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Abstract

Some evidence suggests that memory for serial order is domain-general. Evidence also points to asymmetries in interference between verbal and visual-spatial tasks. We confirm that concurrently remembering verbal and spatial serial lists provokes substantial interference compared with remembering a single list, but further investigate the impact of this interference throughout the serial position curve, where asymmetries are indeed apparent. A concurrent verbal order memory task affects spatial memory performance throughout the serial positions of the list, but performing a spatial order task affects memory for the verbal serial list only for early list items; in the verbal task only, the final items are unaffected by a concurrent task. Adding suffixes eliminates this asymmetry, resulting in impairment throughout the list for both tasks. These results suggest that domain-general working memory resources may be supplemented with resources specific to the verbal domain, but perhaps not with equivalent spatial resources.

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Although many investigators have compared performance on serial verbal and

spatial memory tasks with the aim of determining whether they rely on separate or

predominantly shared memory resources, inconsistencies in results prevent a clear

consensus from emerging. Similar studies have yielded results varying from equal

interference to spatial or verbal memory tasks from verbal and manual suppression

(Jones, Farrand, Stuart, & Morris, 1995), contradicting Baddeley's (1986) multi-

component model of working memory, to convincing evidence of selective interference

between domain-specific memory and rehearsal suppression tasks (Logie, Zucco, &

Baddeley, 1990), at least under certain conditions (Farmer, Berman, & Fletcher, 1986;

Meiser & Klauer, 1999). These disparities stoke controversy about the structure of a

working memory system: to what extent are domain-general and domain-specific

resources involved in serial memory?

Baddeley's prominent multi-component model of working memory (1986; 2007)

proposes independent stores able to hold and rehearse information from different

domains in parallel. The multi-component model of working memory was inspired by the

work of Baddeley and Hitch (1974), particularly their finding that maintaining a small

verbal memory load induced little or no detrimental effect on a concurrent verbal

reasoning task. The finding that tasks requiring different mental operations could be

performed simultaneously suggested some independence between mechanisms needed

for these different mental operations, leading to a modular system including domain-

specific storage buffers specializing respectively in verbal or visual-spatial maintenance.

Proponents of modular models such as Baddeley's vary in the degree of domain-specific separation supposed. Whereas Baddeley envisions a domain-general executive system (1986), others have claimed separate attention systems for verbal and visual-spatial information (Shah & Miyake, 1996; Wickens, 2002).

In Baddeley's (1986) modular system, it is assumed that activities of one storage buffer should not affect activities of another, but this very strict interpretation does not withstand scrutiny. Jones, Farrand, Stuart and Morris (1995) measured serial verbal and spatial recall during concurrent tasks designed to selectively limit verbal or spatial rehearsal capabilities. However, they did not observe selective interference. Instead, they observed that articulatory suppression (repeating aloud a previously learned verbal sequence) impaired memory for sequences of spatial locations as much as it impaired memory for sequences of words. Similarly, repeatedly tapping a series of keys impaired memory for spatial locations and words to an almost equal degree. However, studies of interference with serial memory from rehearsal suppression do not consistently show such strong evidence of domain-general interference (for example, Farmer, Berman, & Fletcher, 1986; Guérard & Tremblay, 2008). In a particularly relevant study, Meiser and Klauer (1999) attempted to replicate the findings of Jones et al., and in addition, compared the impact of rehearsal suppression separately during encoding and retention of sequences of words and spatial locations. Meiser and Klauer observed domain-specific selective interference when articulatory suppression or spatial tapping was carried out during encoding of the to-be-remembered word or location sequences. However, when rehearsal suppression was carried out during retention, a more complex pattern of interference emerged: both articulatory suppression and spatial tapping interfered with

spatial sequence memory (indicated by a significant main effect of performing a secondary task, but no effect of the modality of the secondary task), while articulation interfered selectively with verbal sequence memory. Meiser and Klauer argued in favor of a modular system like Baddeley's multi-component model, but their data are not necessarily consistent with a model that proposes separate domain-specific storage buffers with equivalent capabilities. This pattern could also be interpreted as evidence that spatial sequence memory is sensitive to interference from a variety of sources, and perhaps more vulnerable to domain-general interference than verbal sequence memory.

