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Article

2009

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How to cite

VERGAUWE, Evie, BARROUILLET, Pierre Noël, CAMOS, Valérie. Visual and Spatial Working Memory Are Not That Dissociated After All: A Time-Based Resource-Sharing Account. In: Journal of experimental psychology. Learning, memory, and cognition, 2009, vol. 35, n° 4, p. 1012–1028. doi: 10.1037/a0015859

This publication URL: <https://archive-ouverte.unige.ch/unige:88281>

Publication DOI: [10.1037/a0015859](https://doi.org/10.1037/a0015859)

Visual and Spatial Working Memory Are Not That Dissociated After All: A Time-Based Resource-Sharing Account

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Examinations of interference between visual and spatial materials in working memory have suggested domain- and process-based fractionations of visuo-spatial working memory. The present study examined the role of central time-based resource sharing in visuo-spatial working memory and assessed its role in obtained interference patterns. Visual and spatial storage were combined with both visual and spatial on-line processing components in computer-paced working memory span tasks (Experiment 1) and in a selective interference paradigm (Experiment 2). The cognitive load of the processing components was manipulated to investigate its impact on concurrent maintenance for both within-domain and between-domain combinations of processing and storage components. In contrast to both domain- and process-based fractionations of visuo-spatial working memory, the results revealed that recall performance was determined by the cognitive load induced by the processing of items, rather than by the domain to which those items pertained. These findings are interpreted as evidence for a time-based resource-sharing mechanism in visuo-spatial working memory.

Keywords: working memory, attention, between-domain interference, visuo-spatial cognition

Working memory provides a pivotal interface between perception, attention, memory, and action and has become a central concept in psychology. As noted by Baddeley (1986), this concept is twofold. Working memory can be used as a general unitary concept (i.e., WMG), playing an important role in human information processing by serving both processing and storage operations in ongoing cognition. This WMG perspective can be differentiated from using the concept as a specific model (i.e., WMS), with its specific architecture, structure, and processes involved in tasks requiring WMG. These different approaches have resulted in two research traditions, each with its respective methodologies, assumptions, and implications. Although both traditions are often regarded as complementary, their perspectives on working memory functioning and structure are not always compatible. One of the ongoing debates concerns the existence of multiple resources in working memory. In the WMS tradition, multiple independent domain- and process-specific resources are proposed to underlie working memory performance (e.g., Baddeley & Logie, 1999; Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002; Duff & Logie, 2001; Logie, 1995), whereas a flexible general resource with a mechanism of resource sharing is proposed in the WMG tradition (e.g., Barrouillet, Bernardin, & Camos, 2004; Case, 1985; Daneman & Carpenter, 1980). The present study aims to distinguish between both views of visuo-spatial working memory.

Two Conceptions of Working Memory

Within the WMS tradition, researchers have mainly aimed at characterizing the peripheral slave systems of working memory, the phonological loop for verbal material, and the visuo-spatial sketchpad for visuo-spatial material, while the central component, the central executive, has remained less studied. Passing over the central component of working memory was “intentional, as it seems better to concentrate efforts on the more tractable problems of the two slave systems” (Baddeley, 1996, p. 5). Motivated by this idea, selective interference paradigms were used in which memory tasks involving stimuli pertaining to one of two domains (e.g., either visual or spatial) are combined with different conditions chosen to interfere selectively with one of the memory tasks by generating representations of the same domain or by disrupting the rehearsal process within that domain. Observations of selective interference resulted in the domain-based fractionation of the visuo-spatial peripheral system into a visual component and a spatial component (Baddeley, 2007; Baddeley & Logie, 1999; Logie, 1995). Indeed, early studies demonstrated interference of concurrent movements on spatial maintenance (Baddeley & Lieberman, 1980; Logie, Zucco, & Baddeley, 1990; Smyth & Pendleton, 1989) and interference of viewing irrelevant pictures on visual maintenance (Logie, 1986; Quinn & McConnell, 1996). Furthermore, Logie and Marchetti (1991) observed that viewing irrelevant pictures *selectively* interfered with visual memory, whereas concurrent movements *selectively* interfered with spatial memory. A growing body of research found this pattern in healthy adults (e.g., Darling, Della Sala, & Logie, 2007; Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Hecker & Mapperson, 1997). Based on these results, it appears that working memory consists of multiple domain-specific systems, at least for visual and spatial material.

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Unlike the WMS tradition, the WMG tradition has focused on the central component of working memory and its dual function of carrying out processing and storage operations simultaneously. To capture this dual function, new tasks requiring the maintenance of to-be-remembered items while performing a concurrent activity were created and led to the observation of central interference as reflected in a processing–storage trade-off (Case, 1985; Daneman & Carpenter, 1980). Using computer-paced working memory span tasks, our research group demonstrated that a monotonic trade-off between processing and storage results from a time-based resource-sharing mechanism at the central level of working memory (Barrouillet et al., 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet & Camos, 2007). According to the time-based resource-sharing (TBRS) model of working memory (Barrouillet et al., 2004), a general attentional resource has to be shared between processing and storage activities. Because information to be maintained decays over time, one has to refresh it by attentional focusing. However, as the focus of attention acts as a central bottleneck, attention-demanding processes are constrained to be focused on in a sequential manner. Hence, during the execution of a task requiring both processing and storage, attention will be rapidly switched from processing to storage and vice versa in order to cope with the dual demands of the task. From this, it follows that recall performance in such a task will be a function of the proportion of time during which processing activities capture attention in such a way that the refreshment of decaying memory traces is impeded. This proportion of time is called cognitive load. Importantly, the central attentional resource has to be time-shared between processing and storage regardless of the nature and domain of the information involved. That is, spatial storage should be disrupted by both visual and spatial processing activities and visual storage should be disrupted by both spatial and visual processing activities. Studies in the visuo-spatial domain of working memory are contradictory as to this idea.

Central and Peripheral Interference

Considering experimental studies within the WMS tradition, a distinction has to be made between selective interference studies using passive interference conditions (e.g., viewing irrelevant visual input or spatial tapping) and those using on-line processing (e.g., color discrimination or movement discrimination). Whereas the former are limited to the peripheral level of working memory, the latter could possibly hold extensions to the central level given the involvement of attention-demanding processing activities. The observation that spatial maintenance is disrupted by a passive spatial task, but not (or less) by a passive visual task, and that visual maintenance is disrupted by a passive visual task, but not (or less) by a passive spatial task (Darling et al., 2007; Della Sala et al., 1999; Logie & Marchetti, 1991), does not contradict resource sharing at a central level. Indeed, filling the retention interval with a passive task, which seems unlikely to solicit attentional control, allows distinguishing between peripheral domain-specific systems where representation-based interference can come into play. However, given the lack of on-line processing in these kinds of studies, they do not inform us about the existence of one or different central attentional resources for visual and spatial material in working memory.

As pointed out by Barrouillet et al. (2007), the TBRS model acknowledges the existence of peripheral interference resulting from an overwriting process when representations held in working memory share many common features. Such representation-based interference could become even more probable as representations suffer from more time-related decay, breaking them down into their component features. Based on feature overlap, peripheral interference can occur only within a given domain. However, according to the TBRS model, forgetting in working memory is mainly due to central interference caused by processing activities that occupy attention and impede the refreshing of decaying memory traces. Thus, to observe central interference, studies have to combine maintenance with attention-demanding processing activities. After all, the concept of working memory was primarily introduced as a system with both storage and processing functions, with on-line processing being situated at the central level of the system (Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Duff & Logie, 2001). Studies combining storage and on-line processing in the visuo-spatial domain are scarce. Tresch, Sinnamon, and Seamon (1993) found that spatial on-line processing disrupted spatial storage, but not visual storage, and that visual on-line processing disrupted visual storage, but not spatial storage. Klauer and Zhao (2004) also investigated the disruptive effects of concurrent on-line processing activities and observed that spatial memory was more disrupted by a spatial task than by a visual task and that visual memory was more disrupted by a visual task than by a spatial task. The authors concluded that separate visual and spatial resources exist.

However, using self-paced on-line processing does not allow for control of time-related parameters. That is, even when the processing activity requires attention, self-paced tasks cannot reflect the time-based character of attention sharing between on-line processing and storage, which has been demonstrated by Barrouillet et al. (2004, 2007) in the verbal domain. When participants are allowed to perform processing activities at their own pace, recall performance can remain unaffected because participants are able to postpone processing. Doing so, they can free up some time to refresh memory traces (Liefoghe, Barrouillet, Vandierendonck, & Camos, 2008). For example, Duff and Logie (1999) combined a spatial task with memory for visual forms and found maintenance unaffected. At first sight, this result seems to support the existence of independent domain-specific resources at the central level of visuo-spatial working memory. However, response times on the spatial task were significantly longer when combined with visual maintenance than when performed alone, leaving open the possibility of postponing processing activities so that memory traces could be refreshed. Hence, existing experimental data on interference between on-line processing and storage does not allow one to draw conclusions as to the sharing of a general attentional resource in visuo-spatial working memory.

