory span task in which participants were presented with series of letters to be remembered, each letter being followed by a series of digits. However, in this case, these digits were displayed either in the upper or the lower part of the screen. Two experimental conditions were contrasted that varied in the executive functions they required. A first condition involved retrieval from long-term memory as well as response selection: participants were asked to judge the parity of the digits by pressing appropriate keys. By contrast, the second condition only required response selection: participants were presented with the same items, but they only had to judge the location of the digits on the screen (either up or down). The pace of these intervening activities and the resulting cognitive load was varied by manipulating the number of digits (either 4, 6, or 8) presented in a constant interletter interval of 6,400 ms. The TBRS assumes that both memory retrieval and response selection occupy the central bottleneck that it is consequently unavailable for implementing attentional refreshing. As a consequence, in both experimental conditions, recall performance should be a function of the proportion of time during which processing involves central processes. Because the parity task involved an additional process of memory retrieval and a longer attentional capture, we predicted lower performance in this condition, but in both conditions the effects on recall were expected to depend only on temporal parameters (i.e., the duration of the attentional capture) and not on the nature of the process involved.

The results revealed a strong effect of pace in both tasks, but lower spans in the parity than in the location condition (mean spans of 4.48 and 5.23 respectively), reflecting the longer response times elicited by the parity task (a mean of 554 ms per item compared to 411 ms for the location task). To test the hypothesis that recall performance mainly depends on the time during which the concurrent task involves central processes, a raw estimation of the cognitive load involved by the processing component was calculated in each of the 6 experimental conditions. This was done by dividing the mean total processing time (i.e., the mean sum of the response times for all the digits within the interletter intervals) by the total time allowed (i.e., the duration of these interletter intervals: 6,400 ms)[1]. The mean span scores were then regressed on this approximate cognitive load for each condition, revealing two slopes that were very close (- 7.82 and - 7.68 for the parity and the location tasks respectively) as well as the two intercepts (8.04 and 7.84 respectively). This suggested that recall performance was almost entirely determined by the time allocated to the processing component rather than by its nature (Figure 5).

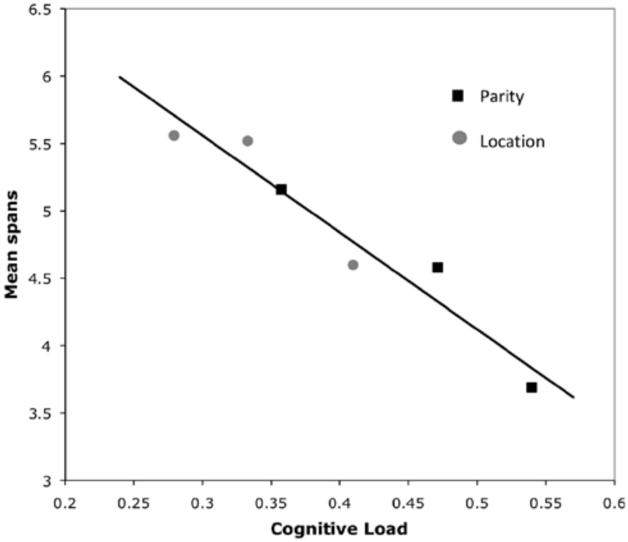

Figure 5
Mean working memory span as a function of the cognitive load involved by the location and the parity tasks for 4, 6, and 8 stimuli presented in each interletter interval with the regression line in Barrouillet, Bernardin, Portrat, Vergauwe, and Camos (2007, p. 570-585) © APA, adapted with permission

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[1] This method only provides us with a raw estimate of cognitive load, because processing times (i.e., the time elapsed from stimulus onset to response) cannot be considered as reflecting a continuous capture of attention. It is possible, for example, that the first steps of perceptual encoding or the execution of the motor response allow for other processes in parallel such as memory refreshing. Nonetheless, variations in response times between two experimental conditions probably reflect variations in the duration of the occupation of attention and thus in the cognitive load that these conditions involve.

What do the results of this study tell us about working memory functioning? First, as Barrouillet et al. (2007) concluded, even a simple response selection is sufficient to disrupt concurrent maintenance and impair recall performance. This fact demonstrated that the effects of processing on maintenance do not entirely rely on the competition of the two functions for a definite process such as memory retrieval, as we surmised in the first elaboration of the TBRS model. Rather, the effect of processing activities on maintenance is a function of the time during which executive functions are involved, such as memory retrieval of course, but also response selection. Moreover, these effects appeared largely independent from the nature of the processes involved: when temporal factors are controlled, a spatial task and a parity task had a comparable effect on verbal memory, strongly suggesting that the critical factor is the time during which the central executive is unavailable to refresh and reconstruct precise representations of the memory items. This conclusion was further tested by studying the effect of task switching on concurrent storage.