The studies of Jones et al. (1995) and Meiser and Klauer (1999) examined memory for verbal or spatial materials during rehearsal suppression tasks. What if a concurrent task also requires storage? Interference between the *maintenance* of two cross-domain stimulus sets does not seem to be negligible. Saults and Cowan (2007) estimated working memory capacity for visual arrays of colored shapes and auditory arrays of several voices speaking at once, and compared estimates of capacity when these tasks were carried out separately or simultaneously. In a subset of their experiments in which sensory masks were employed (presumably eliminating sensory memory traces from which information may be extracted), Saults and Cowan observed summed dual-task capacities equal to single-task capacity, consistent with the possibility that visual-spatial and auditory-verbal materials compete for a common store. Cowan and Morey (2007) also found evidence that storage capacity is constant regardless of stimulus domain. They presented two sets of stimuli, which could be two verbal lists, two visual arrays, or one verbal list and one visual array, and in some conditions, cued participants quickly after the stimulus presentation, letting them know which stimulus set would be

tested after the retention interval. When the retro-cue warned participants which stimulus

set would be tested, participants could then selectively rehearse or refresh this

information throughout the retention interval. Cowan and Morey compared uncued

conditions, in which some items from both stimulus sets were presumably remembered

with retro-cued conditions in which participants could focus their efforts exclusively on

the to-be-tested stimulus set, and found similar costs of maintaining two stimulus sets

regardless of whether the sets contained stimuli from the same or different domains.

However, Cowan and Morey did observe greater interference between two sets from the

same domain than two sets from different domains, reflected in the cost between trials

with only one to-be-remembered stimulus set and retro-cued trials with two stimulus sets,

which suggests that encoding two stimulus sets of the same domain incurred a steeper

cost than encoding stimulus sets from different domains. Together, this evidence suggests

that storage operations involved in working memory maintenance may not be domain-

specific (at least not when information must be preserved for more than a second or so),

but that operations involved in encoding cross-modal sets of information could be more

independent. These findings are consistent with the proposal of brief domain-specific

memory representations, but further suggest that this information must be quickly

consolidated into a domain-general resource.

     Memory for serial lists, which requires the maintenance of some stimuli during

the presentation of subsequent stimuli over time, may also be sensitive to interference

from a concurrent memory task, even if the to-be-remembered stimuli come from distinct

domains or modalities. Even if brief domain-specific memory representations are

available, as Cowan and Morey's (2007) data suggest, these representations might not be

robust enough to withstand interference from consolidating subsequent list items or frequently switching attention to subsequent items, regardless of the domain of the presented information. Depoorter and Vandierendonck (2009) created memory tasks which required retention of item identities or sequential order, and combined them in an experimental design in which either an item and an order task, two item tasks, or two order tasks were performed concurrently. Regardless of the domain of the items in each stimulus set, when both tasks required order memory, interference was observed, whereas little or no interference was observed when remembering two sets of items simultaneously. However, Depoorter and Vandierendonck's results in their concurrent order task conditions seem to confirm the asymmetric pattern we discerned in Meiser and Klauer's (1999) data, in that somewhat more interference was found when the verbal order memory task was embedded within the spatial order memory task (dual-task performance is 76% of single-task performance) than when the spatial order task is embedded within the verbal order task (dual-task performance is 88% of single-task performance). This pattern, in which auditory-verbal tasks seem to interfere more with visual-spatial tasks than visual-spatial tasks interfere with auditory-verbal ones (see also Morey, Cowan, Morey, & Rouder, 2011; Shah & Miyake, 1996) seems persistent and is logically consistent with propositions that spatial memory is more closely related to attention (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) or perhaps requires more attentional support than verbal memory (Gmeindl, Walsh, & Courtney, 2011), or has access to fewer resources for rehearsal than verbal memory (Camos, Lagner, & Barrouillet, 2009). Though the possibility of incorporating these assumptions into

models of working memory has been acknowledged (Barrouillet & Camos, 2010), the implications of these assumptions have not been thoroughly explored.

