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The Maintenance of Cross-Domain Associations in the Episodic Buffer

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The episodic buffer has been described as a structure of working memory capable of maintaining multimodal information in an integrated format. Although the role of the episodic buffer in binding features into objects has received considerable attention, several of its characteristics have remained rather underexplored. This is the case for its maintenance capacity limits and its separability from domain-specific maintenance buffers. The present study addressed these questions, making use of a complex span paradigm in which participants were asked to maintain cross-domain (i.e., verbal–spatial) associations. The 1st experiment showed that the capacity limit for these cross-domain associations proved to be lower than the capacity limit for single features, and did not exceed 3. Cross-domain associations and single features depended, however, to the same extent on attentional resources for their maintenance. The 2nd experiment showed that domain-specific (verbal or spatial) resources were not involved in the maintenance of cross-domain information, revealing a clear distinction between the episodic buffer and the domain-specific buffers. Overall, in line with the episodic buffer hypothesis, these findings support the existence of a central system of limited capacity for the maintenance of cross-domain information.

Keywords: working memory, episodic buffer, cross-domain

When testing Atkinson and Shiffrin's (1968) assumption that the short-term store of the modal model was a working memory (WM), Baddeley and Hitch (1974) concluded that the idea of a WM comprising a single unitary store might be abandoned. Instead, they proposed the well-known three-component model that distinguished between attentional control and temporary storage, which was served by two systems, a verbal and a visuospatial one. This model proved remarkably heuristic, and even though it underwent several evolutions concerned with the specific relationship between its constituent subsystems, it remained basically unchanged in its structure until the introduction of a new component, the episodic buffer (Baddeley, 2000). This episodic buffer was intended to overcome the problems encountered by the multicomponent model. One of the main problems of the three-component model was concerned with the fact that the representations constructed and maintained by WM are essentially multimodal, providing us with integrated and coherent scenes of our environment. That is, the representations that constitute the content of our conscious awareness are multimodal in nature, as opposed to purely verbal or visuospatial. In the three-component model, there was no subsystem that could provide temporary storage for such kind of information. Of course, the central executive was conceived in the original three-component model as playing a crucial role in this integrative function, but this system was itself devoid of any function of storage. And thus a new component was introduced, the episodic buffer, which was conceived as comprising "a limited capacity system that provides temporary storage of information held in a multimodal code, which is capable of binding information from the subsidiary systems, and from long-term memory, into a unitary episodic representation" (Baddeley, 2000, p. 417).

More than 10 years after its introduction, a survey of the literature reveals that among the functions that were initially attributed to the episodic buffer, research has mainly concentrated on binding, and this inquiry has, with rare exceptions, focused on binding within a given domain of WM, either visuospatial (e.g., colors and shapes bound into objects; e.g., Allen, Baddeley, & Hitch, 2006) or verbal (e.g., words bound into chunks or sentences; e.g., Baddeley, Hitch, & Allen, 2009). This is in sharp contrast with one of the distinctive features of this episodic buffer, its function of multimodal information storage. Its capacity to maintain multimodal information, as well as its limited maintenance capacity as opposed to its binding capacity, has remained largely neglected. What is the amount of multimodal information that can be maintained in face of distraction and interference? What are the factors that affect the maintenance of this type of information? To

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what extent can the episodic buffer be separated from the other storage systems of WM? These are the main questions addressed in the present study.

The Episodic Buffer and the Binding Process

The need for a new component of WM came from a series of problems encountered by the multicomponent model, essentially from neuropsychological and developmental studies (Baddeley, 2000). Though the hypothesis of a phonological loop accounted for a series of phenomena, it appeared that patients with an auditory span of one digit were able to recall up to four visually presented digits, suggesting some backup store capable of integrating visual and phonological information. In the same way, the preserved immediate prose recall in densely amnesic patients suggested a temporary activation of long-term memory (LTM) knowledge, but more importantly the capacity to create mental representations within some backup store (Baddeley, 2000). Evidence in children for a capacity of reactivating memory traces before their acquisition of adult subvocal rehearsal strategy, along with the difficulty to give a good account of maintenance mechanism in the visuospatial sketchpad, pointed toward the existence of some sort of general rehearsal that could involve the sequential attention to the items to be recalled (Baddeley, 2000). Overall, the need appeared for a store capable of maintaining information being integrated from both the two slave systems and LTM.

According to Baddeley, Allen, and Hitch (2010), the main question concerning the episodic buffer is its capacity to bind multimodal information into unitary objects, concepts, or episodes. Interestingly, in Baddeley's (2000) seminal article, it was acknowledged that initially the central executive was given a crucial role in binding, ignoring the fact that the central executive did not serve a storage function. The locus of the binding process concerned a very uncertain issue, as in Baddeley et al. (2010) it was acknowledged that the episodic buffer was initially envisaged as a buffer with a substantial but unspecified degree of processing capacity. At the introduction of the episodic buffer, it was conceived as a new component of WM as well as a fractionation of the central executive. More precisely, Baddeley (2000, p. 422) assumed that the episodic buffer could "provide the storage, and the central executive the underlying processing for episodic memory." Indeed, in the revised model (Baddeley, 2000; see Figure 1), it was proposed that information could not be fed into the episodic buffer directly from the slave systems, but either from episodic LTM or through the central executive, suggesting that the central executive was responsible for the binding process. It is probably this uncertainty about the locus of the process of binding that led to concentrate the research effort on this process and to leave the storage function of the episodic buffer rather underinvestigated.

Assuming that everything within WM accesses the episodic buffer via the central executive (see Figure 1), Baddeley and his colleagues developed a research program to test the hypothesis that blocking the central executive would specifically disrupt binding. Two domains were investigated: the binding of visuospatial features into objects and of words in the comprehension and retention of prose. In the visuospatial domain, Allen et al. (2006) assessed through probe recognition the retention of either isolated features such as shapes or colors or combinations of these features into integrated objects. In the former condition, participants were asked whether the probed color or shape was present in an original array of four shapes or four colors (i.e., individual feature conditions), whereas in the latter, they judged whether the probed feature combination had been present in an original set of four colored shapes, requiring a binding of the constituent features (i.e., binding condition). The involvement of the central executive was investigated by requiring participants to count backward in threes during the encoding phase. Adding such a secondary task led to a substantial and significant decrease in recall performance, but importantly this decrease was no larger in the binding than in the individual feature conditions. The authors concluded that binding features into objects does not involve more central executive resources than encoding single features. Likewise, the binding of temporally or spatially separated features was not more dependent on central executive resources than the encoding of already bound features (Karlsen, Allen, Baddeley, & Hitch, 2010), not even when they were presented in different modalities (e.g., visually and auditorily; Allen, Hitch, & Baddeley, 2009). These findings were corroborated by a series of studies showing that the maintenance of feature bindings in visual short-term memory does not require attention over and above that required for maintaining individual features (Delvenne, Cleeremans, & Laloyaux, 2010; Gajewski & Brockmole, 2006; Johnson, Hollingworth, & Luck, 2008; Yeh, Yang, & Chiu, 2005). Baddeley, Allen, and Hitch (2011) concluded from a review of these studies that the perceptual system binds all features automatically and that binding does not appear to depend on the central executive. Yet, not all studies on visuospatial binding would agree with this conclusion, as nonautomacity of binding visuospatial features has been observed in a number of studies (e.g., Olson & Jiang, 2002; Postma & De Haan, 1996; Wheeler & Treisman, 2002).

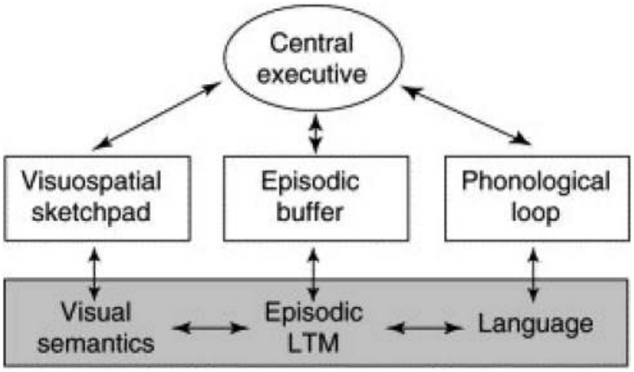

Figure 1. The structure of the multicomponent working memory model after the introduction of the episodic buffer. LTM = long-term memory. From "The Episodic Buffer: A New Component of Working Memory?" by A. Baddeley, 2000, *Trends in Cognitive Sciences, 4,* p. 421. Copyright 2013 by Rightslink. Reprinted with permission.