Task switching

According to Friedman, Miyake, Young, Defries, Corley, and Hewitt (2008), switching or shifting attention from one mental set to another is among the three most often studied executive functions along with working memory updating and inhibition, the switching process having even been referred to as the “gold-standard measure of executive control” (Kane, Conway, Hambrick, & Engle, 2007, p. 35). The study of the potential effect of task switching on concurrent maintenance was of particular interest because Logan (2004) tested the hypothesis that working memory and task switching share a single common set of resources and came to a negative response. Logan (2004) had participants memorise series of task names (*Odd-Even*, indicating a parity judgment, or *High-Low*, indicating a magnitude judgment). These tasks were subsequently applied to series of digits of the same length as the corresponding series of tasks. For each digit in the target list, the corresponding task had to be performed by retrieving the task name from the memorised list and applying it to the presented digit. The maximum number of correctly remembered and executed tasks constituted the span task. The critical fact was that series of task names requiring task switching after every target stimulus (e.g., *High-Low*, *Odd-Even*, *High-Low*, *Odd-Even*, *High-Low*, *Odd-Even*) yielded the same span task as series requiring only one task switching (i.e., *High-Low*, *High-Low*, *High-Low*, *Odd-Even*, *Odd-Even*, *Odd-Even*), suggesting that task switching has no impact on working memory.

Though the span task designed by Logan is a very interesting and original task, it is worth noting that it is self-paced, so that timing parameters were not controlled. Thus, this task is inappropriate for detecting the effects resulting from a time-based resource sharing between switching and storage. As a consequence, we designed a new computer-paced span task in which participants were asked to maintain series of 3 to 6 letters for further recall, each letter being followed by 8 digits successively displayed on screen at the fixed pace of one digit every 1,200 ms, with half of these digits coloured in blue and the other half in red (Liefooghe, Barrouillet, Vandierendonck, & Camos, 2008). Participants were asked to perform a parity task (i.e., *is the number odd or even?*) on the blue digits and a magnitude task (i.e., *is the number larger or smaller than 5?*) on the red digits. Two conditions were compared that involved the same series of digits, the order of which was manipulated in the same way as in Logan (2004) to create either high-switch lists, necessitating 5 or 6 switches, or low-switch lists, that required only 2 or 3 switches. The hypothesis that executive control is needed to maintain working memory traces active led to the prediction that the high-switch lists should have a more detrimental effect on recall performance than the low-switch lists. This is what we observed. Participants recalled a mean of 56.2 out of 72 letters in the low-switch condition compared with 52.9 in the high-switch condition. In a further experiment, this effect was replicated using a Brown-Peterson task instead of a complex span paradigm. In this task, series of 3 to 8 letters to be recalled were presented as a preload before a list of 8 digits requiring either few or many switches, as in the complex span task. Once more, lists with more switches resulted in poorer recall.

Our interpretation of these phenomena was that switching from one task set to the other occupies the central bottleneck, preventing the refreshment of decaying memory traces. More switches mean longer periods during which these refreshing activities are prevented and, as a consequence, greater decay and poorer recall. We were able to corroborate this analysis through an additional experiment. We reasoned that if the poorer memory performance in the high-switch condition was due to the extra occupation time of the focus of attention resulting from additional switches, any other attention demanding activity occupying the central bottleneck for an equivalent period of time should produce the same effect. Thus, within the complex span task described above, we designed a third condition with low-switch lists of digits, but in which these digits were degraded, involving longer processing times. This was done in such a way that processing the digits of the degraded low-switch lists took approximately the same time as processing the digits of the high-switch lists. The results confirmed the predictions of the TBRS model: the high-switch and the degraded low-switch conditions elicited similar and poorer recall performance than the low-switch condition. Thus, as we surmised, the locus of the detrimental effect of the switching process on concurrent maintenance was on the time during which it occupied the central bottleneck and prevented the activities of refreshment of the memory traces that decayed during this period.