Serial position information would yield useful information about potential sources of this asymmetry, but Depoorter and Vandierendonck (2009) required all-or-none recognition or rejection of test sequences, yielding no way to compare interference effects throughout the serial position curve. We therefore lack detailed information on what precisely is forgotten when two lists are concurrently maintained. This information could be essential for reconciling disparities presented by previous research. Across a serial list, early items must be maintained while subsequent items are encoded. We suppose that encoding verbal and spatial materials can be accomplished with minimal interference (Cowan & Morey, 2007), but that a common resource may be necessary for maintenance of both verbal and spatial serial order (Depoorter & Vandierendonck, 2009). This resource may also be supplemented by domain-specific storage buffers or sensory memory stores, which should not be sensitive to cross-domain interference (Baddeley, 2007). Assuming these stores temporarily maintain incoming information, we suppose that they should maintain the most recently presented stimuli. Is there any cross-domain cost for these items? If so, does it occur to both verbal and spatial representations?

We first aim to confirm that interference between two order memory tasks occurs, and then to examine whether this dual-maintenance cost occurs for early-list items, for late items, or both. We approached this problem by comparing single- and dual-task performance on serial reconstruction tasks (Guérard & Tremblay, 2008), which we chose in order to equate the demand of the two tasks as far as possible and because previous research on order memory suggested that two cross-domain order memory tasks would

interfere with each other (Depoorter & Vandierendonck, 2009). In this procedure, lists of

stimuli were presented and then at test, all items re-appeared onscreen. Participants' task

was to indicate the order in which the stimuli were presented. In our version of these

tasks, words were presented aurally and spatial locations (represented by squares) were

presented at unpredictable locations randomly selected from a large area on the screen in

order to reduce any strategic attempt to verbally label the spatial locations. We

constructed the tasks so as to make the to-be-remembered stimuli as similar as possible in

all respects except for their domain, as we wanted to measure interference between two

stimulus sets encoded by different perceptual systems.

       We compared reconstruction performance when only a single list was presented

with reconstruction performance when verbal and spatial lists were presented in an

interleaved fashion. Sometimes, participants were unaware of which of the two

interleaved lists would be tested; in these cases, they should have attempted to maintain

both lists simultaneously. In order to control for the processes involved in perceiving the

interleaved stimuli and to ensure that we could attribute any interference we observed in

the uncued dual-presentation condition to processes involved in maintenance, participants

were sometimes cued prior to stimulus presentation so that they knew which list would be

tested. In this design, observing no interference in the uncued, dual-maintenance

condition would be strong evidence for a model of working memory positing separate

resources for verbal and visual-spatial information, as suggested by Shah and Miyake

(1996). However, if interference in the dual-maintenance condition were found, its locus

in the serial position function will help us better understand the nature of the interference.

Cross-domain interference early in the list would be consistent with the proposal that

maintaining or consolidating incoming items from a list in serial order requires domain-general resources; a lack of interference for items from end of the list would be consistent with the proposal that incoming information is at least briefly segregated into domain-specific stores. Analysis of correlations between the verbal and spatial tasks will also be examined, providing additional information for theorizing about which mental resources are shared by these tasks, and which are separate.

Experiment 1

Method

   Participants. Sixty-four students from the University of Groningen (42 women, 22 men, age ranged 18-29 years, M=20.89 years, SD=1.67) participated as part of their course requirements. All participants in this and subsequent experiments were fluent English-speakers, following a university curriculum taught entirely in English.

   Apparatus, Stimuli, and Design. The stimuli were controlled using E-Prime 2.0 (Schneider, Eschmann, & Zuccolotto, 2002), with a screen resolution of 1024 x 768 pixels. All visually displayed objects were black on a white background. The verbal stimuli were 36 English one-syllable concrete nouns selected using the English Lexicon Project (Balota et al., 2007) for moderate frequency ranging from 8030 and 11722 per million (M=9662) according to the HAL study frequency norms frequency based on HAL corpus (Lund & Burgess, 1996). A native female English speaker recorded the words. The sound files were recorded at 16 bits per sample and 22050 Hz, and normalized. Articulation times ranged from 452 to 799 ms (M=610). Sounds were presented via stereo headphones in a single channel using the onboard sound card. Word sequences were randomly selected without replacement from the 36-word list at the

beginning of each trial. Words used in each of our experiments are given in the

Appendix.

The spatial stimuli were black squares of 75 x 75 pixels (1.98 cm), presented at

different locations in a 500 x 500 pixel (13.23 x 13.23 cm) window in the middle of a the

screen. Locations were determined randomly at the beginning of each trial with the

constraint that no two squares could be closer than 35 pixels (0.93 cm) to each other.