The present study addressed explicitly the fundamental question of central interference in visuo-spatial working memory by examining interference between on-line processing and storage both within and between the visual and the spatial domains of working memory. The computer-paced paradigm developed by Barrouillet et al. (2004, 2007) was applied to visuo-spatial working memory in two types of tasks, each of them representing one of the two research traditions of working memory. In Experiment 1, working memory span tasks (WMG tradition) were used in which spatial

and visual storage components were combined with visual and spatial on-line attention-demanding processing components. In all of the four combinations, the cognitive load of the processing component was manipulated by varying the number of items to be processed within a processing phase of fixed duration. In Experiment 2, we re-examined central interference in one of the most recent selective interference experiments (WMS tradition) using on-line processing tasks in visuo-spatial working memory. Therefore, Experiment 2 replicated the first experiment of the Klauer and Zhao (2004) study in which spatial memory was more disrupted by spatial attention-demanding processing than by visual attention-demanding processing, whereas the reverse was true for visual memory. For both experiments, we predicted that recall performance would depend on the cognitive load the processing component involved, regardless of the domain to which the processing items pertained.

Experiment 1

Spatial storage and visual storage were combined with both visual and spatial on-line processing tasks. Selecting the appropriate tasks calls for exact definitions of the terms *visual* and *spatial*. As mentioned by Rudkin, Pearson, and Logie (2007), there is a continuing lack of consensus in the working memory literature as to the exact definitions of “spatial” and “visual” information.¹ However, in the most recent studies, the term *spatial* has been described as location information as opposed to appearance information (Darling et al., 2007; Darling, Della Sala, Logie, & Cantagallo, 2006). Such a distinction between location and appearance matches nicely the unambiguous “what” versus “where” distinction proposed in the neurophysiological literature. Two clearly separable cortical pathways have been identified in posterior brain regions: a ventral pathway for “what” information and a dorsal pathway for “where” information (Goodale & Milner, 1992; Ungerleider & Haxby, 1994; Ungerleider & Mishkin, 1982), with “what” referring to object features or properties and “where” referring to locations or relations between positions.

Thus, we adopted the “what” versus “where” distinction in the selection of storage and processing components. Spatial storage consisted of recalling sequences of ball movements (Kane et al., 2004), that is, memory for sequences of movements, with movement being a relation between two positions or memory for sequences of locations. Visual storage was tested by using an adaptation of the visual pattern test (Della Sala et al., 1999), a task frequently used to test memory for visual information (e.g., Logie & Pearson, 1997; Pickering, Gathercole, Hall, & Lloyd, 2001; Rudkin et al., 2007; Thompson et al., 2006). The original visual pattern test involves memory for one visual pattern, the complexity of which increases, whereas our adaptation could be described as memory for sequences of visual shapes of fixed complexity (i.e., 2×3 matrices). Importantly, these memory tasks were chosen bearing in mind the four recommendations of Rudkin et al. (2007) for studies attempting to distinguish experimentally between visual and spatial working memory processes. That is, both storage components involved (a) serial maintenance of sequentially presented stimuli, (b) the requirement to maintain order as the storage items had to be recalled in the order of presentation, (c) a constant number of possible storage items, regardless of the span length being presented, and (d) the same procedure at recall. Spatial

processing tasks were a symmetry judgment task (Kane et al., 2004) and a spatial fit task (Roth & Hellige, 1998; Rybash & Hoyer, 1992), with both tasks involving the judgment of geometrical relationships between objects in different locations. Indeed, although symmetry detection may serve perception of shape (Wertheimer, 1958), the present symmetry judgment task comprised complex matrices to be judged, with the non-symmetrical matrices created in such a way that judgments based on the matrix as a whole (e.g., a shape), without considering the exact locations and relationships between them, would lead to wrong answers. A color discrimination task was selected as the visual processing task (Klauer & Zhao, 2004; Tresch et al., 1993).

Four working memory span tasks were created by combining spatial and visual storage with spatial and visual processing. The cognitive load of the processing component was manipulated by varying the number of items to be processed within a processing phase of fixed duration, with more items inducing a higher cognitive load. According to the TBRS model, spatial and visual recall performances should depend above all on the cognitive load induced by the processing task. Decreasing the proportion of time during which memory traces can be refreshed by increasing the attentional capture of a spatial versus a visual processing task should have an isomorphic detrimental effect on spatial recall performance. The same goes for visual recall performance. Thus, we predicted that increasing the cognitive load of the processing task would affect both spatial and visual recall performances, regardless of the domain involved in the processing task. For each of the four combinations, we expected to observe a smooth monotonic relation between cognitive load and recall performance.

Method

Participants and Design

A total of 208 undergraduate psychology students (180 women and 28 men; mean age = 23.4 years) enrolled at the University of Geneva participated for course credit and were randomly assigned

¹ This becomes all the more clear when focusing, for example, on the work of Logie and collaborators, author of a substantial number of articles concerning the fractionation of visuo-spatial working memory and of the well-known model of visuo-spatial working memory (Logie, 1995). According to this model, visuo-spatial working memory consists of two separate subcomponents: a passive, visual cache, responsible for visual information, and an active, spatial inner scribe, responsible for spatial information. A loose description of the term *spatial* was given, stressing the importance of involvement of movement in its broad sense:

scanning in a visual array (via perception or scanning a mental image), movement to a target in the array (with or without visual input) or movements of objects in an array. It could also involve building up a representation of the geometrical relationships between objects by scanning from one to another or moving from one to another. (Logie, 1995, p. 78)

In further descriptions, movement continued to be a crucial characteristic of spatial information that was described as dynamic, such as movement sequences or pathways, in contrast with static visual information (Logie, 2003). However, in more recent writings, movement seems no longer crucial to the term *spatial* (Darling et al., 2006, 2007).

to one of the 12 conditions resulting from the 2 (nature of storage: spatial vs. visual) × 2 (nature of processing: spatial vs. visual) × 3 (number of items to be processed: three, five, or seven) factorial design. All participants had normal or corrected-to-normal vision.

Materials

Four working memory span tasks were created. Storage components comprised either spatial (ball movements) or visual (patterns) items (see Figure 1). Spatial storage was combined with a spatial symmetry judgment task and a visual color discrimination task. Visual storage was combined with a spatial fit task and a visual color discrimination task. When using visual storage, the spatial fit task was preferred to the symmetry judgment task in order to avoid similarity-based interference, as both the visual patterns and the symmetry items consisted of black and white matrices. The spatial processing items are shown in Figure 2.

Spatial storage: Memory for ball movements. Participants were required to memorize series of ball movements of ascending length (two to six movements) with three series of each length. A white box approximately 17 cm × 17 cm was presented in each display. Immediately after the onset of the box, one blue–green ball (approximately 1.5 cm in diameter) appeared in one of the eight possible locations inside the perimeter of the box: one of the four corners, in the middle of the top or bottom row, or in the middle of the leftmost or rightmost column. It then travelled vertically, horizontally, or diagonally to the location on the opposite side of the box, resulting in one of the 16 possible ball movements. Within a series the point of departure of the next ball movement was not necessarily the point of arrival of the prior ball movement. No ball movement was repeated within a series, and each of the ball movements was used approximately equally often.

Visual storage: Memory for visual patterns. Participants were required to memorize series of visual patterns of ascending length (two to six patterns) with three series of each length. A total of 20 patterns were created by filling in half of the cells of a blank 2 × 3 matrix, with each cell measuring 3 cm × 3 cm. No pattern was repeated within a series, and each of the visual patterns was used approximately equally often.

Spatial processing: Symmetry judgment. Forty-eight 6 × 6 matrices (9.5 cm × 9.5 cm) were created with some squares filled in black. Participants were instructed to decide whether the black-

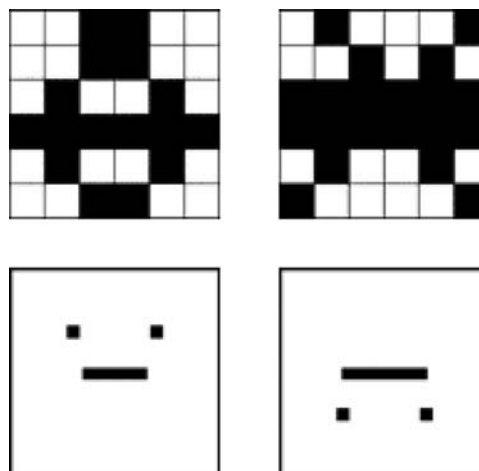


Figure 2. Examples of the spatial processing items used in Experiment 1. Upper panel: Items of the symmetry judgment task. Lower panel: Items of the spatial fit task.

square design was symmetrical along its vertical axis, the design being symmetrical about half the time. No matrix was repeated within a processing phase, and each of the matrices was used approximately equally often.

Spatial processing: Spatial fit task. Twenty-four white boxes (8.2 cm × 8.7 cm) containing a black horizontal line and two black square dots were created. The line, displayed in the center of each box, was 4 mm high, and the dots, positioned on the same horizontal plane as each other, measured approximately 4 mm on each side. The line varied in length (8, 16, 24, 32, 40, or 48 mm), and for each line length, the distance between the dots was either 4 mm shorter or 4 mm longer than the line length (e.g., a 24-mm line was combined with both a 20-mm gap and a 28-mm gap). The dots were situated either 12 mm below or 12 mm above the line, resulting in 24 different boxes, half of them containing a line that could fit into the gap. Participants were instructed to decide whether the horizontal line could fit into the gap between the two dots. No box was repeated within a processing phase, and each of the boxes was used approximately equally often.