Along with task switching, updating and inhibition are commonly considered as the main executive functions (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). Accordingly, we tested their effects on concurrent maintenance in two series of experiments (Camos, Portrat, Vergauwe, & Barrouillet, 2007; Portrat, 2008). Updating is a crucial ability that permits to renew the content of working memory to deal with the continuous changes triggered by modifications of external environment or previous processing episodes. The inhibition of prepotent responses has been considered as one of the major executive functions and is one of the most often studied with memory updating and set shifting (Friedman et al., 2008). The rationale of our experiments was the same as for the study of switching. We used computer-paced complex span tasks in which each item to be memorised for further recall was followed by a series of items to be processed. Requirement of the executive processes of updating or inhibition was manipulated by varying the nature of the stimuli and the nature of the task to be performed on them.

Updating

We studied updating using complex span tasks in which the memoranda were lists of digits while the stimuli to be processed consisted of series of letters. In the updating condition, participants were asked to perform a 2-back task by judging if the letter currently displayed on screen was the same as the letter presented two trials before. This condition that requires a constant updating of the content of working memory was compared with a task in which participants were presented with the same series of letters, but had only to decide if the current letter matched one of the two first letters of the series. This latter task requires that these two letters had to be maintained in working memory, but does not require an updating of its content. Thus, our hypothesis was that the updating condition would involve a longer occupation of the central bottleneck and consequently poorer recall performance. Accordingly, it appeared that processing the letters took longer in the updating than in the control condition and resulted in poorer recall.

It is worth to note that this result provides strong support for the hypothesis that any additional involvement of the central executive has a damaging effect on concurrent storage. Indeed, the two conditions under comparison involved exactly the same lists of digits to be maintained, the same series of letters presented in the same order, the same task of comparison of these letters with targets maintained in working memory. The sole difference was that, in the control condition, these targets remained unchanged in working memory over the series under study, whereas they were continuously renewed in the updating condition, strongly suggesting that the updating process itself caused the memory loss.

Inhibition of prepotent responses

For studying the effect of the inhibition of prepotent responses on concurrent maintenance, we used of the well-known Stroop effect. The complex task still involved lists of digits to be remembered, but the processing component was a colour naming task. Each digit was followed by a series of either neutral words (“soft”, “known”, “rare”, “useful”) or colour words (“red”, “yellow”, “green”, “blue”) that appeared on screen either in blue, red, green, and yellow. In the colour word condition, 50% of the trials were incongruent (e.g., the word “red” appearing in green). Participants were asked to identify this colour. The prepotent response of reading the word displayed on screen created a response conflict that needed to be inhibited in order to name the colour in the colour word condition. This inhibition was not needed in the control condition with neutral words. We verified in an independent pre-test that performing the colour naming task took longer with colour words than with neutral words, testifying for the presence of an inhibitory process. This inhibitory process was expected to disrupt the maintenance of memory traces. Accordingly, the colour condition involved lower mean spans than the neutral condition.

This result was replicated and extended in a further experiment in which the memoranda were lists of words, whereas the processing task consisted of enumerating small sets of either letters or digits successively displayed on screen. The need to inhibit prepotent responses was induced by creating conflicts between the number of digits displayed and their numerical value in incongruent trials (e.g., displaying four digits “3”). This conflict did not occur in the control condition with letters. Once more, the need to inhibit the prepotent response of reading the digits in the incongruent trials of the digit condition resulted in poorer recall performance.

As the studies reported in this section made clear, the involvement of executive functions has a disruptive effect on the concurrent maintenance of information in working memory. Switching attention from one task to another, retrieving an item of knowledge from long-term memory, updating the content of working memory, selecting an appropriate response, and inhibiting prepotent but interfering responses have the same effect of leading to working memory loss. These findings strongly suggest that the central executive plays a pivotal role, not only for processing, but also for storage, and that increasing the attentional demand of processing results in the corollary reduction of the number of items that can be stored and recalled. Moreover, in line with the TBRS model, and as the comparison between the effects of memory retrieval and response selection suggested, this effect is mediated by temporal factors. These points will be the topic of the next and conclusive section.

The relationship between executive control and working memory

In the introduction of this article, we recalled that the standard model of working memory proposed by Baddeley and Hitch (1974; see also Baddeley, 1986, Baddeley & Logie, 1999) issued from a seminal attempt by these authors to consider the short-term store of the modal model of Atkinson and Shiffrin (1968) as a working memory. The outcome is well known: the short-term store was not a good candidate for this role, and an additional central executive was needed to account for processing information when the storage functions of short-term memory were exhausted. Initially considered as fulfilling processing, but also storage functions when needed, this central executive was restricted in the further versions of the theory to its processing functions while slave systems were devoted to storage. The resulting multi-component view of working memory proved to be extraordinarily heuristic and elicited a host of studies that provided strong support to this conception. However, most of the studies reported above contradicted the fractionations proposed by the multi-component model and led to reconsider the relationship between executive control and working memory.