The other domain investigated involved binding in verbal WM and led to basically the same conclusions. Brener (1940) observed that immediate word recall performance dramatically increases when these words form part of a sentence compared with unrelated words, reflecting the recall of larger chunks in the case of prose (Tulving & Patkau, 1962). Using a variety of secondary tasks, Baddeley et al. (2009) observed that concurrent tasks had the same detrimental effect on recall of unrelated words (i.e., individual feature condition) and sentences (i.e., binding condition), suggesting no major role of WM in binding verbal information.

Overall, Baddeley et al. (2010) concluded from their studies that the episodic buffer operates as a multidimensional but essentially passive store that is not responsible for the formation of bindings, which appears to operate outside WM. Though this research program constitutes an extensive investigation of the binding process on two domains, important questions remain. Initially, as we noted above, the episodic buffer was proposed to tackle the problems encountered with the three-component model, the first of them being "the way in which the various components of WM, each using a different code, could be integrated" (Baddeley et al., 2010, p. 229). In this respect, the integration of visual features into objects and of words into sentences are key questions of cognitive psychology, but it could be argued that they do not concern the episodic buffer per se, because they do not primarily require the integration of different codes and occur within the visuospatial and the verbal systems, respectively. Moreover, understanding how binding is achieved is an important question, but the episodic buffer was also defined as a limited capacity system that provides temporary storage of information. Nonetheless, the vast majority of studies focused on very short retention intervals of 900 ms, while WM functioning obviously requires maintaining information over longer periods. Few studies have investigated this maintenance component of binding, and designs involving longer retention intervals led to mixed results. Using intervals of 4,100 ms, Morey and Bieler (2013) did not find any interaction between attentional load and binding in the maintenance of color–shape combinations, though Fougnie and Marois (2009), using even longer intervals of 6,800 ms, did observe that the recognition of bound visuospatial information was more disrupted by an attentive tracking task than was the recognition of single features.

In summary, the research program intended to investigate the episodic buffer seems to have neglected two crucial aspects of this new component of WM that are its storage function and its role of integrating information from the slave systems of WM. In the next section, we address the few studies that have investigated memory for cross-domain bindings through the integration of verbal and visuospatial information.

Cross-Domain Binding

Several studies have provided evidence for an integrated instead of independent maintenance of verbal and spatial information, thus suggesting the existence of the episodic buffer. For example, Elsley and Parmentier (2009), as well as Prabhakaran, Narayanan, Zhao, and Gabrieli (2000), presented participants with letters in locations for further recognition of the letters and the locations. At test, participants were to indicate whether both the letter and the location had been presented before, independently of their original association at study. Both studies observed that exact letter–location combinations were faster and more accurately recognized than recombined letter–location units. This is a result that cannot be accounted for by a model that presumes a separate storage of verbal and spatial features. Further evidence for an integrated maintenance of verbal and spatial features comes from studies showing that effects usually observed with verbal memoranda affect memory for spatial information when verbal and spatial information were shown integrated at study. For example, articulatory suppression, which is known to have no effect on the maintenance of single spatial features, has been shown to affect memory for spatial information when this information was presented in an integrated format with verbal information and this binding explicitly had to be maintained (Morey, 2009). The same phenomenon was observed with the phonological similarity effect (Guérard, Tremblay, & Saint-Aubin, 2009). Thus, little doubt exists about the interdependence of verbal and spatial maintenance.

However, and quite surprisingly, few studies have questioned the role of the central executive in this cross-domain binding process. To our knowledge, the study by Elsley and Parmentier (2009) is the sole study having investigated cross-domain binding while manipulating attentional demands. It appeared that the already reported advantage at recognition of exact letter–location combination compared with recombination disappeared under concurrent acoustic memory load, suggesting a clear involvement of attention, and thus of the central executive, in the binding of cross-domain information. However, this study only tested implicit binding, and results could have been different if participants had been explicitly asked to maintain letter–location associations. Indeed, it was shown by Morey (2011) that memory performance differs quite a lot for intentional and incidental binding, with intentional binding leading to increased feature recall. The underlying systems for both types of binding might thus also be different.

The Present Study

Besides a lack of studies investigating the involvement of attentional resources in the process of cross-domain binding, the maintenance of cross-domain information over longer retention intervals has completely been neglected. Repovš and Baddeley (2006) assumed that in order to further explore the episodic buffer and its role in cognition in the same way as the other components of WM, two classes of tasks needed to be developed, namely measures of capacity and interference tasks. However, to the best of our knowledge, there has been no study focusing on the capacity of the episodic buffer or systematically manipulating the nature of interfering tasks. Thus, it can be concluded that in contrast with the other components of WM, the episodic buffer remains largely unexplored. The present study was conceived as an attempt toward a better comprehension of the episodic buffer and its functioning. Its originality concerns (a) its focus on the maintenance capacity of the episodic buffer, in contrast to its binding capacity, and (b) the study of cross-domain associations, in contrast to within-domain associations.

Our study had a twofold aim. First, we aimed at assessing the amount of cross-domain information that can be maintained in the episodic buffer as well as the cognitive demand incurred by this maintenance compared with the maintenance of single features. For this purpose, in a first experiment, we used a complex span task in which participants had to maintain verbal (i.e., letters), spatial (locations), or cross-domain information (i.e., letters in location) while performing an attention-demanding task. Varying the cognitive load of the secondary task allowed us to evaluate to what extent the maintenance of bound information is more attention demanding than the maintenance of verbal or spatial features. The span procedure informed us about the capacity of WM when maintaining cross-domain information. Second, we aimed at investigating the separation of the episodic buffer from the slave systems. For this purpose, a second study used a selective interference paradigm involving the maintenance of cross-domain information while performing an attention-demanding secondary task intended to produce additional verbal or spatial interference, or to remain neutral in this respect. The hypothesis of a clear separation between the episodic buffer and the slave systems as described in the multicomponent model (Repovš & Baddeley, 2006) would predict maintenance of cross-domain information to be relatively immune to selective interference compared with the maintenance of domain-specific information.

Experiment 1

The aim of this first experiment was twofold. Its first objective was to assess the capacity of the episodic buffer by comparing the maintenance of cross-domain information (i.e., binding verbal and spatial features) with the maintenance of individual features. Participants were presented with a complex span task in which they had to maintain series of letters, spatial locations, or letters in location. Previous studies focusing on the bound storage capacity in the verbal and visuospatial domains have provided convergent results pointing toward a limit of about three or four chunks. This was the case when studying the binding of visual features into objects (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001; but failure to replicate by, e.g., Wheeler & Treisman, 2002; Olson & Jiang, 2002) as well as when investigating the capacity of storing verbal chunks comprising several words (Chen & Cowan, 2009; Cowan, Rouder, Blume, & Saults, 2012). Thus, the same limitation of about four can be expected for the storage of objects integrating verbal and spatial features. However, an open question remains concerning the comparison between visuospatial and cross-domain storage: Will the capacity of storing letters in location equate that of storing spatial locations alone? It has been mentioned before that it is difficult to give a good account of rehearsal within the visuospatial domain (Baddeley, 2000, 2012). This fact, in addition to some experimental results, has led to the idea that the maintenance of visuospatial information might not be subserved by some domain-specific slave system but by a domain-general mechanism that can be assimilated with the episodic buffer. For example, when studying verbal and visuospatial WM, Vergauwe, Barrouillet, and Camos (2010) observed that verbal storage was more affected by a verbal than a visuospatial interfering task, whereas visuospatial maintenance was affected in the same extent by verbal and visuospatial interference. We interpreted these results as suggesting the existence of some domain-specific system of maintenance for verbal information (e.g., a phonological loop), whereas visuospatial WM would be devoid of specific maintenance mechanism, relying on a domain-general attentional system (see Morey & Mall, 2012, for similar conclusions). Now, and contrary to verbal spans, WM spans for visuospatial information are usually rather low and do not seem to exceed four items (Vergauwe, Barrouillet, & Camos, 2009; Vergauwe et al., 2010). At the moment, however, it remains undecided whether WM spans for cross-domain information are lower than spans for visuospatial information. On the one hand, it could be imagined that the episodic buffer can maintain as many verbal–spatial chunks as it can hold spatial features, in the same way as Luck and Vogel (1997) observed that storage capacity was limited to about four objects regardless of the number of features each object comprises. On the other hand, it is also possible that less verbal–spatial chunks can be maintained than single features. Cowan et al. (2012) observed in the verbal domain that the number of chunks held in WM decreases as their size increases, with people recalling fewer chunks when made of triplets than of single words. The number of elements in each chunk could thus matter. Oberauer and Eichenberger (2013) similarly observed that within visual WM recognition accuracy decreased as the number of features making up an object increased. The present experiment addressed this question by comparing the maintenance of verbal–spatial associations with the maintenance of their isolated components.