Visual processing: Color discrimination. Twenty-eight monochromatic displays that filled the entire screen were created. Their

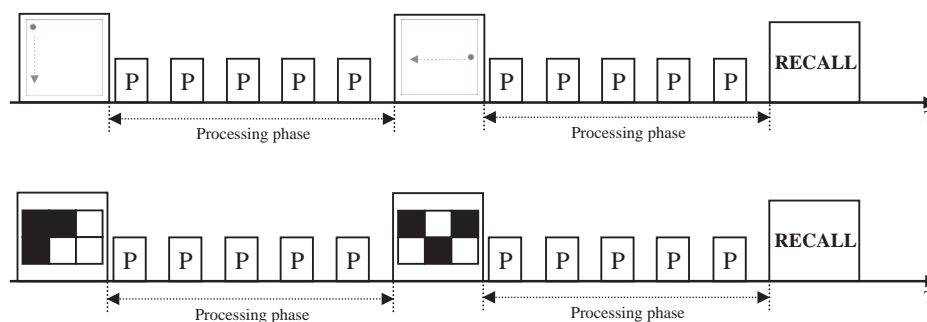


Figure 1. Illustration of the computer-paced working memory span tasks used in Experiment 1. Examples of series of two storage items are shown, with each storage item being followed by a processing phase of fixed duration in which five processing items (i.e., P) have to be processed. Upper panel: Spatial storage items (ball movements). Lower panel: Visual storage items (visual patterns).

red–green–blue (RGB) coordinates, as defined by the RGB-256 color scale, were calculated as follows: $R = 210 - 5i$, $G = 0$, and $B = 45 + 5i$, with i varying between 1 and 32, except for the values 15, 16, 17, and 18. Half of the displays could be categorized in the red family and the other half in the blue family. Participants were instructed to judge whether the presented color was more red than blue or more blue than red. No display was repeated within a processing phase, and each of the displays was used approximately equally often.

Procedure

Tasks were administered using E-prime software (Psychology Software Tools, Pittsburgh, PA). Each series began with an asterisk being centrally displayed for 750 ms, followed by a delay of 500 ms, after which the first storage item (i.e., ball movement or visual pattern) was presented. Each storage item was presented for 1,500 ms and followed by a fixed delay of 8,500 ms. The number of items to be processed within this delay (three, five, or seven) depended on the experimental condition the participant was assigned to. Following a delay of 500 ms, each processing item (i.e., symmetry matrix, spatial fit display, or color display) was displayed on screen for 1,778 ms, 1,067 ms, or 762 ms and followed by a delay of 889 ms, 533 ms, or 391 ms for the three-, five-, and seven-item conditions, respectively. The responses “symmetrical” in the symmetry judgment task, “does fit” in the spatial fit task, and “more red than blue” in the color discrimination task were made by pressing the left key of the keyboard, whereas the responses “not symmetrical,” “does not fit,” and “more blue than red” were made by pressing the right key. Responses and reaction times were recorded by the computer. To avoid delay of reaction time by movement time, participants were asked to rest their index fingers on the corresponding keys.

At the end of a series, the word “rappel” (recall) appeared and participants had to recall the series of storage items in order of appearance by reproducing them on response sheets. For each of the series a separate response sheet was provided. For spatial storage, response sheets presented as many squares as ball movements presented in the corresponding series. These squares consisted of lines corresponding to all 16 possible movement paths. Participants were asked to draw an arrow along one of the lines in each square to indicate the corresponding ball movement. For visual storage, response sheets presented as many blank matrices as visual patterns presented in the corresponding series. Participants were asked to indicate the filled cells of each visual pattern by marking them in the corresponding blank matrix. For both spatial and visual storage, all participants were presented with the same series of storage items, irrespective of the number of items to be processed within a processing phase.

Training preceded the experimental series. First, participants were presented with about 100 processing items (i.e., 33 series of three items, 20 series of five items, or 14 series of seven items). Every time participants made an error or did not respond fast enough (i.e., within 2,667 ms, 1,600 ms, or 1,143 ms for the three-, five-, and seven-item conditions, respectively), they heard a beep. The percentage of correct responses was calculated at the end of the series. To continue the training, participants had to attain 80% correct. If not, the same training stimuli were presented once again. When participants failed to attain 80% correct after three such

attempts, the experiment was terminated. Otherwise, training continued with two 2-storage items and two 3-storage items series in which participants had to maintain the storage items while carrying out the processing task.

No stop rule was used and recall performance was scored by calculating PCU scores (i.e., partial-credit unit scoring; see Conway et al., 2005). Participants were given credit for each movement path and each entire visual pattern correctly recalled in the correct serial position, with the PCU score expressing the mean proportion of items that were recalled correctly with respect to serial order within a series.

Results

Twelve participants, 8 in the symmetry judgment task and 4 in the spatial fit task, failed to achieve the 80% criterion in the first part of training and did not participate in the experimental session. To ensure that participants paid sufficient attention to the processing task during the experimental series, only participants with processing accuracies of at least 80% had their data included in the analyses. We report successively a spatial storage, a visual storage, and a temporal analysis.

Spatial Storage Analysis

The data from 2 participants with less than 80% correct responses on the spatial processing were discarded from further analyses. The remaining 96 participants (i.e., 16 participants for each condition) reached high percentages of correct responses in the spatial and the visual processing tasks (92% and 94%, respectively). A 2 (nature of processing: spatial vs. visual) \times 3 (number of items to be processed: three, five, or seven) analysis of variance (ANOVA) with both variables as between-subjects factors was performed on spatial recall performance. In line with our prediction, increasing the number of items to be processed within a processing phase of fixed duration resulted in poorer recall, $F(2, 90) = 8.63$, $p < .001$, $\eta_p^2 = .16$, with the linear trend explaining 99% of the experimental effect (see Table 1). Neither the nature of the processing component nor the interaction were statistically significant (both $F_s < 1$). Thus, the visual color discriminations disrupted spatial maintenance of ball movements in the same way as spatial symmetry judgments did.²

Visual Storage Analysis

Data from 2 participants with less than 80% correct responses on the spatial processing task were discarded from further analyses. The remaining 96 participants (i.e., 16 participants for each condition) reached high percentages of correct responses in the visual and the spatial processing tasks (92% and 94%, respec-

² In response to a request from one anonymous reviewer, we repeated the analyses excluding male participants, who classically outperform females in visuo-spatial tasks. For both spatial and visual storage, the pattern of effects remained the same: a significant effect of number of items, $F(2, 78) = 9.13$, $p < .001$, $\eta_p^2 = .19$, and $F(2, 76) = 14.89$, $p < .001$, $\eta_p^2 = .28$, respectively; no effect of nature of processing, $F < 1$, and $F(1, 76) = 1.37$, $p = .25$, $\eta_p^2 = .02$, respectively; and no interaction between both variables, both $F_s < 1$.

Table 1
Means and Standard Deviations of Working Memory Spans and Actual Processing Times as a Function of the Number of Stimuli Presented After Each Ball Movement in Experiment 1 (i.e., Spatial Storage)

Number of stimuli	Spatial symmetry task				Visual color task			
	Span		Σ PT		Span		Σ PT	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Three	73	14	2,817	316	77	13	2,320	311
Five	67	13	3,512	364	71	16	2,945	478
Seven	60	14	4,152	260	60	20	3,421	427
<i>M</i>	66		3,494		69		2,895	

Note. Working memory span means and standard deviations were measured in partial-credit units (PCU). Mean processing times (Σ PT) were measured in milliseconds.

tively). An ANOVA with the same design as previously presented revealed that recall performance decreased as the number of items to be processed increased, $F(2, 90) = 14.28, p < .001, \eta_p^2 = .24$ (see Table 2). The linear trend explained 99.5% of the experimental effect. The nature of the processing component had no effect ($F < 1$) and did not interact with the number of items to be processed, $F(2, 90) = 1.00, p = .37, \eta_p^2 = .02$. Thus, spatial fit judgments had the same disruptive effect on the maintenance of visual patterns as did the visual color discriminations.²

Temporal Analysis

To examine the time-based relationship between processing and storage, we studied mean total processing time (i.e., Σ PT), which reflects the time during which attention is captured by processing the stimuli. Σ PT was calculated for each participant by adding up the response times³ within the processing phases. Response times of both correct and incorrect responses were included, but not the non-responses (on average less than 1%). The Σ PTs for processing phases combined with spatial and visual storage are reported in Tables 1 and 2, respectively. Subsequently, we obtained a reflection of the cognitive load a processing component induced by dividing the total time devoted to processing (Σ PT) by the duration of a processing phase (*T*; here 8,500 ms). This procedure enabled us to regress recall performance (i.e., mean PCU of each experimental condition) on the cognitive load (i.e., mean Σ PT/*T* of each experimental condition) for each of the four processing-storage combinations. In line with our prediction, a smooth, linear relationship was observed between recall performance and cognitive load both within the visual ($R^2 = .92$) and the spatial ($R^2 = .999$) domain (see Figure 3) and between the two domains ($R^2 = .94$ for spatial storage-visual processing and $R^2 = .995$ for visual storage-spatial processing; see Figure 4).

Discussion

Experiment 1 examined central interference in visuo-spatial working memory. Both spatial and visual recall performances decreased as the number of items to be processed within a processing phase of fixed duration increased. Importantly, in line with our prediction, this effect was found both within and between the visual and spatial domains. Moreover, the results suggest that resource sharing is accomplished in a time-based way. In line with

the TBRS model, recall performance varied as a monotonic function of the cognitive load that the processing component induced, both within and between the visual and spatial domains.

