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The present study addresses the existence of a central pool of domain-general resources in working memory. For this purpose, we examined interference between processing and storage activities involving information pertaining to different domain (verbal vs. visuo-spatial) while explicitly minimising representation-based interference at the peripheral level of working memory. Experiment 1 required maintenance of auditorily presented letters for further oral recall while concurrently judging visually presented spatial configurations by pressing keys. Experiment 2 required maintenance of visually presented random locations for further manual recall while concurrently judging auditorily presented words by giving oral responses. In both experiments, the cognitive load of processing was manipulated, a manipulation that clearly affected recall performance. This suggests strongly that working memory comprises a pool of domain-general attentional resources at the central level.

Keywords: Working memory; Domains; Modalities; Attention; Resource sharing.

In cognitive psychology, the concept of working memory (WM) was introduced by Baddeley and Hitch (1974) and refers to a limited-capacity system responsible for the simultaneous storage and processing of information (Baddeley, 1986). There is an active debate regarding the nature of the resources supporting this dual functioning and the potential interference between processing and storage activities when performed simultaneously. One widely held view is that WM consists of multiple domain-specific subsystems, each subsystem being fuelled by its own pool of resources (e.g., Baddeley & Logie, 1999). In particular, a distinction is often made between verbal and visuo-spatial resources which should result in interference between processing and storage when they involve material pertaining to the same domain (i.e., both verbal or both visuo-spatial) but no (or less) interference between

processing and storage activities when they involve material pertaining to different domains.

Experimental evidence for such a distinction between verbal and visuo-spatial resources in WM comes from selective interference studies in which verbal and visuo-spatial memory tasks are combined with either verbal or visuo-spatial processing tasks. Doing so, it has been shown that concurrent verbal activities such as continuously reciting the word "the" (i.e., articulatory suppression) or verifying sentences disrupt tasks involving maintenance of verbal information, but not (or less) tasks involving maintenance of visuo-spatial information. Conversely, concurrent visuo-spatial activities such as continuously tapping a sequence of locations (i.e., spatial tapping) or mental rotation disrupt tasks involving maintenance of visuo-spatial information, but not (or less) tasks involving maintenance of verbal

information (e.g., Bayliss, Jarrold, Gunn, & Baddeley, 2003; Logie, Zucco, & Baddeley, 1990; Meiser & Klauer, 1999; Shah & Miyake, 1996). Based on these findings, it appears that WM consists of multiple domain-specific resources, one for verbal material and one for visuo-spatial material.

However, more unitary views on WM resources have been put forward. These propose the existence of a central pool of general-purpose resources in WM (e.g., Barrouillet, Bernardin, & Camos, 2004; Case, 1985; Cowan, 1995). This pool of domain-general resources is often called attention and is thought to be shared between processing and storage activities regardless of the nature of the information involved. As such, these theories assume that verbal and visuo-spatial processing and storage activities compete for a common limited pool of attentional resources. This competition would then result in interference between verbal and visuo-spatial activities when performed concurrently. That is, processing and storage would interfere when they involve information pertaining to the same domain, but also when they involve information pertaining to different domains.

In line with the existence of a domain-general pool of attentional resources, correlational studies have shown that constructs composed of multiple verbal and visuo-spatial complex span tasks (i.e., tasks requiring concurrent processing and storage) were identical or shared 65% or more of their variance (e.g., Kane et al., 2004; but see Shah & Miyake, 1996). More recently, we aimed at demonstrating experimentally the existence of such a domain-general pool of resources supporting verbal and visuo-spatial activities (Vergauwe, Barrouillet, & Camos, 2010). We reasoned that, if processing and storage compete for common domain-general resources, then increasing the demands of processing (i.e., cognitive load) should draw resources away from storage resulting in poorer recall performance, regardless of the nature of the information involved. To test this, we used the computer-paced complex span paradigm developed within the framework of the Time-Based Resource-Sharing (TBRS) model according to which processing and storage share a domain-general pool of attentional resources in a time-based way (Barrouillet et al., 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007). This paradigm allows the combination of processing and storage activities under strict time control, thereby allowing rigorous manipulations

of the cognitive load involved in processing which, in the TBRS model, is defined as the proportion of time during which processing captures attention in such a way that attentional refreshment of memory traces is impeded.