Second, we tested whether the maintenance of bound information requires attention above and beyond the attention needed to maintain isolated components. Szmalec, Vandierendonck, and Kemps (2005) have shown that a pitch discrimination task requires attentional resources while domain-specific verbal or spatial resources are not presumed to be involved. Because of its domain neutrality, this kind of task has been used in several other studies (e.g., Elsley & Parmentier, 2009; Imbo, Vandierendonck, & Vergauwe, 2007) and was also adopted in the present study. After each memory item (i.e., letter, spatial location, or letter in location), participants were asked to judge the pitch, either high or low, of a series of tones. The pace at which tones were presented was varied to create three levels of cognitive load (high, medium, or low) with faster pace resulting in higher cognitive load. Barrouillet, Portrat, and Camos (2011) demonstrated that any task that requires attention, as is the case for the pitch discrimination task, can be tuned to create different levels of cognitive load. The hypothesis of the maintenance of cross-domain information within an episodic buffer fueled by the attentional capacity of the central executive (Repovš & Baddeley, 2006) predicts lower spans with increasing cognitive load of the secondary task. Such an effect has already been observed on the maintenance of verbal and visuospatial information (Vergauwe et al., 2010; Vergauwe, Dewaele, Langerock, & Barrouillet, 2012). However, the question of a greater effect of the secondary task on memory for bound information due to an additional cost associated with the maintenance of the binding itself remains open. A specific cost of this maintenance would result in an interaction between the cognitive load of the secondary task and the type of memoranda, with a stronger effect on the maintenance of bound information compared with the maintenance of letters or spatial locations. Of course, we reviewed above several studies that have shown that retaining bound objects in WM does not require attention over and above that required for maintaining featural information. However, these studies focused on visuospatial WM and often concerned bindings of features such as shape and color. As suggested by Baddeley et al. (2011), these bindings could be too basic and automatic to be affected by concurrent cognitive load. A recent study by Ecker, Maybery, and Zimmer (2013) has suggested a difference in the automacity of binding based on the perceived coherence of the to-be-bound features. Features that are perceived as belonging to a same object are defined as intrinsically related (e.g., color and shape) and resulted in an obligatory and automatic binding and retrieval of the binding. Features that are extrinsically related are part of the same global encoding, but are not perceived as inherent characteristics of a same object (e.g., shape and location). This extrinsic relation between features did not, however, result in this kind of obligatory and automatic binding and retrieval, as was the case for intrinsically related features. It remains thus possible that the maintenance of cross-domain bindings between verbal and spatial elements involves an additional attentional demand as location is typically defined as an extrinsic feature. Nevertheless, automatic binding of location to letters (but not of letter to locations) has been observed in several studies focusing on verbal–spatial associations (e.g., Campo et al., 2010; Guérard, Morey, Lagace, & Tremblay, 2013). We adopted the methodology used in several studies; that is, the maintenance of either single or bound features was compared under different levels of concurrent attentional demand (e.g., Allen et al., 2006; Morey & Bieler, 2013).

Method

Participants. Eighty-five students (mean age = 22.06 years, *SD* = 5.63 years; 73 women, 12 men) were given course credits for participation. The experimental session lasted between 30 and 60 min. Due to this rather lengthy procedure, each participant accomplished only one maintenance domain condition. Maintenance domain (verbal, spatial, or cross-domain) was thus manipulated between subjects while attentional demand (low, medium, or high cognitive load) was manipulated within subjects.

Materials and procedure. The complex span tasks involved the presentation of series of two to seven letters, spatial locations, or letters in location in ascending length. Letters were consonants (*W*, *Y* and *Z* were excluded) presented in a square centered on-screen. Spatial series consisted of squares successively lighting up in gray and filled with the same letter *X* among 16 possible locations indicated by 16 empty squares randomly distributed on the screen to avoid verbal coding of their position. Cross-domain maintenance items consisted of letters displayed within these squares lighted up in gray. In each memory condition, series were counterbalanced across cognitive load conditions in such a way that each series appeared equally often for each cognitive load condition over all participants. The processing task was a choice reaction task in which participants had to decide by pressing appropriate keys whether a presented tone was low (262 Hz) or high (524 Hz) in frequency (Szmalec et al., 2005). The occurrence of high and low tones was random.

By making use of a complex span task, the secondary task was only to be performed during the maintenance stage and not during encoding or retrieval. Studies using a secondary attention-demanding task during explicit binding and its subsequent maintenance (e.g., Karlsen et al., 2010) and retrieval (e.g., Allen et al., 2006) did not show any difference in terms of attentional demand by encoding, maintenance, or retrieval for bound items as compared to single items. In order to measure the attentional demand for maintenance over extended retention intervals, the secondary task was administered only during the maintenance stage of the task.

The experiment began with training for the maintenance task, for the processing task, and for the combination of both. Figure 2 shows the trial design. Each trial began with a 750-ms indication of the pace of the processing task (“lent” [slow], “moyen” [medium], or “rapide” [fast]) displayed on the center of the screen) followed by a centrally displayed asterisk for 750 ms. Hereafter, the first maintenance item was presented for 1,500 ms, followed, after a blank screen of 500 ms, by a series of tones presented through headphones at a computer-paced rate. Each tone was presented for 200 ms. The low, medium, and high cognitive load conditions were the same as in Vergauwe et al. (2010) and created by presenting either four tones at a rate of one tone every 2,000 ms, four tones at a rate of one tone every 1,293 ms, or eight tones at a rate of one tone every 1,000 ms, respectively. Thus, cognitive load was varied either by manipulating the number of items within a fixed interval of 8 s or by manipulating the rate at which a fixed number of items was presented. A new maintenance item was presented immediately after the processing phase, followed by a 500-ms blank screen and a new processing phase. At the end of the trial, the word *RAPPEL* (*RECALL*) appeared on-screen and subjects were to recall the maintenance items in correct order. For the series of letters, they typed the consonants in succession and validated their responses by pressing Enter after each letter. For spatial locations, they used the mouse to click successively on each location. Each click on a square turned it gray until the Enter key was pressed to validate the response and recall the following location. For letters in locations, the same procedure was used, but participants typed the appropriate letter after having clicked the location.

Series of two to seven memory items were presented in ascending length with three trials per cognitive load condition, resulting in nine trials per length presented in random order. For a given length, if participants correctly recalled two trials at a given cognitive load, the third trial was omitted and counted as correct. If participants recalled no more than one trial for each cognitive load condition correctly, the experiment terminated after this block. These rules were implemented in order to avoid a drop in motivation due to too-easy or too-difficult series. A span score was calculated adding 1/3 for each trial correctly recalled (all letters, locations, or letters in location in the correct order). Each participant started with a basis score of 1 (as series of one item were not presented because of their estimated ease). The maximum span score for each cognitive load condition was thus 7.