According to the TBRS model, cognitive load reflects the proportion of time during which processing activities capture attention in such a way that the attentional refreshing of memory traces is impeded. Hence, by increasing the number of items to be processed within a processing phase, this proportion of time increases, resulting in poorer recall performance. This conception of cognitive load as a time-ratio follows directly from one of the main assumptions of the TBRS model, according to which attention is shared in a time-based way because the focus of attention acts as a central bottleneck, thereby constraining attention-demanding activities to be sequential. One could, however, assume that a general attentional resource is continuously shared between processing and storage activities at any point of time (e.g., Case, 1985), with more difficult processing tasks using a larger amount of resources, resulting in a smaller amount of resources available for maintenance activities and hence in poorer recall. In that case, cognitive load would reflect task difficulty, rather than the aforementioned time-ratio. Assuming that processing more items would increase task difficulty, pure resource sharing could account for the present findings without this resource sharing necessarily being time-based. However, previous work by our research group has demonstrated that cognitive load is a matter of time rather than task difficulty (see Barrouillet & Camos, 2007, for an overview). Furthermore, at least two findings support the time-ratio conception as proposed by the TBRS model. First, regressing the cognitive load (i.e., the time-ratio as defined by Σ PT/*T*) on the corresponding number of processed items for each of the four processing-storage combinations of Experiment 1 showed that cognitive load is linearly related to the number of items processed within a processing phase (all R^2 s $> .993$). Second, in an additional experiment using

³ One could argue for using presentation times instead of response times to calculate Σ PT. However, we added up response times (i.e., time from presentation to response) instead of presentation times for two reasons. First, including presentation times would result in including times even when no response is made. Second, it can be assumed that the online processing of an item is finished once a response has been made. Hence, the time during which an item captures attention is better reflected in response times than in presentation times.

Table 2

Means and Standard Deviations of Working Memory Spans and Actual Processing Times as a Function of the Number of Stimuli Presented After Each Visual Pattern in Experiment 1 (i.e., Visual Storage)

Number of stimuli	Visual color task				Spatial fit task			
	Span		ΣPT		Span		ΣPT	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Three	69	13	2,321	321	68	18	2,836	433
Five	56	14	2,968	272	58	16	3,613	271
Seven	52	13	3,561	364	43	18	4,509	310
<i>M</i>	59		2,950		56		3,653	

Note. Working memory span means and standard deviations were measured in partial-credit units (PCU). Mean processing times (ΣPT) were measured in milliseconds.

the same tasks as in Experiment 1, we manipulated the cognitive load of concurrent processing by decreasing the time available to process a constant number of same-domain items. By doing so, only time-related parameters were manipulated while task difficulty remained unchanged. Still, poorer recall performance was observed in the condition with the higher cognitive load.⁴

The findings of Experiment 1 have important implications for theoretical accounts of visuo-spatial working memory performance. The fact that spatial maintenance was disrupted by visual processing and that visual maintenance was disrupted by spatial processing is clearly at odds with domain- and process-based fractionations of central resources in visuo-spatial working memory. Moreover, the observed relationship between recall and the cognitive load induced by concurrent on-line processing suggests that spatial and visual recall performances depend above all on the amount of central interference between processing and storage, regardless of the domain involved in concurrent processing. Furthermore, the absence, for both spatial and visual memory, of any interaction between the domain of the processing component and its cognitive load indicates that the memory loss due to concurrent

processing is not domain specific. All of these findings are incompatible with the domain-specificity of central working memory resources as postulated by multiple-resource views on visuo-spatial working memory.

Importantly, such domain-specific views on visuo-spatial working memory are mainly supported by the observation of a double dissociation between the spatial and the visual domains in experimental studies combining storage and on-line processing within selective interference tasks (e.g., Klauer & Zhao, 2004; Tresch et al., 1993). Experiment 1, however, used computer-paced working memory span tasks. Besides the fact that our tasks were computer-paced, there are at least three crucial differences between both types of tasks. The selective interference tasks usually require (a)

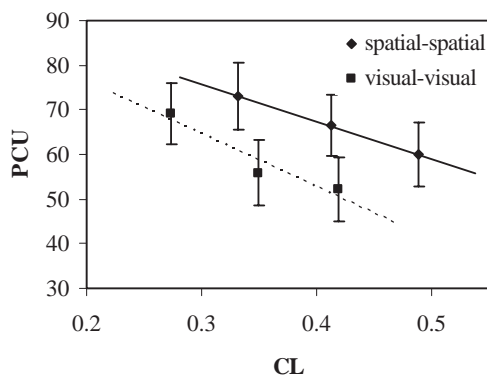


Figure 3. Mean recall performance (i.e., partial-credit unit [PCU] score) for each of the six within-domain experimental conditions of Experiment 1 as a function of the cognitive load (CL) induced by the processing component, along with the linear regression line for the spatial storage–spatial processing combination (i.e., storage of ball movements combined with symmetry judgments; solid line) and the visual storage–visual processing combination (i.e., storage of visual patterns combined with color discriminations; dotted line). Error bars represent 95% confidence intervals.

⁴ Sixty-eight undergraduate psychology students (56 women and 12 men; mean age = 23.1 years) at the University of Geneva participated and were randomly assigned to one of the four conditions resulting from the 2 (domain: spatial vs. visual) × 2 (pace: slow vs. fast) factorial design. Two complex span tasks were created by combining memory for ball movements with spatial symmetry judgment (i.e., spatial domain) and combining memory for visual patterns with color discrimination (i.e., visual domain). Material, procedure, and scoring method were those used in Experiment 1, except that each storage item was followed by five items to be processed sequentially within a processing phase, the duration of which varied as a function of the experimental condition the participant was assigned to: 6,500 ms in the slow pace condition and 10,500 ms in the fast pace condition. Within these processing phases, following a delay of 500 ms, each processing items was displayed on screen for either 1,333 ms or 800 ms and followed by a delay of either 667 ms or 400 ms for the slow and fast pace conditions, respectively. Thus, the time available to process one item was 2,000 ms and 1,200 ms for the slow and fast pace conditions, respectively. Four participants exhibiting a percentage of correct responses lower than 80% on the processing task had their data discarded from further analyses. Recall performance of the remaining 64 participants (i.e., 16 participants for each condition) were analyzed by running a 2 (domain: spatial vs. visual) × 2 (pace: slow vs. fast) ANOVA. Spatial recall performance (72%) was better than visual recall performance (55%), $F(1, 60) = 21.73, p < .001, \eta_p^2 = .27$. More importantly, the higher pace of processing induced poorer recall performance, $F(1, 60) = 17.76, p < .001, \eta_p^2 = .23$, an effect that did not interact with the domain of the task, $F(1, 60) = 1.03, p = .32$. Indeed, increasing the cognitive load by increasing the pace of processing while keeping constant parameters related to task difficulty impaired recall performance in both spatial working memory (78% vs. 66%), $F(1, 60) = 5.12, p < .05$, and visual working memory (64% vs. 45%), $F(1, 60) = 13.66, p < .001$.

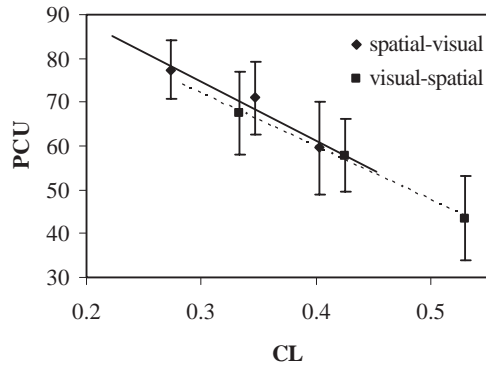


Figure 4. Mean recall performance (i.e., partial-credit unit [PCU] score) for each of the six between-domain experimental conditions of Experiment 1 as a function of the cognitive load (CL) induced by the processing component, along with the linear regression line for the spatial storage–visual processing combination (i.e., storage of ball movements combined with color discriminations; solid line) and the visual storage–spatial processing combination (i.e., storage of visual patterns combined with spatial fit judgments; dotted line). Error bars represent 95% confidence intervals.

maintenance of a one single item, as opposed to maintenance of a sequence of items, (b) recognition as opposed to recall of memory material, and (c) on-line processing of information during one retention interval, as opposed to on-line processing of information interspersed between the presentations of successive storage items. Hence, before drawing firm conclusions with regards to the structure and functioning of visuo-spatial working memory, it is important to determine to what extent the findings of Experiment 1 generalize to selective interference tasks.

Accordingly, instead of applying a paradigm heavily influenced by the WMG tradition, Experiment 2 examined central interference in visuo-spatial working memory by adopting tasks typically used within the WMS tradition. On that account, we decided to replicate one of the most recent selective interference experiments demonstrating a double dissociation between spatial and visual on-line processing and storage activities, namely the first experiment of Klauer and Zhao's (2004) study. Importantly, as time is considered to be crucial in the dual functioning of working memory, this replication was done under strict time control by using a computer-paced version. We hypothesized that if the findings of Experiment 1 apply generally, then central interference should

show similar effects on recall performance in the selective interference tasks used in Experiment 2.