Four computer-paced complex span tasks were created in which verbal and visuo-spatial storage were combined with either verbal or visuo-spatial processing. Verbal storage consisted of maintaining series of visually presented letters, while visuo-spatial storage required the maintenance of series of visually presented locations within a 4×4 matrix. Verbal processing consisted of judging whether visually presented words were animal nouns or not by pressing one of two keyboard keys. Visuo-spatial processing consisted of judging whether a horizontal line could fit into the gap between two dots or not (see Figure 1) by pressing one of two keyboard keys. In all four tasks, we manipulated the cognitive load of concurrent processing[1]. We observed that recall performance was affected by the cognitive load induced by concurrent processing in all four tasks. The observations that increasing the cognitive load of a visuo-spatial processing task disrupted verbal recall performance and that increasing the cognitive load of verbal processing task disrupted visuo-spatial recall performance were interpreted as evidence for the existence of a central domain-general pool of resources supporting the dual functioning of WM.

However, three shortcomings might compromise such a conclusion. First, in the Vergauwe et al. (2010) study, verbal storage items were presented visually which might have encouraged participants to encode the letters visually and to use this visual code to support recall at the end. The use of visual codes might have been encouraged even more so by the requirement to recall the letters by writing them down. As such, the

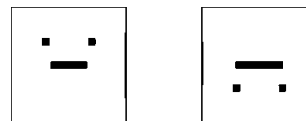**Figure 1.** Examples of the visuo-spatial processing items used by Vergauwe et al. (2010) and in the present Experiment 1.

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[1]Cognitive load was manipulated by varying two factors: the number of items to be processed after each storage item and the total duration of a processing phase. This was done so as to avoid accounts of the data in terms of either one of these variables instead of in terms of their ratio.

interference that was observed between visuospatial processing and verbal storage might, at least in part, be due to peripheral representation-based interference between the visuo-spatial processing stimuli and the visual codes of the letters to be maintained. Second, the fact that the locations for the visuo-spatial storage task were presented within a 4×4 matrix might have encouraged participants to encode these locations verbally and to use this verbal code to support recall at the end. Thus, the interference that was observed between verbal processing and visuo-spatial storage might, at least in part, be due to peripheral representation-based interference between the verbal processing stimuli and the verbal codes of the locations to be maintained. Finally, still concerning the combination of visuo-spatial storage and verbal processing, the requirement to judge the words manually by pressing one of two keys might have added a visuo-spatial component to the verbal processing task by means of the spatial codes used in the Stimulus–Response mapping for this task (press left if word is an animal, press right if not). As such, peripheral representation-based interference between the spatial response codes used in the verbal processing task and the locations to be maintained might explain the interference observed between visuo-spatial storage and verbal processing. Taken together, at least part of the interference between processing and storage activities involving information that pertains to different domains that was observed by Vergauwe et al. (2010) might be due to an overlap of representations at the peripheral level of WM instead of resource sharing at the central level of WM. What is needed to conclude for the existence of a central pool of domain-general resources in WM that supports both processing and storage activities, is the demonstration of interference between processing and storage activities involving information pertaining to different domains while explicitly minimising possible overlap of processing and storage at the peripheral level of WM. This was the aim of the present study.

Here, we used modified versions of the between-domain complex span tasks previously used by Vergauwe et al. (2010). As in Vergauwe et al. (2010), Experiment 1 combined verbal storage (letters) with visuo-spatial processing (fit judgment). Responses in the visuo-spatial processing task were given by pressing one of two keys. However, to minimise overlap at the peripheral level due to visual encoding of the letters, they

were presented auditorily instead of visually and they were to be recalled orally instead of manually. Concerning Experiment 2, as in Vergauwe et al. (2010), visuo-spatial storage (locations) was combined with verbal processing (semantic judgment). Although the locations were still to be recalled by marking them on a response sheet, they were no longer presented in a 4×4 matrix. Indeed, to minimise verbal encoding of the locations, random locations on screen were used as visuo-spatial storage items (see Figure 2, for a comparison; see Darling, Della Sala, & Logie, 2007, for a similar visuo-spatial memory task). Moreover, to minimise peripheral interference between spatial response codes and locations, responses in the verbal processing task were given orally instead of manually.