Results

Four participants were excluded from further analysis. One participant in the verbal condition did not reach the predetermined criterion of 80% correct on the processing task, and two others had recall scores exceeding 2 standard deviations from the mean on at least one of the cognitive load conditions. This was also the case for one participant in the spatial condition. Each condition contained thus 27 participants for further analysis. A 3 (maintenance domain: verbal, spatial, cross-domain) × 3 (cognitive load: low, medium, high) repeated-measures analysis of variance (ANOVA) was performed with maintenance domain as between-subject and cognitive load as within-subject factors. There was a significant effect of maintenance domain, $F(2, 78) = 59.32$, $p < .001$, $\eta^2 = .60$ (see Figure 3). Planned comparisons showed that verbal recall was significantly better than spatial recall, $F(1, 78) = 44.74$, $p < .001$, $\eta^2 = .37$ (mean spans of 5.76 and 3.92, respectively), which was in turn significantly better than cross-domain recall (mean span of 2.79), $F(1, 78) = 16.81$, $p < .001$, $\eta^2 = .18$. There was also a significant effect of cognitive load, $F(2, 156) = 16.12$, $p < .001$, $\eta^2 = .17$ (mean spans of 4.36, 4.21, and 3.91 for the low,

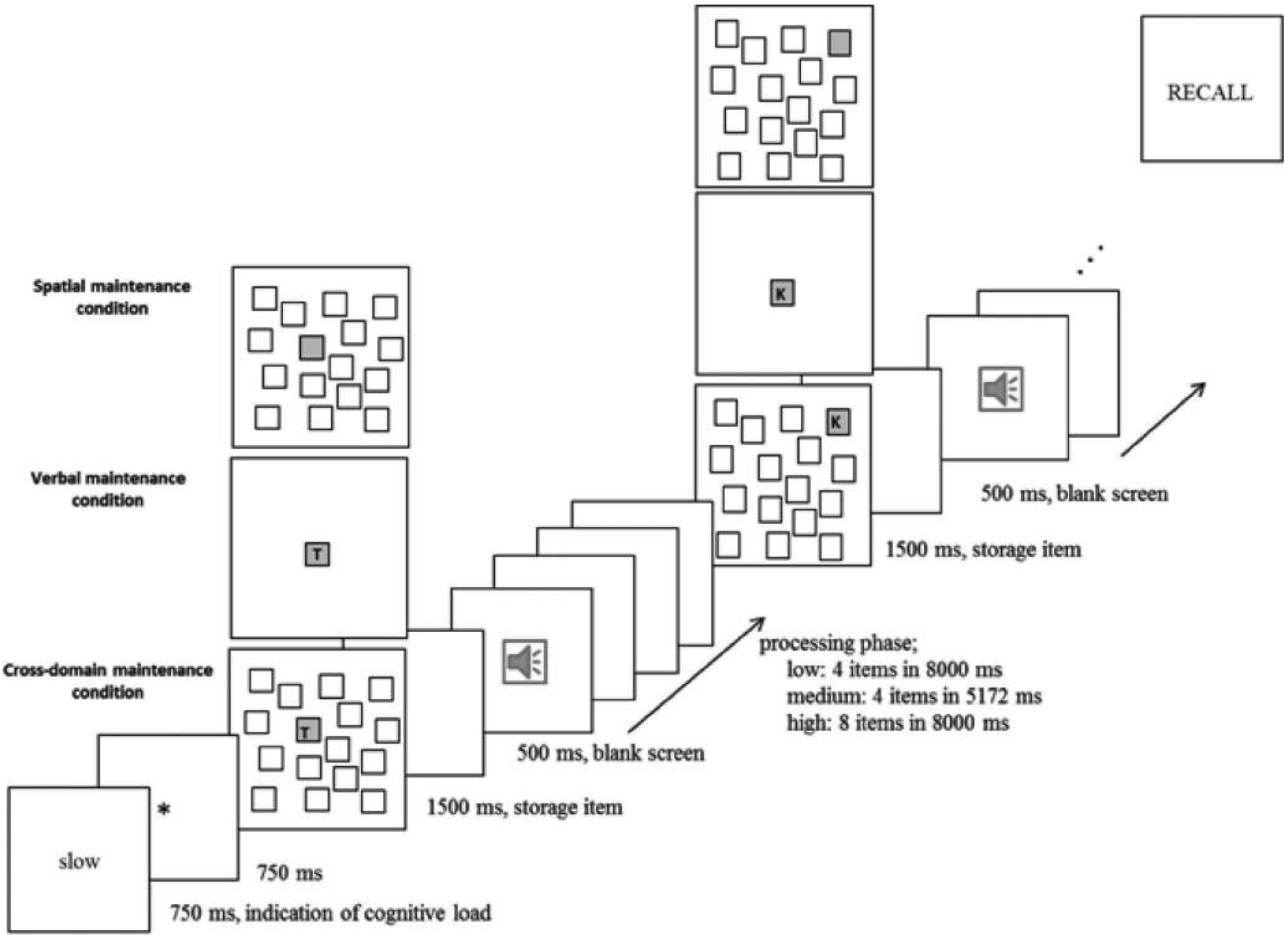

Figure 2. Structure of a trial for Experiment 1.

medium, and high cognitive loads, respectively), with a highly significant linear trend, $F(1, 78) = 26.58$, $p < .001$. This linear trend accounted for 96% of the variance associated with the effect of cognitive load. There was no interaction between maintenance domain and cognitive load, $F(4, 156) < 1$. As the repeated-measures ANOVA did not allow us to reject the null hypothesis on the absence of an interaction, we calculated the posterior probability that the data favor the null hypothesis. To do so, we used the Bayesian information criteria (Masson, 2011), which resulted in $p_{\text{BIC}}(H_0|D) = .99$.

Discussion

According to Repovš and Baddeley (2006), maintenance of the information within the episodic buffer would rely on the attentional resources of the central executive. Consequently, the amount of information held in the episodic buffer would be affected by the amount of attention captured by concurrent processing. In line with this assumption, we observed that WM span for cross-domain information decreased when the cognitive load induced by concurrent response selections increased, a phenomenon already observed with a variety of memoranda (Barrouillet & Camos, 2012; Barrouillet et al., 2011). This suggests that the resources needed for maintenance of cross-domain information were used by the processing component of the complex span task. However, there was no interaction between cognitive load and the nature of memoranda, either verbal, spatial, or cross-domain, indicating that the maintenance of cross-domain information involves no additional demand over and above that required for the maintenance of its constituents. Thus, as Baddeley et al. (2011) stated, binding features into composite memory traces at encoding does not seem to involve attentional resources, but in addition the present results show that the maintenance of these bindings themselves during extended periods is not more costly. According to the study by Ecker et al. (2013), extrinsically related features (as is the case for letters in locations) should not result in an obligatory and automatic retrieval of the binding. Nevertheless, they showed that in an explicit binding task, the association between extrinsic features did not come up automatically but could anyhow be retrieved on demand.

The present results allow us to specify the conclusions drawn by Baddeley et al. (2010) from the exploration of the episodic buffer that he described as a passive store. The episodic buffer is passive

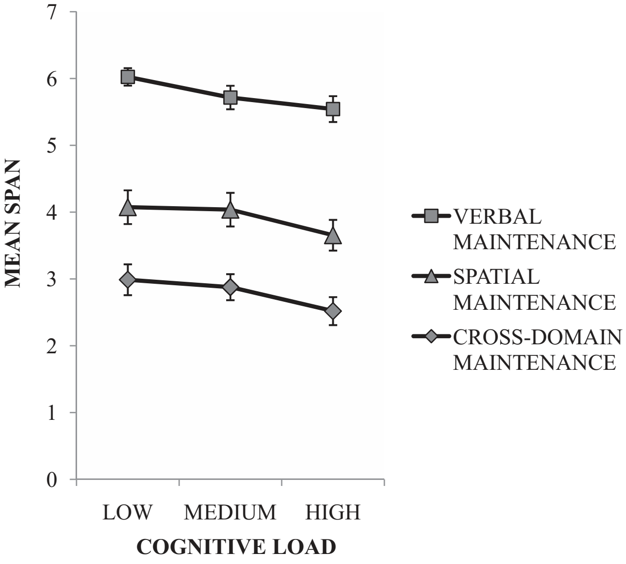

Figure 3. Mean recall performance as a function of maintenance domain and cognitive load in Experiment 1. Error bars represent the standard error of the mean.

in that sense that it does not seem to play any active role in the binding process itself, which is probably automatic and resulting from attentional focusing at encoding (Cowan, 1995, 2005). Cowan (1995) has suggested that chunking and learning are functions of the focus of attention, elements focused on at the same time being tied together and to their context. Anticipating the concept of episodic buffer, Cowan suggested that these new links would comprise an episodic record that becomes part of LTM. The episodic buffer could also be considered as passive because contrary, for example, to the phonological store that is coupled with an articulatory loop, it is devoid of any specific mechanism of maintenance, relying only on the executive resources of the central executive. However, it could also be argued that the mechanism of attentional refreshing described by several theories of WM (Barrouillet, Bernardin, & Camos, 2004; Cowan, 1999, 2005) and for which neural correlates have been identified (Raye, Johnson, Mitchell, Greene, & Johnson, 2007) constitutes the mechanism by which the representations held in the episodic buffer are maintained in an active state. This refreshing mechanism refers to the retrieval of memory traces by attentional focusing. In this sense, the episodic buffer does not appear as a passive store, or at least no more passive than the phonological loop.