Experiment 2

Experiment 2 replicated the selective interference experiment of Klauer and Zhao's (2004, Experiment 1) study under strict time control. Klauer and Zhao's study is one of the more recent and, according to Baddeley (2007), is also one of the most careful and thorough studies to make a case for separate visual and spatial resources, by demonstrating a double dissociation in visuo-spatial working memory. Either one Chinese ideograph (visual storage) or the location of one dot (spatial storage) had to be maintained during the 10-s period prior to recognition. The retention interval was either empty (i.e., no intervening task) or filled with a spatial or a visual processing task. For spatial processing, participants saw a display of 12 asterisks, 11 of which were moving. They were given 5 s to find and click on the one that remained stationary and their response (or non-response within the 5 s) was followed by the next display after a 200-ms delay. Visual processing consisted of a binary choice task in which colors had to be judged as "more red than blue" or "more blue than red." Participants had 3 s to discriminate each of the monochromatic displays, and their response (or non-response within the 3 s) was followed by the next color after a 600-ms delay. The expected selective interference pattern was observed. Memory for dot locations was more impaired by discriminating movements than by discriminating colors, whereas the reverse was observed for memory for Chinese ideographs. The authors interpreted this pattern of selective interference as evidence for a domain-based fractionation of visuo-spatial working memory into separate spatial and visual resources.

However, three shortcomings compromise such a conclusion. First, as the processing tasks were self-paced, the time parameters and hence the proportion of time during which the respective processing tasks hamper the attentional refreshment of memory traces were poorly controlled. Second, as we will see below, the two tasks differed in their central demand. Last, the two processing tasks differed in their potential to produce similarity-based interference with the memory items. As mentioned by Klauer and Zhao (2004), although it is difficult to see how similarity-based interference can come into play between colors and any of the memory tasks, dot locations and moving asterisks share many visuo-spatial features (see Figure 5). Furthermore, as the asterisks moved ran-

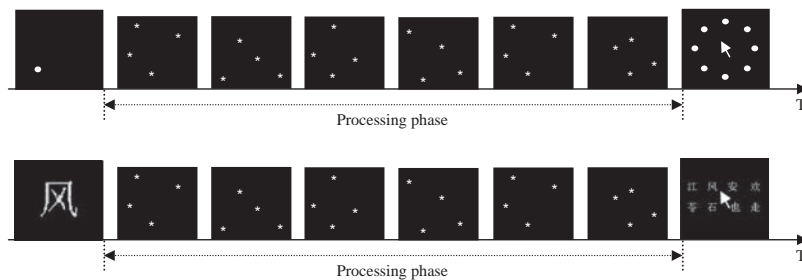


Figure 5. Illustration of the computer-paced selective interference tasks used in Experiment 2. Examples of trials are shown with the single storage item followed by a processing phase of fixed duration (i.e., retention interval) in which six movement displays have to be judged. Upper panel: Spatial storage item (dot location). Lower panel: Visual storage item (Chinese ideograph). T = time.

domly across the screen, one or more of the asterisks could be moving in a location that was close to the location of the dot to be remembered. Hence, the combination of differential central demand and peripheral interference, rather than separate visual and spatial resources, could underlie the observed effects.

In the present experiment, the same dot locations and Chinese ideographs were used as spatial and visual storage items in the recognition paradigm. One item had to be maintained during the 10-s retention interval, which was either empty or filled with color discriminations or movement discriminations. The binary color discriminations were the same as in Klauer and Zhao's (2004) study. The original movement discrimination task was slightly modified in order to convert it into a binary decision task. Each display comprised four asterisks where either all of them or all but one of them were moving. Participants were asked to decide whether the former or the latter condition was true. Importantly, in contrast to Klauer and Zhao's study, it was not up to the participants to decide the number of items to be processed or the pace at which the processing tasks were to be performed. For each of the storage components, the 10-s retention interval was filled with either six visual or six spatial processing items at a constant pace. A fourth condition was added to provide an extra test for the effect of cognitive load on recall performance in visuo-spatial working memory. For the between-domain combinations (i.e., spatial storage-visual processing and visual storage-spatial processing), the number of items to be processed within the 10-s retention interval was raised to 12.

Three predictions were put forth. First, we expected spatial as well as visual recall performance to be disrupted by both visual and spatial processing. Second, in line with the TBRS model, but unlike multiple-resource views, we expected the cognitive load of the processing component to be the main determinant of recall performance and not its domain. Hence, we expected a monotonic relationship between cognitive load and recall performance, with the processing task involving the highest cognitive load causing the largest disruptive effect on recall performance, regardless of the nature of the items included. In Klauer and Zhao (2004), participants made almost twice as many color discriminations than movement discriminations in the 10-s retention interval (respectively, an average of 8.4 and 4.4 discriminations), suggesting that the movement discrimination task captures attention for the longest period of time. A pretest (reported below) confirmed that it takes longer to make a binary decision when discriminating movements compared to discriminating colors. Assuming that these longer reaction times reflect longer periods of attentional capture, we predicted that both spatial and visual recall performances should be disrupted the most by the spatial discrimination task.

These effects were expected not only in recall accuracy but also in recall latency. Although recall latencies were not reported in the Klauer and Zhao (2004) study, they could bear compelling information. For example, Darling et al. (2007) found no evidence of selective interference effects in recall accuracy but observed longer recall latencies when memory items and passive interference were from the same domain. Indeed, both the probability and the time to retrieve an item should be a function of the level of degradation of the memory traces (Anderson, 1993; Anderson, Reder, & Lebiere, 1996). According to the TBRS model, this level of degradation should be a function of the cognitive load

induced by the processing component induced, regardless of its domain.

Finally, due to the nature of the stimuli used, we expected to observe similarity-based interference in addition to central interference between memory for dot location and movement discriminations. Whereas similarity-based interference was explicitly avoided in Experiment 1, this was not possible in Experiment 2, as the material was borrowed from Klauer and Zhao's (2004) study. This peripheral similarity-based interference between the maintenance of a dot location and the movement discrimination task should cause a larger disruption of recall performance than the one expected based on cognitive load alone. As such additional interference is thought to be similarity based instead of domain specific, it was not expected within the visual domain where colors and Chinese ideographs were combined.

Method

Participants and Design

A total of 24 undergraduate psychology students (21 women and 3 men; mean age = 23.1 years) enrolled at the University of Geneva participated for course credit. Using a within-subjects design, all participants completed both memory tasks under four different experimental conditions. All participants had normal or corrected-to-normal vision. Twelve additional participants (11 women and 1 man; mean age = 26.6 years) were included for the pretest.

Materials and Procedure

Spatial processing: Movement discrimination. First, six displays were created in which four white asterisks (5 mm in diameter) were located in six different, randomly determined locations on a black background. For each set of locations, 5 different displays with moving asterisks were created: 1 with all the asterisks moving and 4 displays with all but one asterisk moving, each of them corresponding to a different asterisk being stationary. In doing so, 30 different displays were used, 6 with all asterisks moving and 24 with all but one asterisk moving. Participants were instructed to judge whether all the asterisks were moving or not by pressing the left or the right key, respectively. For each trial and participant, movement displays were sampled randomly without replacement from a pool of 48 displays. These consisted of the 24 different all-but-one displays plus 4 times each of the 6 all-asterisks-moving displays.

Visual processing: Color discrimination. The 28 monochromatic displays described in Experiment 1 were used and participants were instructed to judge whether the presented color was more red than blue or more blue than red by pressing the left or the right key, respectively. For each trial and participant, monochromatic displays were sampled randomly without replacement from this pool of 28 different displays.

Spatial storage: Memory for dot locations. Spatial storage was tested using the same memory for dot locations task as Klauer and Zhao (2004). Participants were required to memorize the location of a dot (4 mm in diameter) presented for 500 ms on a black background at one of the eight equally spaced locations along the outline of a centrally placed invisible circle (8 cm in diameter).

After a 500-ms blank screen and a 10-s retention interval, the eight dot locations that could occur as storage items were displayed on screen along with a mouse cursor in the shape of an arrow, pointing initially at the center of the screen. Participants were instructed to use the mouse to click on the location at which the memorized dot had appeared. The retention interval was either empty or filled with 6 movement displays, 6 color displays, or 12 color displays, with each of these displays to be judged as fast as possible without making errors.

Visual storage: Memory for Chinese ideographs. Visual storage was tested using memory for one Chinese ideograph out of the set of eight different unfamiliar Chinese ideographs used by Klauer and Zhao (2004). Participants were required to memorize the white Chinese ideograph (2 cm in diameter) presented for 500 ms centrally on a black background. After a 500-ms blank screen and a 10-s retention interval, the eight Chinese ideographs were displayed on screen along with a mouse cursor in the shape of an arrow, pointing initially at the center of the screen. Participants were instructed to click on the ideograph that corresponded to the memorized one. The retention interval was either empty or filled with 6 color displays, 6 movement displays, or 12 movement displays, with each of these displays to be judged as fast as possible without making errors.

The experiment, administered using E-prime software, consisted of two experimental blocks, one for spatial storage and one for visual storage, the order of which was counterbalanced across participants. Each of the eight storage items was combined with all four processing conditions, resulting in 32 trials in each block. The order of presentation of the trials within each block was counterbalanced. In both blocks, a trial began with a screen that informed the participant about the processing condition of the given trial. Processing items were displayed on screen for either 1,200 ms or 600 ms and followed by a delay of either 467 ms or 233 ms for the 6- and 12-item conditions, respectively. For the condition without processing, participants were asked to rest their index fingers on the two response keys while watching a black screen.