Our design included three repeated-measures factors: three different presentation

conditions (single, cued, and uncued), two task domains (verbal and spatial), and three

list lengths (3, 5, and 7). In the single presentation condition, either a verbal or a spatial

list was presented and tested, with inter-stimulus timings equal to those in the dual-

presentation conditions. In the cued and uncued presentation conditions, the verbal and

spatial lists were presented in an interleaved fashion, always with an equal number of

items in each list. In the cued presentation condition, participants saw a cue that read

either "word" or "location" prior to stimulus presentation, which always accurately

indicated which list would be tested. In the uncued condition, participants saw a "?"

instead of an informative cue, and therefore should have tried to maintain both lists until

the test screen appeared. The cued condition was included as a fairer control for dual-

maintenance comparison than the single presentation condition; stimulus presentation

was identical to that in the uncued condition, with the only difference being that

participants knew in advance which list would be tested in the cued condition. We

included short lists, for which serial position data could not be very informative, in order

to ascertain whether any dual-task costs we observed occur for sub-span as well as supra-

span lists. Stimulus presentation order (i.e., whether interleaved stimulus presentation

began with a word, then a square, then another word, etc., or began with a square, then a word, then another square, etc.), varied between participants with approximately equal numbers taking part in the word-square order (*N*=34) and the square-word order (*N*=30). The order of the within-participants conditions was randomized.

  Procedure. A depiction of a cued trial is given in Figure 1. All trials began with presentation of a fixation cross for a total of 2 seconds followed by the stimulus sequence. In both the cued and the uncued conditions, the first item (spoken word or square) was presented and the next item (square or spoken word) was presented 1 second after the onset of the first item. In both these conditions, the interleaving of an equal number of verbal and spatial items was repeated until the end of each list. For the single-presentation conditions, the stimulus timing was kept the same as for one of the interleaved lists in the dual-presentation conditions. Thus, in the single-presentation condition, the 1-second delay between offset of one item and the onset of the next item was unfilled, whereas in both dual-presentation conditions, presentation of the other stimulus occurred during this period. Cued and uncued dual-presentation conditions differed in what must be done with the intervening item; in the uncued condition, the intervening item should be encoded for possible later recall, whereas in the cued condition, the intervening item should be ignored.

  One second after the offset of the last item, the serial reconstruction test screen appeared showing either all words, printed in a randomly-ordered vertical list in the middle of the screen with 25 pixels (0.66 cm) in between each word, or all squares at their original locations. Using the mouse, participants clicked the items in order until all words or squares were chosen. Clicking on an item marked it in green, so that the

participant always knew which options had been selected. No omissions were allowed.

Each trial ended with instructions to press the space bar to continue to the next trial.

Participants completed 12 practice trials with feedback before the experiment began, to

ensure that they understood the instructions, and then 90 experimental trials (5 for each

combination of within-participant factors). The whole experimental session lasted

approximately 50 minutes.

Results

Our threshold for declaring statistical significance was always $p<.05$. In any case

in which the sphericity assumption of the analysis of variance (ANOVA) was violated,

the Greenhouse-Geisser correction was applied.

Whole List Accuracy. With mean number of correct responses per trial as the

dependent variable, we conducted separate ANOVAs for each task domain, each with

presentation condition (single, cued, uncued) and list length (3, 5, 7) as within-participant

factors and stimulus presentation order as a between-subjects factor. Descriptive statistics

for each of these combinations of variables are given in Table 1.

For the verbal task, we uncovered main effects of both presentation condition

($F(2,124)=42.50$, $MSE=.33$, $\eta^2_p=.41$, $p<.001$) and list length ($F(2,124)=162.16$,

$MSE=.85$, $\eta^2_p=.72$, $p<.001$), which must be considered in light of significant interactions

between presentation condition and order ($F(2,124)=3.42$, $MSE=.33$, $\eta^2_p=.05$, $p<.05$), and

all three factors ($F(4,248)=3.73$, $MSE=.47$, $\eta^2_p=.06$, $p<.02$).