The other main finding revealed by this first experiment concerns the capacity of the episodic buffer. Concerning the maintenance of either verbal or spatial items, we observed higher WM spans for verbal than for spatial information. This difference might have occurred due to a difference in distinctiveness between verbal and spatial stimuli (Murdock, 1960), with spatial locations being less discriminable. Another option is a difference in maintenance mechanism between verbal and spatial stimuli. Although there is ample evidence for the existence of a phonological loop performing verbal rehearsal in order to maintain verbal information, the nature of the rehearsal mechanism for visuospatial information is less clear (Baddeley, 2012). Several authors even argue that the maintenance of visuospatial information would be devoid of specific mechanism (Morey & Mall, 2012; Vergauwe et al., 2010; Vergauwe, Camos, & Barrouillet, 2013). According to this assumption, the maintenance of visuospatial information would rely on the sole attentional resources assumed to fuel the episodic buffer, while the maintenance of verbal information could benefit from these attentional resources as well as from verbal rehearsal (Camos, Lagner, & Barrouillet, 2009). In line with previous estimates (Cowan, 2001, 2005), our participants were able to maintain about four spatial locations. However, WM spans for objects integrating verbal and spatial information did not exceed three objects. It should be noted that this estimate is slightly lower than the one deducted from a study by Cowan, Saults, and Morey (2006). Their task, though, might have been slightly easier, as children and adult participants had to reconstruct the association between three to seven names and three to seven spatial locations, instead of recalling the associations. However, their result suggested similarly that this cross-domain maintenance limit is lower than a spatial or name span. Where does this difference come from?

Though the episodic buffer remains, as Baddeley et al. (2010, p. 240) stated, a "shadowy concept," it is assumed to hold a limited number of chunks. This makes the episodic buffer akin to the focus of attention described by Cowan (2001) or the object files hypothesized by Kahneman, Treisman, and Gibbs (1992). Accordingly, it could be imagined that its capacity is defined in terms of the number of objects that can be maintained rather than in terms of the number of their constitutive features. Studies that have compared capacity for individual features with capacity for objects have led to divergent results. In a recognition task of memory items presented sequentially, Allen et al. (2006) reported that the retention of color–shape bindings was inferior to the recognition of either color or shape, even if the memory for feature conjunctions was no more affected than the memory for features by a demanding concurrent task. Our task involved recall instead of recognition, but we also observed poorer memory for feature conjunctions than single features, whereas the two types of memoranda were affected in the same way by a concurrent attentional demand. However, and in line with the conception of a capacity of the episodic buffer in terms of chunks or objects, Chen and Cowan (2009) reported a constant capacity of three chunks made either of singletons or of previously learned pairs of words provided that covert verbal rehearsal is prevented. Luck and Vogel (1997) made the same observation in the visuospatial domain, with objects defined by a conjunction of features being retained just as well as single-feature objects.

However, more recent investigations indicated that the size of the chunks to be maintained could matter. Cowan et al. (2012) observed that the number of chunks maintained in verbal WM decreases as their size increases. Whereas participants were able to maintain slightly more than 3.5 chunks containing single words, this number dropped below 3.5 for chunks made of pairs of words, and was about 2.5 for word triplets. Cowan et al. invoked some chunk decomposition factor by which within-chunk associations fail or a given chunk gives rise to several chunks that can only be remembered by occupying different slots in WM. The same phenomenon could occur here. Although only about three chunks were remembered, participants often correctly recalled an additional letter or location in isolation. The spatial and verbal span scores of the cross-domain maintenance condition (i.e., the maximum number of locations and letters correctly recalled whatever the recall accuracy of their counterpart) were thus higher (4.02 and 3.09 for the mean verbal and spatial span, respectively) than the cross-domain maintenance span (i.e., the number of chunks completely and correctly recalled; mean span score 2.79), corroborating the idea of chunk decomposition. However, these spatial and verbal span scores of the cross-domain maintenance were lower than the spans observed in the pure spatial and verbal maintenance conditions. These findings seem at odds with the hypothesis suggested by Cowan et al. (2006) of the maintenance of cross-domain information as separated features held in parallel in their respective domain-specific buffers (i.e., letters and spatial locations separately maintained) and simply associated at recall on the basis of order information. Indeed, such a strategy would result in recalling as many associations as items retained in the shortest ordered list, that is the list maintaining the spatial locations. We have seen that this was not the case. Nonetheless, at least two alternatives remain. First, it could be supposed that verbal and spatial features are maintained in separated buffers but that these buffers are fueled by a common resource. This would result in a reduced number of items that can be maintained when verbal and spatial items have to be held simultaneously (Morey & Cowan, 2004). Second, it could be supposed that verbal and spatial features are bound in a buffer separated from the domain-specific systems, which is the hypothesis of the episodic buffer by Repovš and Baddeley (2006). The present results cannot disentangle these two possibilities. Therefore, the following experiment addressed more directly the construct of the episodic buffer as a separate entity, dissociated from the domain-specific maintenance buffers, through the selective interference paradigm.

Experiment 2

The selective interference paradigm has played a main role in establishing the separability of the different slave systems hypothesized by the multicomponent model (Baddeley, 1986). Its underlying logic is that if there exists different systems devoted to the maintenance of either verbal or visuospatial information, then verbal activities would selectively interfere with verbal maintenance while leaving visuospatial maintenance relatively unaffected, whereas visuospatial activities would selectively interfere with visuospatial maintenance but not (or less) with verbal maintenance. In the present experiment, we extended this logic to the study of the episodic buffer. If cross-domain bindings are maintained in some distinct buffer separated from both the verbal and the visuospatial systems and fueled by a general-domain attentional resource, maintenance of bindings should be affected by a concurrent attentional demand, but would remain immune from both verbal and visuospatial interference. If the maintenance of cross-domain associations would anyhow prove to be prone to verbal or spatial domain-specific interference, then this would question the existence of the episodic buffer, or at least its separation from the verbal and visuospatial maintenance systems.

Both Morey (2009) and Guérard et al. (2009) showed spatial features to be subject to domain-specific verbal interference when these were to be maintained integrated. Although this finding supports an integrated verbal–spatial maintenance, this does not exactly fit with the hypothesis of an independent structure responsible for the maintenance of cross-domain associations. However, Morey also showed verbal features to be less prone to verbal domain-specific interference when information had to be maintained integrated. This in contrast does seem to fit with independent structure responsible for the maintenance of cross-domain associations. For the maintenance of cross-domain associations, domain-specific interference seemed thus to act more between domains but less within domains in comparison with the maintenance of isolated features.

In order to clarify the influence of domain-general and domain-specific interference on the maintenance of cross-domain associations, this second experiment will investigate its influence on the level of cross-domain associations, instead of on the feature level, as was done by Morey (2009) and Guérard et al. (2013). We are above all interested in the maintenance of cross-domain associations as a whole and not the maintenance of its isolated components.