A training session similar to the one proposed by Klauer and Zhao (2004) preceded the experimental series. Participants were familiarized with each of the storage components (five trials each) before practicing the four on-line processing components, which were movement discrimination with slow and fast pace and color discrimination with slow and fast pace, respectively (10 trials each). Finally, eight practice trials combined spatial and visual storage with the corresponding processing components. As in the Klauer and Zhao study, participants were told to perform all tasks as accurately as possible, but that the memory tasks were the primary ones, and articulatory suppression was added. Participants were required to repeat the syllable “ba” in a continuous manner throughout the experiment.

Pretest. Participants were presented with two blocks of 48 trials, the order of which was counterbalanced between subjects. One block consisted of 48 movement displays for which participants had to decide whether all asterisks or all but one asterisk moved, whilst the other consisted of 48 color displays for which participants had to decide whether the color was more red than blue or more blue than red.

Results

The pretest confirmed that binary decisions in the movement discrimination task take longer than the ones in the color discrimination task (847 ms and 472 ms, respectively), $t(11) = 11.08$, $p < .001$. The results are reported in three successive steps. First, the selective interference pattern reported by Klauer and Zhao (2004) was tested by including the three processing conditions that were in common for visual and spatial storage. Recall accuracy and recall latency were analyzed by running two repeated-measures ANOVAs with nature of storage (two levels: spatial and visual) and processing conditions (three levels: none, six visual discriminations, and six spatial discriminations) as two within-subject factors. Second, the effect of increasing the number of items to be processed within the retention interval of between-domain conditions was tested. Recall accuracy and latency were analyzed by running two repeated-measures ANOVAs with nature of storage (two levels: spatial and visual) and number of items (two levels: 6 and 12) as two within-subject factors. Finally, a temporal analysis was performed including all eight experimental conditions.

Data from 2 participants who exhibited a percentage of recall accuracy lower than 75% for visual recall without processing were excluded from further analyses. The remaining 22 participants had mean recall accuracy without processing of 98% for spatial storage and 95% for visual storage, indicating that they paid attention to the task. In terms of accuracy in the processing tasks, the mean percentages of correct responses were of 93%, 89%, and 86% when 6 colors, 6 movements, and 12 colors had to be judged, respectively, in combination with spatial storage. In combination with visual storage, the percentages were 92%, 89%, and 70% when 6 colors, 6 movements, and 12 movements had to be judged, respectively.

Recognition Rates and Latencies

In line with our first prediction, spatial and visual recall performances were disrupted by both spatial and visual processing. Spatial recall accuracy was poorer when the retention interval was filled with spatial processing (movement discrimination) than when it was empty (83% of the locations correctly recognized, compared to 98%), $F(1, 21) = 24.97$, $p < .001$, $\eta_p^2 = .54$, but the same was true when visual processing (color discrimination) filled the retention interval (93% correctly recognized), $F(1, 21) = 6.18$, $p < .05$, $\eta_p^2 = .23$ (see Table 3). In the same way, visual maintenance was disrupted by visual processing (86% of the ideographs correctly recognized, compared to 95% in the empty condition), $F(1, 21) = 10.34$, $p < .01$, $\eta_p^2 = .33$, but spatial processing had an even more damaging effect (81% correctly recognized), $F(1, 21) = 10.93$, $p < .01$, $\eta_p^2 = .34$ (see Table 3).

Thus, the selective interference pattern predicted by the multiple-resource view, with visual maintenance selectively impaired by visual processing and spatial maintenance selectively impaired by spatial processing, did not appear. In contrast, as we predicted, spatial processing had a more damaging impact than visual processing on both spatial (83% vs. 93%) and visual maintenance (81% vs. 86%), $F(1, 21) = 6.83$, $p < .05$, $\eta_p^2 = .25$, and this effect did not interact with the nature of storage ($F < 1$; see Figure 6). The same pattern of results was observed with recognition latencies. Spatial processing induced longer latencies than

Table 3

Means and Standard Deviations of Recall Accuracy and Recall Latency as a Function of the Interference Condition That Filled the Retention Interval in Experiment 2

Interference condition	Spatial storage items				Visual storage items			
	Accuracy		Latency		Accuracy		Latency	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
No interference	98	6	1,681	381	95	7	2,187	435
6 colors	93	14	1,975	230	86	14	2,904	698
12 colors	89	19	2,013	267	—	—	—	—
6 movements	83	16	2,146	331	81	21	3,255	864
12 movements	—	—	—	—	80	17	3,389	916
<i>M</i>	91		1,954		85		2,934	

Note. Recall accuracy was measured by the percentage of items correctly recalled. Recall latency was measured in milliseconds.

visual processing for both spatial (2,146 ms vs. 1,975 ms) and visual recognition (3,255 ms vs. 2,904 ms), $F(1, 21) = 15.15$, $p < .001$, $\eta_p^2 = .42$, without any significant interaction, $F(1, 21) = 1.24$, $p = .28$, $\eta_p^2 = .06$ (see Figure 6).

Number of Items

For both measures of recall performance, there was no effect of the number of items (6 vs. 12), nor was there an interaction with the nature of storage (all $F_s < 1$; see Table 3). These findings were not in line with our expectations, nor with the results of Experiment 1, and are addressed below.

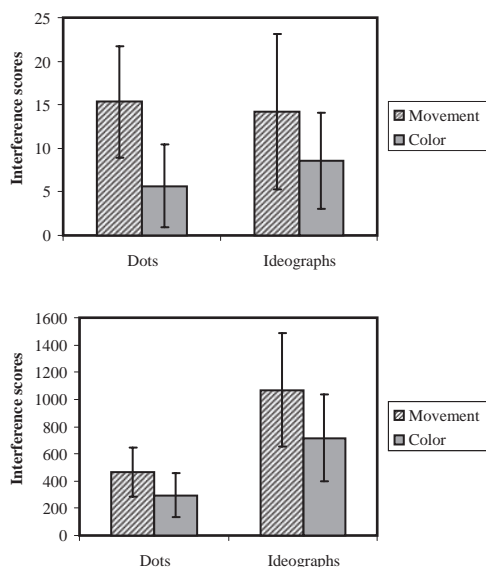


Figure 6. Mean interference scores for the experimental conditions of Experiment 2 including either six movement discriminations or six color discriminations (i.e., difference in performance relative to the experimental condition without interference). Upper panel: Interference scores in recall accuracy (i.e., difference in percentage of storage items correctly recognized). Lower panel: Interference scores in recall latency (i.e., difference in time needed for recognition, in ms). Error bars represent 95% confidence intervals.

Temporal Analysis

Finally, a temporal analysis was performed including the eight experimental conditions. Comparison of the total processing times confirmed that the six movement discriminations took longer than the six color discriminations, in combination with both spatial (4,722 ms and 2,962 ms, respectively), $t(21) = 17.00$, $p < .001$, and visual storage (4,623 ms and 2,971 ms), $t(21) = 15.33$, $p < .001$. As we predicted, the task involving longer processing times, rather than the task involving items pertaining to the same domain as the storage item, had the largest detrimental effect on recall performance. In order to examine more closely the time-based interplay between processing and maintenance activities, we studied the relationship between the observed recall performance and the corresponding cognitive load induced by the processing components.

We obtained a reflection of the cognitive load a processing component induced by dividing the ΣPT by the fixed duration of the retention interval (i.e., the total time available to refresh when no processing would be required, here 10,500 ms). As in Experiment 1, we regressed recall accuracy on the cognitive load (i.e., mean $\Sigma PT/T$ of each experimental condition). The relationship between cognitive load and recall accuracy should be the clearest when no peripheral interference can come into play. Hence, for both spatial and visual recall, we first plotted recall performance for the between-domain experimental conditions against the corresponding cognitive load. For the between-domain conditions, a linear relationship was observed between recall accuracy and cognitive load for both spatial ($R^2 = .999$; see Figure 7) and visual ($R^2 = .98$; see Figure 8) storage, confirming our prediction of a monotonic relationship with cognitive load as the main determinant of recall accuracy. Next, the expected percentage of correct recognition for the two within-domain conditions was calculated based on the parameters of the aforementioned between-domain linear regressions. In line with our prediction, there was no difference between the observed recall accuracies and the predicted ones for the within-domain condition of visual storage in which no similarity-based interference was expected ($p > .90$). This is illustrated in Figure 8 with the corresponding point being exactly located on the regression line. However, as can be seen in Figure 7, and as predicted, the within-domain condition of spatial storage in

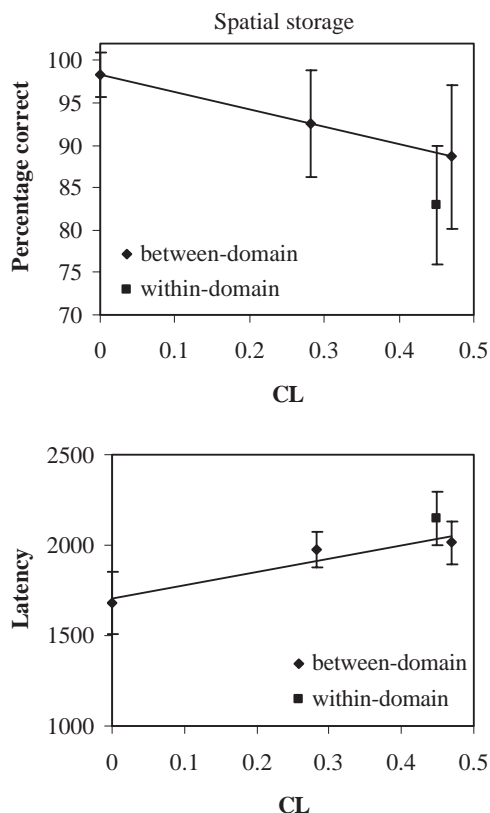


Figure 7. Mean recall performance for the four experimental conditions involving spatial storage in Experiment 2 (i.e., memory for dot locations combined with an empty delay, 6 color discriminations, 6 movement discriminations, or 12 color discriminations) as a function of the cognitive load (CL) induced by the processing component, along with a linear regression line for the between-domain combinations (i.e., empty delay, 6 color discriminations, and 12 color discriminations). Upper panel: Recall accuracy (percentage of locations correctly recognized). Lower panel: Recall latency (in ms). Error bars represent 95% confidence intervals.

which similarity-based interference was expected induced an additional decrease of 6% that approached significance, $t(21) = 1.84$, $p = .08$.