Thus, Experiment 1 required maintenance of auditorily presented letters for further oral recall while concurrently judging visually presented spatial configurations by pressing keys. Experiment 2 required maintenance of visually presented random locations for further manual recall while concurrently judging auditorily presented words by giving oral responses. In both experiments, the cognitive load of processing was manipulated. If a central pool of domain-general resources is shared between processing and storage activities, regardless of the nature of the information involved, then recall performance should be affected by this manipulation despite the fact that the possibility for peripheral representation-based interference was strongly reduced, if not abolished. In line with the TBRS
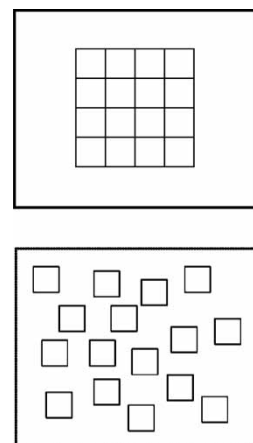

Figure 2. The 16 locations used as visuo-spatial storage items by Vergauwe et al. (2010); upper panel) and in the present Experiment 2 (lower panel).

model, we expected that recall performance would decrease as a direct function of cognitive load in both experiments.

EXPERIMENT 1

Method

Participants and design

Thirty-nine undergraduate psychology students (36 females[2], mean age = 20.08) enrolled at the university of Geneva participated for course credit. Cognitive load (low, medium or high) was manipulated within subjects.

Tasks and materials

As in Vergauwe et al. (2010), a complex span task was created by combining a letter span task (storage component) with a spatial fit judgment task (processing component). For the storage task, series of consonants of ascending length (3 to 6) were used. All consonants excluding W were used approximately equally often. No consonant was repeated within a series. Acronyms and alphabetically ordered series were avoided. These letters were recorded with a female voice, French native speaking and were presented auditorily. The duration of each letter was approximately 500 ms. The processing task was a two-choice reaction time task for which the stimuli were the same as those used by Vergauwe et al. (2009, 2010). They consisted of a set of 24 white boxes containing a black horizontal line and two black square dots (see Figure 1). The horizontal line was centrally displayed on screen and the dots were 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. Participants were instructed to decide whether or not the line could fit into the gap. No box was repeated within a processing phase and the 24 boxes were used approximately equally often.

Procedure

Each series began after an asterisk centrally displayed for 750 ms, followed by a 500-ms delay after which the first letter of a series was auditorily presented. The total time for encoding one letter was 1500 ms during which the screen remained blank. Each encoding phase was followed by a processing phase. The duration of the processing phases and the number of items to be processed sequentially within these phases depended on the cognitive load (i.e., CL) condition: 4 items in 8000 ms for low CL, 4 items in 5172 ms for medium CL and 8 items in 8000 ms for high CL. Thus, one processing item was presented every 2000 ms, 1293 ms or 1000 ms for low, medium and high CL conditions respectively. Participants were asked to rest their index fingers on a left- and a right-handed keyboard key and to judge each processing item by pressing one of these as fast and as accurately as possible: left for 'does fit' and right for 'does not fit'. Responses were recorded. At the end of a series, the word 'rappel' (i.e., 'recall') appeared and participants recalled the letters orally in order of presentation.

All participants were required to perform 36 series, presented in four consecutive blocks of 9 series. Each block corresponded to one of the four ascending lengths of series of storage items. Within each block, 3 series of storage items were associated with each CL condition. For each 9-series block, this association and the order of presentation of the series was counterbalanced across participants. As in Vergauwe et al. (2010), recall performance was scored by calculating a span score for each CL condition with each correctly recalled series counting as 1/3. As series started from 3 letters on, 2 was added to the sum of thirds. The experiment started with a training phase in which participants were trained on the processing task before performing 6 practice trials of the complex span task (i.e., two for each CL condition).