In this experiment, participants performed a WM span task in which they were asked to remember letters in spatial locations while performing choice reaction time tasks intended to produce verbal or spatial interference, or to remain neutral in this respect. In order to appropriately differentiate between attentional and domain-specific interference, all these distracting tasks required response selection and involved thus an attentional demand that was manipulated to establish their detrimental effect on the maintenance of bindings. This attentional demand was kept approximately constant across tasks by presenting the same number of distractors at the same rates. However, these distractors were varied in nature to selectively interfere with verbal or spatial maintenance, or to remain neutral in this respect, resulting in a verbal, a spatial, and a neutral interference condition, respectively. For this purpose, participants were asked to perform either semantic judgments on words, spatial judgments about the length of a line compared with the interval between two dots (both tasks are derived from Vergauwe et al., 2010), or judgments about the pitch of tones as in Experiment 1. The hypothesis of an episodic buffer separated from the slave systems and fueled by attentional resources predicts that the maintenance of verbal–spatial bindings should be affected by variations in the attentional demand of the distracting tasks but should remain unaffected by the nature of the distractors to be processed and the specific interference they elicit. Consequently, the neutral condition was predicted to be as disruptive as the verbal and the spatial conditions. A control experiment established that the distracting tasks were appropriate to produce the intended selective interference.

Method

Participants. Ninety-one undergraduate students (mean age = 21.48 years, *SD* = 3.53 years; 77 women, 14 men) were given course credits for participation. The experimental session lasted between 45 and 60 min. Each participant was randomly attributed to one of the three processing domain conditions. Processing domain (neutral, verbal, or spatial) was thus manipulated between subjects, while attentional demand (low–medium–high cognitive load) was manipulated within subjects.

Materials and procedure. The three complex span tasks (incorporating a verbal, a spatial, or a neutral processing task, respectively) had the same structure as the cross-domain maintenance condition used in Experiment 1. Based on the performance from Experiment 1, series of letters in location ranged from one to five. In each memory condition, series were counterbalanced across cognitive load conditions in such a way that each series appeared equally often for each cognitive load condition over all participants. The three processing tasks had the same structure and the cognitive load was manipulated in the same way as in Experiment 1, with either four distractors at a rate of one distractor every 2,000 ms, four distractors at a rate of one distractor every 1,293 ms, or eight distractors at a rate of one distractor every 1,000 ms for the low, medium, and high cognitive load conditions, respectively. In the verbal task, distractors were nouns selected out of 12 animal and 12 nonanimal nouns auditorily presented in a random order, with presentation times ranging from 440 to 660 ms depending on word length. Participants decided by pressing keys whether the noun presented was an animal or not. The spatial condition consisted in a spatial fit task involving 24 white boxes containing a black horizontal line centrally displayed on-screen and two black square dots positioned on the same horizontal plane as each other, either above or below the horizontal line. The line varied in length, and the distance between the dots was chosen in such a way that for half of the boxes, the line could fit into the gap between the dots. These distractors were displayed on-screen for 1,333 ms, 862 ms, and 667 ms, and followed by blank screens of 667 ms, 431 ms, and 333 ms in the low, medium, and high cognitive load conditions, respectively. Participants were instructed to decide whether the line could fit into the gap by pressing appropriate keys. The neutral condition involved the same tone discrimination task as in Experiment 1.

In each task, the trials had the same structure as in Experiment 1, and the same procedure was followed. The only difference concerned the presentation time of the memoranda, which was reduced to 1,000 ms instead of 15,00 ms. Series of one to five memory items were presented in ascending length with nine trials per length (three trials for each cognitive load condition in random order) for a total of 45 trials. Each series correctly recalled (all letters recalled in correct order in their exact location) was scored 1/3 for a maximum span score of 5 for each cognitive load condition.

Results

One, eight, and two participants in the neutral, verbal, and spatial processing task conditions, respectively, were excluded from further analysis, as they did not reach the predetermined criterion of 80% correct responses in the processing task. Another three, two, and two participants were excluded, as their scores exceeded 2 standard deviations from the mean on at least one cognitive load condition. This left us with 24, 24, and 25 participants in the three conditions of the processing task, respectively.

A 3 (processing domain: neutral, verbal, spatial) × 3 (cognitive load: low, medium, high) repeated-measures ANOVA was performed with processing domain as between-subject and cognitive load as within-subject factors. There was a significant effect of cognitive load, $F(2, 140) = 55.38$, $p < .001$, $\eta^2 = .44$ (see Figure 4). Planned comparisons showed that recall in the low cognitive load condition was significantly better than in the medium cognitive load condition, $F(1, 70) = 37.71$, $p = < .001$, $\eta^2 = .31$, which was in turn significantly better than in the high cognitive load condition, $F(1, 70) = 24.60$, $p < .001$, $\eta^2 = .26$. There was no significant effect of processing domain, $F(2, 70) < 1$, and the interaction between processing domain and cognitive load was not significant either, $F(4, 140) = 1.36$, $p = .25$.[1] For both null effects, we calculated the posterior probability favoring the null hypothesis. This probability was $p_{\mathrm{BIC}}(H_0|D) = .98$ for the null effect of processing domain and $p_{\mathrm{BIC}}(H_0|D) = .99$ for the interaction between processing domain and cognitive load. The difference that occurred at a descriptive level between the three conditions of processing task at a high cognitive load did not reach significance, $F(2, 70) = 1.42$, $p = .25$, even when the neutral condition was contrasted with the verbal, $F(1, 70) = 1.20$, $p = .28$, or spatial condition, $F(1, 70) = 2.75$, $p = .10$.

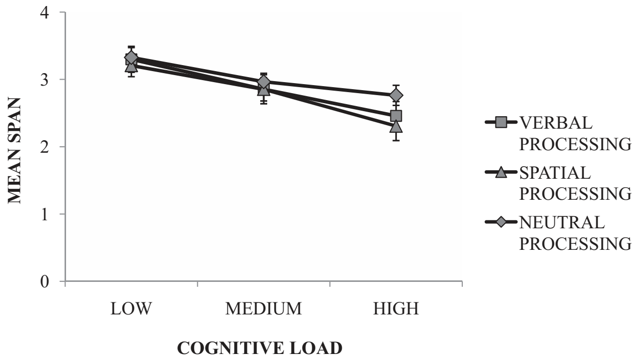

Figure 4. Mean cross-domain recall performance as a function of processing domain and cognitive load in Experiment 2. Error bars represent the standard error of the mean.

Discussion

Two important results came out of this experiment. First of all, the assumption of the episodic buffer to be dependent on attention was once more confirmed. Varying the attentional demand of the three intervening tasks had a detrimental effect on recall with higher cognitive load resulting in poorer recall. Like the maintenance of individual features, the maintenance of cross-domain information depends thus clearly on attention. On the contrary, no

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[1] Although no significant difference was observed in Experiment 2 between verbal, spatial, and neutral interference, increasing cognitive load seemed to move the results in that direction (see Figure 4). It should nonetheless be mentioned that though the three processing tasks involved two-choice reaction, the number of possible stimuli the choice should be made on was 24 in both the verbal and spatial processing tasks and only two in the neutral processing task. It has been shown by Merkel (1885; cited by Hyman, 1953) that reaction times are longer when one has to make a choice reaction time for one stimulus drawn from a pool of 10 alternatives instead of two alternatives. In Experiment 2, this has as a result that the actual cognitive load is slightly higher when using the verbal and spatial processing tasks than when the neutral processing is used. The difference in actual cognitive load between the verbal or spatial processing task and the neutral processing task increases as our manipulation of the cognitive load increases. Although the difference in actual cognitive load between the neutral and the verbal or spatial processing tasks at the low level of cognitive load might have been too small to have an effect on recall, at higher levels of cognitive loads this can lead to small differences in recall. However, at a statistical level, this difference is still nonsignificant.

evidence was shown for domain-specific resources to be involved in the maintenance of cross-domain information. Neither the verbal nor the spatial processing task was able to create any more interference than the neutral processing task. The three interfering tasks had the same detrimental effect on the maintenance of cross-domain information with no indication of selective interference.