The same procedure was followed for recall latency, which, for the between-domain conditions, was plotted against the corresponding cognitive load, and a linear relationship was observed between recall latency and cognitive load for both spatial ($R^2 = .91$; see Figure 7) and visual recall ($R^2 = .985$; see Figure 8). Expected recall latencies for the two within-domain conditions were calculated based on the parameters of the obtained linear regressions. The observed recall latencies and the predicted ones did not differ for the within-domain condition of visual storage ($p > .50$), the corresponding point being located on the regression line in Figure 8. However, as can be seen in Figure 7, spatial recognition took 110 ms longer when combined with spatial processing than expected from the effect of cognitive load as reflected in the between-domain regression line, though this difference did not reach significance, $t(21) = 1.61$, $p = .12$.

Discussion

Experiment 2 investigated central interference in visuo-spatial working memory by replicating the first selective interference experiment of Klauer and Zhao's (2004) study in a computer-paced version. More specifically, the role of cognitive load was examined directly by controlling time-related parameters without changing the nature of the stimuli involved. Three predictions were tested in this experiment, the corresponding results of which are discussed in turn. First, in line with the general resource-sharing view of visuo-spatial working memory, visual and spatial recognition were both impaired by filling the retention interval with an attention-demanding processing task. Furthermore, disrupted recall performance was observed, regardless of the nature of the items to be processed within the retention interval. Memory for locations was less accurate and took more time when spatial or visual items had to be processed within the retention delay than when no task had to be performed. The same was observed for memory for Chinese ideographs. Besides being at odds with the results of Tresch et al. (1993), who found no interference between processing and storage when they involved different domains, the

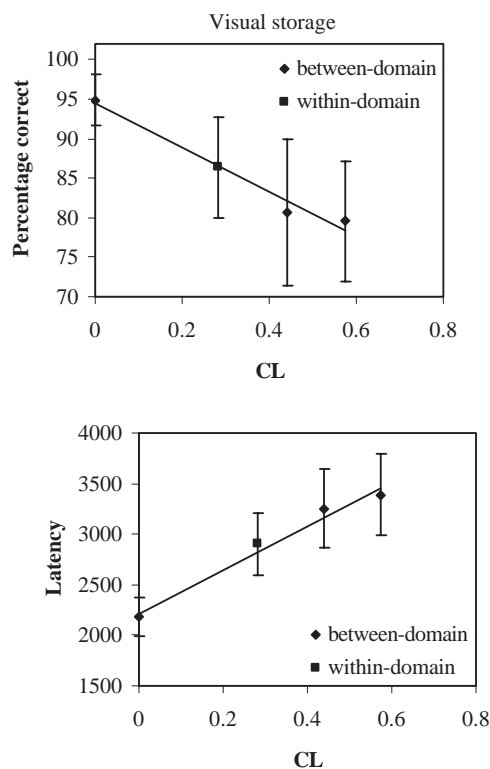


Figure 8. Mean recall performance for the four experimental conditions involving visual storage in Experiment 2 (i.e., memory for Chinese ideographs combined with an empty delay, 6 color discriminations, 6 movement discriminations, or 12 movement discriminations) as a function of the cognitive load induced by the processing component, along with a linear regression line for the between-domain combinations (i.e., empty delay, 6 movement discriminations, and 12 movement discriminations). Upper panel: Recall accuracy (percentage of ideographs correctly recognized). Lower panel: Recall latency (in ms). Error bars represent 95% confidence intervals.

observation of both within- and between-domain disruption is at odds with any view on visuo-spatial working memory that does not include a possibility of central interference through the sharing of a common resource. As visual maintenance was more disrupted by the processing of six spatial items than by the processing of six visual items, it appears that the domain of the items involved in the processing component is not the main determinant of recall performance. Instead, in line with our second prediction, the processing component involving six movement discriminations, which impedes attentional refreshment for a longer period of time, caused a larger impairment of both visual and spatial recall performance than did the processing component involving six color discriminations. These results strongly suggest that the main determinant of visual and spatial recall performance is the proportion of time during which the processing of items impedes attentional refreshment of memory traces, rather than the domain to which the processing items pertain. Accordingly, we observed that both recall accuracy and latency were a monotonic, linear function of the cognitive load induced by the processing components. The probability of retrieving a storage item and the time needed to retrieve it smoothly vary as a direct function of the proportion of time during which memory traces can be refreshed through attentional focusing, regardless of the domain of the items preventing such attentional refreshment. This confirms that the level of degradation of memory traces is provoked by central interference and, hence, is not domain specific.

However, one effect, or rather the absence of it, appears to challenge this conclusion. The effect of increasing the number of discriminations to be performed within the retention interval of between-domain conditions did not reach significance when spatial storage was combined with either 6 or 12 color discriminations and was not significant when visual storage was combined with either 6 or 12 movement discriminations. This might seem at odds with the prediction of the TBRS model. Indeed, concerning spatial storage, increasing the number of color discriminations from 6 to 12 resulted in a significant increase of the time during which processing captures attention, $t(21) = 17.62$, $p < .001$ (mean Σ PTs, respectively, 2,962 ms and 4,929 ms). However, as can be seen in Figure 7, although the observed drop in spatial recall performance was not significant, the point corresponding to the observed spatial recall performance in the 12-color condition is located exactly on the regression line representing the expected recall performance based on a TBRS mechanism. Hence, in line with the TBRS model, spatial recall performance was a direct function of the cognitive load induced by the color discrimination task.

With regard to visual storage, although increasing the number of movement discriminations from 6 to 12 resulted in a significant increase of Σ PT (4,623 ms and 6,030 ms, respectively), $t(21) = 4.15$, $p < .001$, recall performance was practically the same in both conditions. Why is that? Adopting the procedure from Klauer and Zhao (2004), participants were told that the memory task was the main task. Hence, participants could have tried to lower the cognitive load of the processing task involving 12 movement discriminations in order to have more time at their disposal to refresh decaying memory traces. This explanation is supported in that in the 12-movement discrimination task only 70% of responses were correct, whereas for all the other processing tasks more than 85% of responses were correct. A simple calculation shows that a 70%

correct rate (i.e., 8.4 correct discriminations out of 12) could easily be obtained by participants who concentrated on 6 out of the 12 discriminations, resulting in 5.4 correct responses out of those 6, given the obtained percentage of 90% in the six-movement discrimination task. The remaining six discriminations could be done without paying attention, obtaining three correct responses out of those six, which is a result participants might be expected to obtain by chance. Applying such a strategy results in attention being captured for practically the same proportion of time for the 6- and the 12-movement discrimination conditions, and hence, very similar recall performances in both conditions.

Taken together, it seems that, once time-related parameters are controlled and attentional involvement assessed, functioning of visuo-spatial working memory in a selective interference paradigm can best be described as time-based resource sharing, a mechanism also observed in the working memory span tasks in Experiment 1. Furthermore, the fact that the main findings of Experiment 1 were replicated here under concurrent articulation suggests that these phenomena cannot be accounted for by a hypothesis of verbal recoding of the memory items.

Finally, a tendency toward peripheral interference was observed between the maintenance of a dot location and movement discriminations, whereas no such additional interference was observed between the maintenance of a Chinese ideograph and color discriminations. This might suggest that the observed additional interference within the spatial domain was similarity based, rather than domain specific. It could also point to the existence of a second maintenance mechanism for spatial material, in addition to central attentional refreshment, but not for visual material, as suggested by Logie (1995, 2003). Either way, based on the results of Experiment 2, the functioning of visuo-spatial working memory can be accounted for by a combination of two mechanisms without the need for separate resources in visuo-spatial working memory: (a) one of time-based sharing of attention resulting in a monotonic relationship between cognitive load and both recall accuracy and latency and (b) one of representational overlap resulting in peripheral interference, which is reflected in the additional drop of recall performance when combining memory for dot location with movement discriminations. Although our results do not allow one to draw conclusions concerning the nature of peripheral mechanisms, it brings evidence for a common pool of resources in visuo-spatial working memory, shared in a time-based way between the visual and the spatial domains. This is further discussed in the General Discussion.

General Discussion

The key finding of the present study is the observed interference between on-line processing and storage of items when they pertain to different domains of visuo-spatial working memory. Theoretical implications of these results concern both the structure and the functioning of working memory, and the visuo-spatial domain of working memory in particular. Although structure and functioning are very closely related, they are discussed in turn.