Results and discussion

Six participants that did not reach the 80% criterion after 5 training blocks were not included. Two participants with accuracy below 80% during the experimental trials were also dropped from the sample. For the remaining participants, mean accuracy was 92% in the spatial fit task. Recall performance was analysed by running an

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[2]Although sex differences have been a significant source of controversy in the literature, our study cannot make a useful contribution to this issue. We did not systematically sample our participants on the basis of sex.

ANOVA with Cognitive load (low, medium or high) as repeated measure. Cognitive load had a significant effect on recall performance, $F(2,60) = 6.02$, $p < .01$. There was a significant linear trend, $F(1,30) = 12.15$, $p < .01$, that explained 97% of the experimental effect (5.44, 5.34 and 5.15 for low, medium and high CL, respectively). Thus, as we predicted, increasing the cognitive load of visuo-spatial processing impaired verbal recall performance, even though visual encoding of verbal storage items was avoided. This observation suggests that a central pool of general resources is shared between verbal storage and visuo-spatial processing, resulting in central interference between these activities when performed concurrently. However, before drawing such a firm conclusion, this observation needs to be replicated in Experiment 2 in which visuo-spatial storage was combined with verbal processing while minimising overlap at the peripheral level of WM.

EXPERIMENT 2

Method

Participants and design

Thirty-seven undergraduate psychology students (34 females[2], mean age = 20.70) enrolled at the university of Geneva participated for course credit. They did not participate in Experiment 1. Cognitive load (low, medium or high) was manipulated within subjects.

Tasks and materials

As in Vergauwe et al. (2010), a complex span task was created by combining a location span task (storage) with a semantic judgment task (processing). For the storage task, series of screens containing 16 squares randomly displayed on screen with one square coloured in red were used (see Figure 2). Series were of ascending length (2 to 5), each red square appeared at a different location within a series and each of the 16 locations was used approximately equally often. The verbal processing task was a two-choice reaction time task for which the stimuli were the same as those used by Vergauwe et al. (2010). They consisted of a set of 24 five-letter words, half of them being animal nouns. Words were recorded with a female voice, French native speaking and were presented auditorily. The

animal and non-animal words were matched for word frequency in French. Throughout the experiment, the 24 words were used approximately equally often and no word was repeated within a processing phase. Participants were instructed to judge orally whether the presented word was an animal noun or not.

Procedure

The procedure and temporal course of events in the three cognitive load conditions were the same as in Experiment 1. Each screen containing a red square was shown for 1000ms and followed by a blank delay of 500ms resulting in an encoding duration of 1500ms per item. During the processing phase, the screen remained blank. Participants were asked to judge each processing item by uttering as fast and as accurately as possible: 'oui' if the word was an animal noun, 'non' if not. Responses were recorded. At the end of a series, the word 'rappel' (i.e., 'recall') appeared and participants recalled the locations by reproducing them on response sheets. As in Experiment 1, all participants were required to perform 36 series, presented in 4 consecutive blocks of 9 series corresponding to one of the 4 ascending lengths of series of storage items (2–5) with 3 series of storage items being associated with each CL condition. The same rules of counterbalancing were used as in Experiment 1. Recall performance was scored as in Experiment 1 except that 1 instead of 2 was added to the sum of thirds because series started from 2 locations on.

Results and discussion

All participants reached the 80% criterion after a maximum of 5 training blocks. One participant with accuracy below 80% during the experimental trials was dropped from the sample. For the remaining participants, mean accuracy was 91% in the semantic judgment task. Recall performance was analysed by running an ANOVA with Cognitive load (low, medium or high) as repeated measure. Cognitive load had a significant effect on recall performance, $F(2,70) = 7.05$, $p < .01$. There was a significant linear trend, $F(1,35) = 11.66$, $p < .01$, that explained 99.8% of the experimental effect (2.81, 2.59 and 2.33 for low, medium and high CL, respectively). Thus, as we predicted, increasing the cognitive load of verbal processing impaired visuo-spatial recall performance, even

though verbal encoding of locations and spatial coding of responses were avoided. This finding is entirely in line with our proposal of a central pool of general resources that has to be shared between visuo-spatial storage and verbal processing resulting in central interference between these activities when performed concurrently.