To understand this higher order relationship, we carried out separate ANOVAs

with presentation condition and order as factors for each list length. For 7-item lists, a

significant main effect of presentation condition ($F(2,124)=26.88$, $MSE=.74$, $\eta^2_p=.30$,

p<.001) was qualified by an interaction between presentation condition and order

(F(2,124)=4.84, MSE=.74, η^2_p=.07, p<.02). Bonferroni-corrected post-hoc comparisons

indicate that for both orders, recall in the uncued condition (refer to means in Table 1)

was worse (ps<.02) than in single-task or cued conditions, which did not significantly

differ in either comparison (ps from .07-.87). The difference between the cued and

uncued conditions was larger in the word-square order (p<.05). For 5-item lists, there was

a main effect of presentation condition (F(2,124)=16.06, MSE=.23, η^2_p=.21, p<.001)

characterized by the same pattern as in 7-item lists, but no effect of order (p>.59) and no

presentation condition by order interaction (p>.67). For 3-item lists, no significant effects

or interactions were observed (ps from .52-.94). Thus, for the verbal reconstruction task,

we observed a dual-task cost in the uncued condition for 5- and 7-item lists, and in 7-item

lists, this cost increased for the participants who heard the word before seeing the

location during interleaved presentation. For the 3-item lists, verbal reconstruction

performance was always near ceiling, and no effects on it were observed.

For the same analysis in the spatial task, main effects of presentation condition

(F(2,124)=43.33, MSE=.48, η^2_p=.41, p<.001) and list length (F(2,124)=86.35,

MSE=1.22, η^2_p=.58, p<.001) were qualified by a significant interaction between these

factors. No other effects or interactions reached criteria for statistical significance (ps

from .06-.74). For the sake of comparison, we performed the same follow-up analyses on

spatial task data as we performed on the verbal task data. For 7-, 5-, and 3-item lists, the

effect of presentation condition was always statistically significant (η^2_p s from .06-.35,

ps<.03). For 5- and 7-item lists, reconstruction in the uncued condition was lower

(ps<.003) than in the cued or single-task conditions, which did not significantly differ

(*p*s>.83; see Table 1 for means). For 3-item lists, reconstruction in the uncued condition was lower than in the cued condition (*p*<.02), while the other comparisons were not statistically significant (*p*s>.19). Neither the effect of order nor its interaction with presentation condition ever reached the criterion for statistical significance (*p*s from .06-.81).

Comparing verbal with spatial reconstruction performance, the verbal task seems more sensitive to stimulus presentation order than the spatial task and the spatial task perhaps more sensitive to cross-domain interference than the verbal task, because uncued performance was significantly impaired even for the shortest lists. While we observed some differences between the effects of list length, presentation condition, and stimulus order on verbal and spatial reconstruction, generally the patterns we observed were quite similar. Importantly, for both tasks cross-domain interference was observed for the longest list lengths, enabling us to analyze interference patterns across the serial position function.

Accuracy by Serial Position. We analyzed serial position only in the 7-item lists, which afford richer data for this analysis than shorter lists because accuracy is sufficiently far from ceiling. We compared the proportion of correct responses for each serial position in the 7-item lists and analyzed the data using 3-way ANOVA with the factors task domain, presentation condition and serial position (1 to 7). These curves are depicted in Figure 2, with the verbal task data in the upper panel and the spatial task data in the lower panel. We found main effects of presentation condition ($F(2,126)=66.82$, $MSE=.10$, $\eta^2_p=.52$) and serial position ($F(2,756)=152.88$, $MSE=.06$, $\eta^2_p=.71$). Two significant 2-way interactions, between presentation condition and serial position

$(F(12,756)=3.36, MSE=.03, \eta^2_p=.05)$ and domain and serial position $(F(12,756)=26.02,$

$MSE=.04, \eta^2_p=.29)$ were qualified by a significant 3-way interaction $(F(12,756)=2.70,$

$MSE=.03, \eta^2_p=.04)$. The interaction between presentation condition and task domain was

nonsignificant $(F(2,124)=0.92, p>.39)$, as was the main effect of domain $(F(1,62)=.76,$

$p>.38)$.

To understand the 3-way relationship, we carried out separate 2-way ANOVAs

for the spatial and verbal tasks. Examining Figure 2 suggests that the 3-way interaction

could be due to differences between the effects of presentation condition on memory for

the final item's position. In the both tasks, performance seemed lower in the dual-

maintenance condition than in the other conditions for the first 6 items, but for the verbal

task, performance in the uncued condition did not seem to be impaired for the final item[1].