The Structure of Working Memory

The implications of our findings for the structure of working memory are twofold. First, the observation of a detrimental effect

of processing on storage within the visual and the spatial domains demonstrates that, at least within a given domain of working memory, the two activities rely on the same resource. Therefore, any view on (visuo-spatial) working memory that does not provide a common resource for processing and storage is contradicted by our findings. Second, this effect of processing on storage was also observed between the visual and the spatial domains. Consequently, models of (visuo-spatial) working memory need to consider the existence of some type of domain-general supply required for both activities, regardless of the nature of the material involved. Whereas the existence of such a flexible domain-general resource pool for processing and storage activities is one of the fundamental assumptions of theories in the WMG tradition (e.g., Barrouillet et al., 2004; Daneman & Carpenter, 1980; Engle, Kane, & Tuholski, 1999), the opposite is true for multiple-resource views on working memory in the WMS tradition (e.g., Baddeley & Logie, 1999; Logie & Duff, 2007). To clarify this point, we need to distinguish between a strong and a weak version of the latter view.

According to the strong version, peripheral systems are literally stores, meaning that they are exclusively responsible for the storage of the respective kind of information. They are never involved in the processing of information, just as much as the central executive is responsible only for processing and never involved in storage (e.g., Cocchini et al., 2002; Duff & Logie, 2001). Together with earlier studies by our research group that demonstrate interference between processing and storage in the verbal domain (Barrouillet et al., 2004, 2007), the present observations of interference between processing and storage in the visuo-spatial domain completely contradict the strong hypothesis of independence of processing and storage resources in working memory. The weak version of the multiple-resource view describes peripheral systems as “specialized for the processing and temporary maintenance of material within a particular domain” (Baddeley & Logie, 1999, p. 29). In doing so, it allows for interference between processing and storage when both activities generate representations that would be maintained and/or processed by the same domain-specific peripheral system. However, we observed interference between processing and maintenance activities both within and between the visual and the spatial domains of working memory. Therefore, our results cannot be accounted for by any of these multiple-resource views on visuo-spatial working memory.

What is required to account for our findings is a common resource for processing and maintenance of both visual and spatial material. Such a resource could be a visuo-spatial one, separate from the resources of the verbal domain (Shah & Miyake, 1996), or a domain-general one that is also involved when verbal material is to be processed and/or maintained. Although the present study does not allow one to distinguish between either proposal, other studies suggest the existence of a domain-general attentional resource in working memory (e.g., Barrouillet et al., 2007; Kane et al., 2004; Kyllonen, 1993; Maehara & Saito, 2007; Oberauer, Süß, Wilhelm, & Wittmann, 2003; but see Shah & Miyake, 1996). For example, both spatial (Klauer & Stegmaier, 1997) and visual (Stevanovski & Jolicoeur, 2007) recall performances were found to be disrupted by an attention-demanding task such as tone pitch discrimination, suggesting the involvement of attention in the maintenance activities of visuo-spatial material. In the same way, Morey and Cowan (2004, 2005) as well as Allen, Baddeley, and

Hitch (2006) observed interference between visual and verbal maintenance activities, suggesting that the resource needed to maintain visuo-spatial information in working memory is not a visuo-spatial one, but a domain-general one shared with the verbal domain. Consistent with the idea of domain-general attentional maintenance, Barrouillet et al. (2007) observed a monotonic relationship between the cognitive load induced by spatial binary decisions and verbal recall performance.

A limited-capacity and domain-general maintenance mechanism could be provided by the episodic buffer, recently added to the multiple-component model (Baddeley, 2000). As maintenance of its content would be accomplished through attentional refreshment (Baddeley & Larsen, 2007; Repovs & Baddeley, 2006), this domain-general buffer could account not only for maintenance activities of different domains interfering with each other but also for interference between processing and storage activities both within and between the different domains of working memory. Therefore, it appears that the newer version of the multiple-component model is moving closer to the WMG tradition. However, this conclusion seems somewhat contradicted by accepting at the same time the existence of separate domain-specific resources for spatial and visual material in working memory (Baddeley, 2007; Repovs & Baddeley, 2006), which is partly based on the results of Klauer and Zhao (2004). Indeed, if one includes a domain-general storage component the content of which is refreshed through attentional focusing, one has to reconsider the results of studies that do not directly assess central interference between processing and storage.

The existence of a common attentional resource for the processing and maintenance of visual and spatial material does not, however, equal the non-existence of domain-specific subsystems in working memory on a more peripheral level. In line with Kane and Engle (2002), we support a hierarchical view of working memory. Kane and Engle proposed an executive-attention domain-general system, residing in the dorsolateral prefrontal cortex that is networked to different more posterior domain-specific regions. Within such a view, central and peripheral interference can coexist. Broadly speaking, peripheral interference could arise because the secondary task interferes with a domain-specific maintenance mechanism (i.e., an extra mechanism of maintenance) or because the processing and storage activities generate representations that share some overlapping features (i.e., an extra source of forgetting). The multi-component view of working memory seems to prefer the first proposal. However, the exact number of peripheral domain-specific maintenance mechanisms in visuo-spatial working memory is still a matter of debate between only one (Logie, 1995, 2003), two (Klauer & Zhao, 2004; Repovs & Baddeley, 2006), or three separate mechanisms (Wood, 2007). The present findings do not allow us to disentangle the mechanisms underlying peripheral interference but do demonstrate that peripheral interference cannot be studied without assessing the role of central interference resulting from attention sharing.

Indeed, we agree with Klauer and Zhao (2004) that the effects of passive interference tasks are not well understood and are still a matter of debate. This is nicely demonstrated in the Klauer and Zhao study, which mentions the lack of any selective interference effect on recall performance when they presented, in an additional experiment, the same movement and color stimuli in the retention interval without the requirement to make a response to them,

although they found the irrelevant stimuli to interact with visual and spatial recall performance. Such a passive condition was also included in the study by Zhao (2005), but irrelevant input had no effect at all on recall performance this time. Movement discrimination even tended to interfere with memory for Chinese ideographs ($p = .08$, whereas all other $ps > .20$). As a consequence, examining the nature of peripheral interference in working memory should be done including on-line processing tasks as did Tresch et al. (1993) and Klauer and Zhao. However, without explicitly assessing the impact of cognitive load as in our Experiment 2, the effects of on-line processing tasks can neither be understood nor interpreted. The present study established central interference in visuo-spatial working memory and hence, its role in domain-specific effects should always be assessed in order to fully understand the nature and the functioning of peripheral systems. We believe that our computer-paced method offers a unique opportunity to (re)examine peripheral interference over and above central interference, as it allows for careful control of time-related parameters, which our study demonstrates are crucial to the functioning of visuo-spatial working memory.

The Functioning of Working Memory: Time-Based Resource Sharing

Concerning the dual functioning of working memory, the present study has four unique empirical contributions. They all consider the generality of the TBRS mechanism and its theoretical and methodological implications. The first concerns task generality. Central interference due to the time-based sharing of an attentional resource was observed in both experiments and hence both in paradigms involving (a) the maintenance of a one single item, as opposed to maintenance of a sequence of items, (b) recognition as opposed to recall of memory material, and (c) processing tasks filling one retention interval, as opposed to processing phases inserted between the presentations of the storage items. Hence, the present study confirms that the mechanism of time-based resource sharing is not limited to a certain type of task. The second concerns domain generality. The monotonic relationships between recall accuracy and the cognitive load induced by concurrent processing activities as observed in the present study extend earlier observations of time-based resource sharing within the verbal domain (Barrouillet et al., 2004, 2007) to the visuo-spatial domain and show that working memory functions in a similar way at the central level for both domains. The third concerns sharing generality. In line with the core assumptions of the TBRS model, we observed the aforementioned monotonic relationship both within and between the visual and the spatial domains of working memory. This confirms that a resource is shared between processing and storage activities, not only within but also between different domains of working memory. Thus, it is a domain-general attentional resource that is time shared, and central interference should be observed between any two domains in working memory. It should be clear now that interference between processing and storage activities within or between any two domains of working memory cannot be done without carefully controlling for the parameters related to attentional involvement and time. Finally, the fourth concerns measure generality. The use of a recognition paradigm in Experiment 2 enabled us to demonstrate that the time needed to retrieve a stored item is mainly determined by the

proportion of time during which the attentional refreshment of the memory trace of that item has been prevented. So for the first time we were able to demonstrate that not only recall accuracy but also recall latency is a direct function of the cognitive load involved by concurrent processing activities. Taken together, by demonstrating the generality of the TBRS mechanism, it becomes clear that it is a powerful mechanism that determines the dual functioning of working memory across tasks, procedures, stimuli, and domains. In other words, it captures the general laws of human information processing.

Conclusion

The adaptation of computer-paced tasks, as developed within the TBRS framework, enabled us to demonstrate central interference within visuo-spatial working memory, both in working memory span tasks and selective interference tasks. Central interference between on-line processing and maintenance activities was reflected in a monotonic relationship between the cognitive load of the processing task and recall performance, both within and between the visual and the spatial domains. All of our results are at odds with process- and domain-based fractionations of visuo-spatial working memory at the central level. Instead, our findings strongly suggest that visual and spatial on-line processing and maintenance activities rely on one and the same attentional resource through a time-based sharing mechanism.

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Received September 22, 2008

Revision received February 11, 2009

Accepted February 21, 2009 ■

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