GENERAL DISCUSSION

In the present study, we observed interference between visuo-spatial processing and verbal storage (Experiment1) and between verbal processing and visuo-spatial storage (Experiment 2). These results not only replicate but considerably extend the findings of Vergauwe et al. (2010). Unlike this previous study, the present experiments were explicitly designed to minimise overlap between the activities at the peripheral level of WM. Though the opportunity for peripheral representation-based interference was strongly reduced, if not abolished, we observed clear interference effects between processing and storage, which strongly suggest that the dual functioning of WM is supported by a central pool of domain-general resources.

Though the present experiments strongly reduced the opportunity for peripheral interference compared with Vergauwe et al. (2010), the results of the two studies are strikingly similar[3]. As can be seen in Figures 3 and 4 comparing the present data with those of Vergauwe et al. (2010), verbal and visuo-spatial recall performance clearly vary as a function of the cognitive load involved in processing but hardly do so as a function of whether processing and storage involve the same input/output modalities (Vergauwe et al., 2010) or different input/output modalities (present study). This was statistically confirmed. For both combinations of processing and storage, a 2 (Modality: same versus different) × 3 (Cognitive Load: low, medium, high) ANOVA with Cognitive Load as repeated measure and Modality as between-subject factor was run. As far as the combination of verbal storage with visuo-spatial processing is concerned, there was a significant effect of Cognitive Load, $F(2,106) = 13.93$, $p <.001$, but no significant effect of Modality, $F<1$, nor did Cognitive Load and Modality
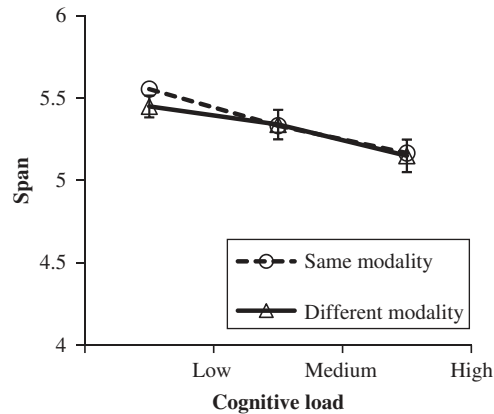
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[3]Because the studies used the exact same tasks and stimuli, the exact same cognitive load manipulations, the exact same scoring and a similar subject pool, such comparison is justified.

Figure 3. Comparison of mean verbal recall performance (i.e., span score) as a function of the cognitive load (low, medium, or high) involved in the visuo-spatial processing task and as a function of whether the information is presented in the same modality (Vergauwe et al., 2010) or in different modalities (Experiment 1 of the present study). Error bars represent standard errors for Experiment 1 of the present study.

interact, $F <1$. As for the combination of visuo-spatial storage with verbal processing, there was again a significant effect of Cognitive Load, $F(2,116) = 16.91$, $p <.001$, but no significant effect of Modality, $F<1$, and no interaction, $F<1$. Thus, it seems that the degree of interference between verbal and visuo-spatial processing and storage activities is not influenced by the modality of input or output at all. The fact that the degrees of interference in both studies are so similar suggests that the interference observed by Vergauwe et al. (2010) was entirely central in nature. Moreover, the descriptive difference between the present results and those of Vergauwe et al. (2010) suggests slightly better performance when processing and storage information are presented in the same modality and require the same output modality than when different input/output modalities are used.