To simplify our hypothesis testing, we included presentation condition and 2 levels of

serial position, the average of the first 6 positions versus the 7th position, as factors in

each ANOVA. We observed a significant interaction between presentation condition and

serial position for the verbal task $(F(2,126)=17.81, MSE=.02, \eta^2_p=.22, p<.001)$, which

must be due to the equivalent performance on the final item regardless of presentation

condition, but no interaction for the spatial task $(F(2,126)=1.61, p>.20)$. We observed the

same pattern even when single-item lists were excluded (verbal reconstruction: $\eta^2_p=.29,$

$p<.001$; spatial reconstruction: $\eta^2_p=.02, p>.26)$.

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[1] Alternatively, this interaction could be due to the somewhat blunted serial position
curves for some of the spatial task conditions. However, when we analyzed serial
position separately for each domain and presentation condition combination, it was
always statistically significant, with bowing reflecting significantly higher accuracy for
the early and late items compared to the middle items.

Discussion

Reflecting the state of the published literature on this topic, we observed mixed evidence regarding the modularity of working memory resources. First, we observed clear dual-task costs for simultaneously maintaining verbal and spatial sequences. Simultaneously maintaining a verbal and a spatial sequence resulted in significantly worse memory performance than maintaining either sequence alone or maintaining either sequence while ignoring an interleaved sequence. This was true for spatial order reconstruction at each list length we measured, and for verbal order reconstruction at all but the 3-item lists. Examining serial position data in our longest lists, we found that the dual-task cost was present throughout the list in the spatial task but for the early and middle-list items only in the verbal task. The final verbal item was maintained without dual-task cost, but the final spatial item was not privileged in this manner. This suggests some difference in the resources available to maintain verbal and spatial information.

Identifying the source of the cost-free maintenance of the final verbal items is the key to theorizing about the asymmetric pattern we reported, and possibly to accurately characterizing modular resources in working memory. In two follow-up experiments, we consider two possible sources for this differential advantage. One possibility we considered was that the concrete nouns we used in the verbal lists activated long-term memory representations, while the spatial locations we used did not. Possibly, verbal information in our paradigms could be represented in at least two different manners, which helped to alleviate effects of dual-task interference. At least two popular conceptions of working memory include interfaces with long-term memory; in Baddeley's (2007) conception, activated long-term memory representations might be held

in the episodic buffer, and in Cowan's (1995; 2005) framework, working memory is embedded in activated long-term memory. Items encountered more recently might be more strongly activated in long-term memory or more likely to be represented in the episodic buffer at the time of recall, which would improve performance for them. If verbal information generally is more likely to activate long-term memory representations than spatial information, then this might give them additional protection from interference and explain some of the asymmetries previously observed. To test this possibility, we conducted Experiment 2, in which we repeated Experiment 1 but also measured serial reconstruction for lists of pronounceable non-words. Although non-words might still be more salient than spatially located squares, they should be less likely to activate long-term memory representations than highly imaginable concrete nouns (Ward, Avons, & Melling, 2005).

We also considered the possibility that verbal and spatial representations differ in their access to a short-term store or rehearsal mechanisms, or possibly in the perseverance of information maintained in a short-term store. Evidence suggests that two separate processes, articulatory rehearsal and attentional refreshing, may support the maintenance of verbal information (Camos, Lagner, and Barrouillet, 2009), but the asymmetric pattern that we have found suggests that possibilities for temporarily representing spatial order information may be more restricted. We investigated this possibility in Experiment 3.

Experiment 2

Method

Participants. Thirty-six new participants recruited from the student population of the University of Groningen chose to take part in partial fulfillment of a course requirement. Two participants did not complete all experimental conditions due to equipment malfunctions leaving a final sample of 34 (28 women, 6 men, ages ranged 18-25 years, M=20.82 years, SD=1.89).

Apparatus, Stimuli, Design, and Procedure. The stimulus materials were the same as those in Experiment 1, except that new verbal stimuli, lists of comparable words and non-words, were introduced and only lists of four and seven items were included.