Central executive and working memory functioning

When presenting the standard theory of working memory, we concluded that it has resolved the question of the relationships between working memory and executive control by separating *working* from *memory*, the former function being fulfilled by the central executive, while the latter is taken in charge by a collection of slave systems. Though this fractionation is appealing, it has so often been contradicted by facts that there is no doubt that what is known as the central executive is involved in storage and maintenance of information in working memory, whatever the nature of this information. Two main facts support this assumption. First, we observed that variations in the attentional demand of processing have an impact on the concurrent maintenance of information. This is true when both processing and storage involve representations pertaining to the same domain, but also when these representations pertain to different domains. Second, all of our studies revealed that not only processing has an impact on storage, but that there is a quasi perfect trade-off between the two functions. Increasing the demand of processing always results in a smooth decline of the amount of information that can be concurrently maintained. Far from being two clearly separate functions subserved by distinct systems and fuelled by different pools of resources, processing and storage appear as closely related with each other as the two sides of the same coin.

As our inquiry into the impact of executive functions on working memory revealed, the simplest way to account for all these phenomena is to assume that the central executive is involved in both functions of working memory. Any additional involvement of an executive function in the processing component of a complex span task results in memory loss and poorer recall performance. This means that the central executive is also in charge of the maintenance of information in working memory. The mechanism whereby this function is assumed has been described as a covert retrieval by Cowan (1992) or a minimal executive function by Raye et al. (2007). Moreover, our studies did not only reveal the role of the central executive in the maintenance of any type of information in working memory, but they also demonstrated that this role is mediated by time.

A role mediated by time

The assumption that the close relationship between processing and storage in working memory is mediated by time is perfectly illustrated by the data reported in Figures 1 and 5. As the TBRS predicts, recall performance in complex span tasks is a function of the cognitive load involved in processing, with cognitive load being defined as the proportion of time during which processing occupies attention. Moreover, all of our studies suggest that this function is linear. The simplest explanation of this phenomenon is to assume a serial functioning of the central executive, which would alternate between maintenance episodes during which working memory items are maintained active or refreshed by attentional focusing, and processing episodes during which these same memory traces suffer from some degradation. Once more, the simpler hypothesis concerning this degradation is to assume that it occurs through time-related decay, with recall performance being a direct function of the balance between the respective durations of the periods of decay and refreshment.

Of course, it could be assumed that these phenomena can be accounted for without any recourse to a temporal decay hypothesis, and that memory traces are degraded through interference resulting from the encoding and treatment of the representations involved in processing. According to such an alternative hypothesis, the time-related trade-off function between processing and storage observed in Figure 5 would result from the fact that cognitive load, as defined by the TBRS, determines the time during which attention is available to repair the damages provoked by interference. These damages are then independent from the duration of the processing episodes. This explanation, suggested by Lewandowsky, Oberauer, and Brown (2009; see also Lewandowsky & Oberauer, 2009) may seem plausible, but is implausible in regard of most of the results we gathered. For example, when considering the between-domain function relating spans to cognitive load as reported in Figure 4, we have to assume that the verbal and the visuo-spatial tasks (semantic categorisation of words and spatial fit judgments on lines respectively) would provoke the same amount of representation-based interference on memory for locations in 4 x 4 matrices, something which is at odds with all the current models of interference in short-term memory.

Assuming a time-related decay of working memory traces while attention is occupied by processing and a mechanism of refreshment of these memory traces when attention is available for maintenance purpose appears to be the simplest way to account for the time-related trade-off function between processing and storage. As we stressed above, such a conception closely relates executive control with both functions of working memory.

Is executive control coextensive with working memory?

Is working memory something else than executive control, and do we need two different concepts for the same system if the central executive is in charge of both processing and storage functions in working memory? It can be noted that some theorists adopted such a unitary conception of working memory. For example, Just and Carpenter (1992) proposed a model in which working memory corresponds approximately to the central executive described by Baddeley (1986) and in which there is no modality-specific system of storage. In the same way, Engle, Kane, and Tuholski (1999) and Cowan (1999, 2005) propose unitary conceptions in which working memory is that part of long-term memory activated above threshold. In these conceptions, there is no structure corresponding to slave systems, but rather different coding strategies and procedures for maintaining information under the supervision of the central executive. As our studies on central interference suggest, the mechanism of refreshment of memory traces through attentional focusing described by the TBRS model is domain-general, and we could conclude that working memory may be restricted to executive control. However, this would probably constitute an over simplification.