It should be clear that the present findings are inconsistent with any model of WM that does not include a domain-general pool of resources supporting processing and storage (e.g., Baddeley & Logie, 1999; Shah & Miyake, 1996). Indeed, the dynamic functioning of WM as observed in our studies can only be accounted for by a mechanism of domain-general resource sharing between processing and storage in WM (e.g., Barrouillet et al., 2004, 2007). This fits nicely with the observed domain-general construct underlying WM performance in individual differences studies (e.g., Kane et al., 2004) and with the recent demonstration of
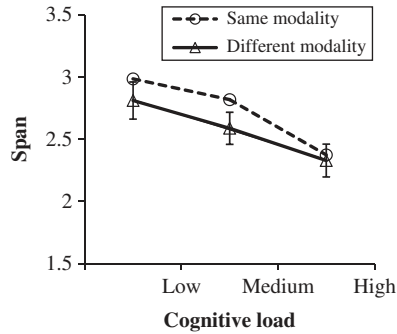
Figure 4. Comparison of mean visuo-spatial recall performance (i.e., span score) as a function of the cognitive load (low, medium, or high) involved in the verbal processing task and as a function of whether the information is presented in the same modality (Vergauwe et al., 2010) or in different modalities (Experiment 2 of the present study). Error bars represent standard errors for Experiment 2 of the present study.

brain regions supporting domain-general mechanisms in complex span tasks (Chein, Moore, & Conway, 2011). It is worth noting that a central domain-general construct has also been proposed when accounting for dual-task interference observed between two processing tasks in the psychological refractory period (PRP) literature (e.g., Pashler, 1994; Tombu & Jolicoeur, 2003). It seems then that WM, and, more generally, human information processing includes a central level of domain-general resources.

Interestingly, the present findings also shed light on the active debate concerning forgetting of stored information. Two alternative hypotheses have been put forward, the time-based decay and the interference-based hypotheses. According to the first, forgetting from WM is time-related in that memory traces of to-be-maintained information decay over time (e.g., Baddeley, 1986; Barrouillet et al., 2004, 2007; Cowan, 1995). According to the latter, forgetting from WM occurs because other (incoming) representations degrade the representations of to-be-maintained information. This happens either because they are similar (e.g., Saito & Miyake, 2004) or because they share some features (e.g., Oberauer & Lange, 2008). If forgetting in WM was purely interference-based, one would not expect recall performance in the present experiments to be affected by manipulations of the cognitive load involved in

processing, especially because the combination of verbal and visuo-spatial activities is considered to be "a baseline with minimal feature overlap" (Oberauer & Lange, 2008). Indeed, we used stimuli for which it is very hard to imagine what exactly would be the common features or similarities between them that could cause forgetting. Yet, in Experiment 1, spoken words were forgotten when combined with a task involving visual images containing dots and lines and in Experiment 2, random spatial locations were forgotten when combined with a task presenting spoken words. Thus, interference-based accounts of WM cannot account for the present findings. Conversely, the present pattern of results is entirely in line with the TBRS model of WM according to which forgetting occurs when concurrent activities capture attention in such a way that attentional refreshment of decaying memory traces of storage material is impeded (Barrouillet et al., 2004, 2007). Indeed, the present results point to a mechanism of time-based sharing of domain-general resources between processing and storage at the central level of WM.

However, this does not necessarily mean that there are no domain-specific resources in WM or that memory traces do not suffer from representation-based interference. Although we did not observe any domain-specific effects in the disruptive effect of processing on storage, several studies have demonstrated the existence of such effects (e.g., Bayliss et al., 2003; Logie et al., 1990; Meiser & Klauer, 1999; Shah & Miyake, 1999). How can these findings of selective interference be reconciled with the present findings? We believe that the answer lays in our recent proposal by which WM comprises both a central and a peripheral level (see Barrouillet & Camos, 2010; Vergauwe et al., 2009, 2010). While the first would be independent of domains and modalities, the latter would comprise domain-specific and modality-specific mechanisms (see Guérard & Tremblay, 2008; Jarrold, Tam, Baddeley, & Harvey, 2011, for similar proposals). As such, even though there are situations in which processing and storage activities interfere more with each other as they have more overlap in input modality, processing domain, and output modality, any demanding activity such as online processing can disrupt any other concurrent demanding activity

such as storage because they both tap into the central pool of general attentional resources of WM and, as such, of the human information processing system.

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