This has important implications for the concept of the episodic buffer. The verbal processing task was supposed to create verbal interference in the same way the spatial processing task was supposed to create spatial interference, that is, over and above their attentional demands, whereas the effect of the neutral processing task was supposed to be restricted to its attentional demand. The observation that the maintenance of information in the episodic buffer is not more prone to verbal or spatial than to neutral interference might suggest that the episodic buffer is indeed a storage system separated from the phonological loop and the visuospatial sketchpad, for which selective interference has widely been shown (Baddeley, 1986). One might, however, question the capacity of our tasks to create the intended domain-specific interference. A control experiment was designed to discard this possibility of nonadequacy of our tasks.

Control Experiment

The objective of this control experiment was to show the adequacy of the processing tasks used in Experiment 2. As no difference was found between the three processing tasks, it has to be established that this is not due to the processing tasks not being efficient in their objective.

The verbal processing task is supposed to create verbal interference over and above its attentional demands, just like the spatial processing task is supposed to create spatial interference over and above its attentional interference. Though visuospatial interference has been demonstrated on several occasions (e.g., Logie, 1986; Shah & Miyake, 1996), other studies did not show any evidence for a visuospatial processing task to produce selective interference (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Vergauwe et al., 2010). Different patterns of selective interference between the verbal and visuospatial domain have consequently questioned the existence of a domain-specific visuospatial resource (Morey, 2009; Morey & Mall, 2012). As this actual debate is not to be resolved here, we chose to focus only on the adequacy of the verbal processing task to create verbal interference.

In Experiment 2, the verbal task had the same effect on the maintenance of cross-domain information as the spatial task. To confirm the ability of the verbal task to create domain-specific interference, it has to be demonstrated that it is more disruptive on the maintenance of pure verbal information than a spatial task, thus revealing a selective interference. This was the purpose of this control experiment. We compared the relative impact of a verbal and a spatial processing task on the maintenance performance of single verbal features, on the one hand, and on the maintenance of cross-domain information, on the other. This was done under a medium cognitive load. If it is indeed observed that the maintenance of cross-domain associations is affected to the same extent by the verbal and spatial processing tasks, while the maintenance of single verbal features is more affected by the verbal than by the spatial processing task, then we could indeed conclude that our verbal processing task is apt to create verbal interference.

Method

Participants. Forty-six undergraduate students (mean age = 21.93 years, *SD* = 6.55 years; 44 women, two men) were given course credits for participation. Maintenance domain (cross-domain or verbal) was manipulated between subjects, while the nature of the processing task (verbal or spatial) was manipulated within subjects.

Materials and procedure. Series of two to seven cross-domain (letter in location) items or verbal features were presented in a complex span task. The presentation mode of the memoranda was the same as in Experiment 1. The processing task was either verbal or spatial in nature. The verbal processing task was the semantic decision task used in Experiment 2. The spatial processing task was the spatial fit task equally used in Experiment 2.

After training on the memory task, the processing task, and a combination of both, the experiment started. Participants were first presented with an indication of the processing task this trial would incorporate. Then a fixation cross was displayed for 750 ms, followed by the presentation of the first memorandum for 1,000 ms and a 500-ms blank screen. Then the processing phase started. During the processing phase, four items to process were presented in a 5,172-ms interval, equalizing the medium cognitive load in the previous two experiments. Hereafter a new memorandum was presented and followed by a processing phase. This continued until the word *RAPPEL* (*RECALL* appeared on-screen). At this moment participants had to recall the memoranda in the same way as they did in Experiment 1. Verbal features were entered using solely the keyboard, and cross-domain items were entered using the mouse and the keyboard. To keep the performances on the processing task above 80%, participants received feedback on their processing task accuracy after each trial.

For each list length, three trials incorporating the verbal processing task and three trials incorporating the spatial processing task were randomly performed. Scores were calculated according to the span procedure. Each series correctly recalled gave rise to 1/3 of a point. As the series of one memorandum were omitted, 1 point was added to the scores. The maximum score by processing task was thus 7.

Results and Discussion

Two participants in the cross-domain maintenance condition and two participants in the verbal maintenance condition were excluded, as they did not reach the criterion of 80% correct on the verbal or spatial processing task. Furthermore, one participant in the cross-domain maintenance condition and one participant in the verbal maintenance condition were excluded, as their performances exceeded 2 standard deviations from the mean. A 2 (maintenance domain: cross-domain or verbal) × 2 (processing task: verbal or spatial) repeated-measures ANOVA was performed with the nature of the processing task as within-subject and the maintenance domain as between-subject factors. As expected, verbal maintenance was significantly higher than cross-domain maintenance, $F(1, 38) = 184.50$, $p < .001$, $\eta^2 = .83$ (see Figure 5). The effect of the nature of the processing task was also significant, $F(1,$

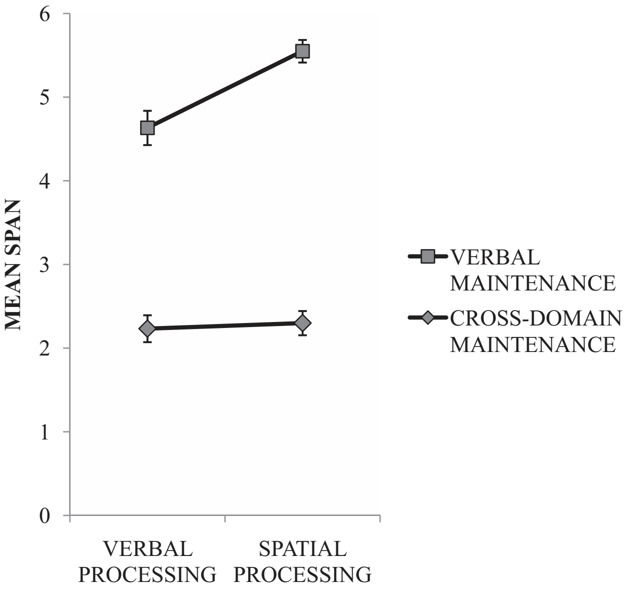

Figure 5. Mean recall performance as a function of maintenance domain and processing domain in the control experiment. Error bars represent the standard error of the mean.

38) = 23.46, $p < .001$, $\eta^2 = .38$, as was the interaction, $F(1, 38) = 17.53$, $p < .001$, $\eta^2 = .32$. A further analysis of this interaction showed that the verbal processing task had a more detrimental effect than the spatial processing task in the verbal maintenance condition, $F(1, 38) = 40.78$, $p < .001$, $\eta^2 = .52$, but not in the cross-domain maintenance condition ($F < 1$).

The control experiment showed a clear selective interference, confirming the adequacy of the verbal processing task to create verbal interference. Once again, the maintenance of cross-domain associations was not prone to this verbal interference, endorsing the hypothesis that the episodic buffer is an independent maintenance system, well separated from the domain-specific maintenance buffers.

So notwithstanding the absence of effect of the domain of the processing task in Experiment 2, the control experiment was able to valorize these results. As stated by Baddeley (2012), negative results can be as valuable as positive results in guiding the development of WM models.

General Discussion

The goal of the present study was to investigate the underexplored characteristics of the episodic buffer, that is, its maintenance capacity and its separability from domain-specific maintenance systems. We chose to tackle these issues through the method of WM span measure and selective interference. For this purpose, we used a complex span task paradigm in which participants were asked to memorize verbal–spatial cross-domain associations (i.e., letters in location) while performing processing tasks varying in their verbal, spatial, and attentional demands. In the first experiment, it was shown that WM spans are lower for verbal–spatial associations than for their isolated verbal or spatial components. Irrespective of these capacity limits, a decrease in attentional availability resulted in an equal drop in maintenance performance for single features and cross-domain items, suggesting thus no additional attentional demand to maintain cross-domain multifeature information. Although this first experiment left open the possibility that the verbal and spatial features composing the cross-domain memoranda were separately maintained in domain-specific buffers instead of in some episodic buffer, the second experiment discarded this option. A selective interference paradigm showed the maintenance of cross-domain information to be solely dependent upon attentional resources, with no domain-specific interference. This result reinforces the hypothesis of independence of the episodic buffer from the domain-specific maintenance buffers. In the following, we discuss these main findings.