As we noted above, Vergauwe et al.'s (2010) study revealed a striking phenomenon. When exploring central interference, we observed that both a verbal and a visuo-spatial task had the same disruptive effect on visuo-spatial memory. However, this was not true for verbal information that was disrupted in a greater extent by a verbal than by a visuo-spatial task. This suggests that manipulating verbal information in the secondary task not only occupied the central mechanism of attentional refreshing, but also blocked or at least impaired some mechanism of maintenance specifically devoted to verbal memory. This could be the mechanism of verbal rehearsal as described by Baddeley, a mechanism that remained unaffected by visuo-spatial processing.

In a recent study, we investigated the existence of these two mechanisms and their relationships by manipulating both the cognitive load and the level of articulatory suppression involved by the processing component of a complex span task (Camos et al., 2009). We assumed that increasing the cognitive load would affect attentional refreshing, whereas a concurrent articulation would affect verbal rehearsal. Participants were presented with series of letters to memorise with each letter followed by 6 digits. Two tasks were designed differing in cognitive load. In a low cognitive load condition, participants were asked to press the space bar when they detected the digit 5, whereas in the high cognitive load condition, they were asked to verify that the 3rd and 6th digits were the correct sum of the two previous digits by pressing one of two keys for either the "correct" or the "incorrect" responses. In order to manipulate the level of articulatory suppression, participants were asked to perform these tasks either silently or to read aloud all the digits. The results revealed that both factors had an effect on recall performance, which was poorer for the verification than for the detection task, and poorer when participants read the digits aloud rather than silently. Interestingly, these two effects were additive and did not interact with each other. This suggests that verbal information may be maintained by two independent mechanisms (i.e., attentional refreshing and verbal rehearsal) that can work jointly, because a processing component combining a high cognitive load and an articulatory suppression resulted in greater memory loss than a task involving only one of these two constraints.

This result suggests that the mechanisms responsible for the maintenance of information in working memory go beyond executive control and that, at least for verbal information, a specific mechanism can supplement attentional refreshing and increase the efficiency of storage. We have noted above that the results of Vergauwe et al. (2010) suggested that such a specific mechanism does not exist for visuo-spatial information, something that could account for the fact that visuo-spatial working memory spans are regularly found to be lower than verbal spans. However, this is not to say that there is no other specialised domain-specific mechanism devoted to the maintenance of, for example, auditory, motoric, musical, or olfactory information. Thus, it can not be assumed that executive control is coextensive with working memory, even if the two mechanisms are closely related.

Concluding comments

We noted above that the hypotheses proposed by the multi-component model of working memory, including the sharp distinction between the two functions of processing and storage with their specific structures as well as the fragmentation between domains that would not allow for central interference are no longer tenable. We have reported empirical evidence of a quasi perfect trade-off between processing and storage, indicating a competition for a unique resource, and that between-domain central interference appears as soon as temporal parameters are carefully controlled. Thus, instead of considering working memory as a composite structure in which each element is devoted either to processing or to storage functions, our results point to a more integrative view in which both functions are subserved by the same mechanisms of executive control that direct attention alternatively to processing and maintenance operations. Although being contradictory with the standard version of the multi-component model (Baddeley, 1986; Baddeley & Logie, 1999), the present proposal is not at odds with its later developments, and more precisely with the hypothesis of an episodic buffer that would hold multi-modal representations, binding together features issued from several distinct slave systems (Baddeley, 2000). Indeed, and contrary to the slave systems, this episodic buffer is not supposed to have its own mechanism for refreshing information such as an articulatory loop or an inner scribe. This function is assumed to be controlled by the central executive through attention (Repovs & Baddeley, 2006). Even if there is no mention of temporal parameters that proved so important in all the experiments that we reported in this article, this hypothesis of multi-modal representations maintained active by the central executive is meshed with our proposal of a central executive in charge of both processing and storage functions. As such, the evidence of the involvement of executive control in the maintenance of all kind of information delineates the agenda of our further investigations of working memory functioning and structure. As Camos et al. (2009) did for verbal information, disentangling central and peripheral interference would provide us with a clearer picture of the relationships between a central executive in charge of the maintenance and processing of integrated representations, and specialised peripheral mechanisms maintaining active domain-specific information. What the findings reported in this article suggest is that this structure could prove different from the widely accepted standard model of working memory and that its functioning is strongly constrained by temporal factors.

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