The first issue addressed in this study concerned the capacity limit of the episodic buffer conceived as a system for the assimilation of information from different domains into integrated objects. Consequently, we focused on the maintenance of verbal–spatial associations. The results of the first experiment clearly indicated the capacity limit of the episodic buffer in terms of objects to be lower than the capacity limit for single features. While under a low attentional load induced by the concurrent task, WM spans for verbal and spatial features were six and four, respectively, only three cross-domain associations could be maintained. Under medium and high attentional loads, this limit dropped to 2.9 and 2.5. In the control experiment, applying the medium cognitive load condition, participants were not able to maintain more than 2.3 cross-domain associations. This even lower capacity limit in the control experiment was probably due to a higher stress on the importance of the processing task, as participants received feedback about their performance after each trial. Overall, this capacity limit for cross-domain associations was always lower than the capacity limit for single features and did not exceed three objects. This result is novel, as no other study had yet given rise to clear maintenance capacity estimates for cross-domain associations.

Several previous studies have aimed at measuring the maintenance capacity limits of associations formed within the same domain, with divergent estimates of this limit as a result. For example, using a change-detection paradigm in which participants had to detect whether something had changed in an array previously studied, Luck and Vogel (1997) found a capacity limit for multifeature visual objects of four. Surprisingly, this capacity limit proved to be the same as for the maintenance of single features. Wheeler and Treisman (2002) attempted to replicate some of the results of Luck and Vogel but remarkably failed in this objective. Using the same paradigm as these authors, they found lower maintenance performance for multifeature objects than for each of their components. However, changing the recognition paradigm introduced by Luck and Vogel to the use of a single probe instead of the whole test array gave rise to an intermediate pattern of results. Recognition accuracy was lower for bound visuospatial features than for the best remembered feature, but equal to the less remembered feature. Capacity limits in the recognition of objects seemed to be constrained by the less remembered of their constituents. Allen et al. (2006) observed this same pattern for the maintenance of separate colors and shapes as compared to bound color–shape objects on several occasions. However, a methodological change of allowing repetition of features within a trial altered the results to a lower recognition rate of bound objects as compared with either one of the single features. The same phenomenon was observed by Cowan, Blume, and Saults (2013), who studied memory for color–shape associations. The number of items in WM for these combinations was surprisingly low, only slightly more than one. However, when incomplete objects were taken into account (only color or shape), the number of maintained items was as high as single-feature maintenance (i.e., about three items). This same idea has been applied to the maintenance of verbal information (Cowan et al., 2012). Chunks composed of different numbers of words (either one, two, or three) were learned prior to testing. About three "chunks" could be maintained, while these chunks were often incomplete. Cowan et al. (2012) described this phenomenon as chunk decomposition. Chunks can fall apart in their different components and in that case occupy more than one slot within WM. According to this principle, it is very reasonable to accept that fewer objects than single features can be maintained.

Our results concerning memory for cross-domain associations were more in line with Allen et al. (2006) and Cowan et al. (2012) for within-domain combinations and revealed a lower capacity for objects than single features. Cowan et al.'s idea of chunk decomposition could explain the results obtained in the present study and as such apply to the maintenance capacity limit of the episodic buffer. However, our aim was to study the capacity of the episodic buffer as a cross-domain system of maintenance. Because it is unclear whether isolated features are maintained in the episodic buffer or in domain-specific peripheral systems, we restrain our estimation of the episodic buffer capacity to the number of integrated objects recalled. Our estimates indicate that this number is quite low and varies between two and three.

The notion of chunk decomposition would nevertheless be able to explain the parallel decline rate of single features and cross-domain associations as a function of attentional availability. The results of the present study showed the recall of verbal features, spatial features, and cross-domain associations to decline to the same extent as less attentional resources were available. This result makes sense if one assumes, following Cowan (2001), each cross-domain association to occupy one of a fixed number of slots available in WM. The decrease in attentional availability would then act in the same way on all slots resulting in a poorer recall, independently of their content. One could, however, imagine that the more filled slots would require more attention for their maintenance. Our results do not provide evidence for this, as this would have resulted in a steeper decline for the cross-domain associations than for the verbal or spatial feature maintenance. Although the often cited study of Wheeler and Treisman (2002) claimed an additional need for attention to maintain visuospatial features in an integrated format, this issue has subsequently often been questioned, with most studies agreeing on the fact that attention is not more necessary for the maintenance of bound information than for the maintenance of single features (e.g., Allen et al., 2006; Johnson et al., 2008; Morey & Bieler, 2013). Remarkably, one of the rare studies showing the need for attention to maintain multifeature objects was a study on the maintenance of verbal–spatial associations (Elsley & Parmentier, 2009). However, two comments should be made on the Elsley and Parmentier (2009) study. First, their study was based on implicit binding between verbal and spatial features. As already stated in the introduction, Morey (2011) has shown that the maintenance of intentionally bound features can give rise to a higher memory performance than the maintenance of incidentally bound features. Second, and more importantly, their results do not contradict our observations. As with Elsley and Parmentier, the present study confirms that attention is needed to maintain cross-domain associations as its recall diminishes with reduced attentional resources. Crucially, the present results show that the maintenance of cross-domain associations does not depend more on attention than the maintenance of single features. In the same way as the studies on binding concluded that creating bindings is effortless, the maintenance of these bindings over prolonged periods does not lead to additional costs compared with the maintenance of isolated features.

Although the phenomenon of chunk decomposition might thus offer an explanation for the observed result, there are other options that are worth being considered in accounting for the maintenance of cross-domain associations. One could, for example, suppose that the default strategy to maintain objects is to separately maintain their constituents in domain-specific buffers. Objects could then be reconstituted on the basis of serial position information, with item in position *n* in one buffer being associated with the item occupying the corresponding position in the other (Cowan et al., 2006). However, the second experiment in this study does not seem to support this alternative. In this experiment, it was shown that the maintained cross-domain associations are not more prone to verbal or spatial interference than they are to neutral interference of a concurrent task. It is largely agreed on that the maintenance of verbal features decreases in the presence of verbal interference (e.g., Bayliss et al., 2003; Jarrold, Tam, Baddeley, & Harvey, 2011), and there is also evidence that visuospatial interference leads to a decrease in the maintenance of visuospatial features (e.g., Farmer, Berman, & Fletcher, 1986; Logie, 1986; Logie, Zucco, & Baddeley, 1990). If the maintenance of cross-domain associations was to depend on the maintenance of these separate features, then we should have observed a lower recall performance when combining the cross-domain storage with the verbal and spatial processing task than when combining with the neutral processing task. However, this was not the case.

The second experiment of the current study along with its control showed that the maintenance of cross-domain associations is less prone to domain-specific interference than the maintenance of single features. This suggests that cross-domain maintenance is not accomplished in domain-specific buffers, but rather in a domain-general or domain-neutral maintenance system, as the episodic buffer is presumed to be. This result is supported by the study of Morey (2009), who showed that when participants had to maintain cross-domain objects, the verbal information was less prone to verbal interference (articulatory suppression) than when they only had to maintain verbal features. However, Morey also observed more verbal domain-specific interference on the maintenance of spatial locations when these were part of a cross-domain association than when maintained in isolation. Our results did not show evidence for any kind of domain-specific interference when cross-domain items were to be maintained. This difference might be due to the fact that we were only interested in the maintenance of intact cross-domain associations, as compared to overall feature maintenance. The ensemble of results led Morey to the conclusion that cross-domain objects are probably stored in a domain-general store, while additional information might also be stored in domain-specific storage buffers. Though this additional storage was less evident for visuospatial information, it most certainly was the case for verbal information.

In summary, the present study has shown that WM is capable of holding a limited number of cross-domain associations. This capacity limit, however, is lower than the capacity limits for single verbal or spatial features. Cross-domain associations are assumed to be maintained as integrated objects in a domain-general buffer. Indeed, this maintenance relies on attention, as the detrimental effect of attention-demanding concurrent tasks testifies, but not more than the maintenance of single features. Moreover, this maintenance proved immune to domain-specific interference. These findings converge toward the hypothesis of some episodic buffer as hypothesized by Baddeley (2000) and described by Repovš and Baddeley (2006) as a capacity-limited system dependent on central executive resources and separable from peripheral buffers.

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