We selected 41 English two-syllable, six-letter nouns using Equiword (Lahl & Pietrowsky, 2006). We chose words that would contrast in strength of semantic content as much as possible with non-words: words with average frequency (London-Lund M=7, SD=11.2; Brown, 1984), high concreteness (M=580, SD=32; Paivio, Yuille, & Madigan, 1968) and high imaginability (e.g. window, palace; M=587, SD=31; Toglia & Battig, 1978). Our non-word list also included 41 two-syllable, six-letter pronounceable items (e.g. dublip, catter), selected using the English Lexicon Project (Balota et al., 2007). The recorded pronunciations for the words ranged from 239 to 962 ms (M=629 SD=123) and for the non-words from 480 to 935ms (M=684, SD=127).

Besides serial position, four factors were manipulated within-subjects: Presentation condition (single-presentation, cued, and uncued), task domain (verbal and spatial), word type (words and nonwords), and list-length (four and seven). However, the list length factor was unbalanced. We only included 4-item trials in the cued and uncued

conditions, and we included four times as many 7-item trials as 4-item trials. We did not

analyze the 4-item trials. Our main reason for including 4-item trials at all was to prevent

participants from finding an experimental session filled with difficult 7-item lists too

discouraging (Pratte & Rouder, 2009). Each participant completed 96 7-item trials, with

stimulus presentation order randomized within-participants.

Results

Our goal with Experiment 2 was to test whether the interaction between task

domain, presentation condition and serial position would remain with non-words rather

than words as the verbal stimuli. As in Experiment 1, we begin with an analysis of the

effect of presentation condition on overall serial reconstruction performance. We

manipulated 4 factors, but will not dwell on a full 4-way ANOVA; instead, we restrict

our analysis to 7-item lists and consider only nonword trials. We included word type in a

preliminary analysis and found a significant interaction between domain and word type

($F(1,43)$=11.46, *MSE*=0.61, η^2_p=.26, p<.05), caused by lower performance on verbal lists

of nonwords (*M*=3.16 items correct per list, *SEM*=.10) than words (*M*=3.59, *SEM*=.10),

but no difference in spatial reconstruction performance between the word and nonword

conditions (*p*=.13). Because there appeared to be no effect of the type of phonological

material maintained on spatial memory, the word trials only served to replicate

Experiment 1's findings with two-syllable words. We therefore restricted the rest of our

analysis to the trials with nonwords as memoranda.

Whole List Accuracy. We carried out a 2-way ANOVA with presentation

condition and task domain on average number of correct responses in a trial for 7-item

lists in the non-word condition. Means and standard deviations corresponding to this

analysis can be found in Table 2. This analysis revealed main effects of presentation

condition ($F(2,66)=45.85$, $MSE=0.36$, $\eta^2_p=.58$, $p<.001$) and task domain ($F(1,33)=10.90$,

$MSE=1.21$, $\eta^2_p=.25$, $p<.003$). Their interaction was nonsignificant ($p=.52$). Performance

was better overall on the spatial task ($M=3.57$, $SEM=.16$) than the verbal task ($M=3.06$,

$SEM=.13$). This differs from Experiment 1, but it appears to be only due to measuring

nonword memory performance instead of word memory performance; if word and

nonword lists are both included in a similar analysis, the effect of task domain is not

statistically significant ($p=.55$). Performance in the uncued trials, for which both stimulus

sets must be encoded and briefly retained ($M=2.74$, $SEM=.15$), was worse than

performance in the single-presentation ($M=3.64$, $SEM=.14$) or cued conditions ($M=3.56$,

$SEM=.13$), which did not significantly differ from each other ($p=.42$). This result is

broadly consistent with what we observed for 7-item word lists in Experiment 1.

Serial Position Accuracy. We proceeded to carry out an analysis of presentation

condition as a function of serial position, running a 3-way ANOVA on mean proportions

correct with domain, presentation condition, and serial position as factors. We included

only nonword list trials in this analysis. Our primary interest was to attempt to replicate

the interaction between domain, presentation condition, and serial position we observed

in Experiment 1, which we attributed to preserved memory for the final item in verbal

lists only. We reasoned that one explanation for this advantage could have been stronger

semantic activation of verbal concepts than spatial locations, and if so, then the

interaction may be weaker with nonword stimuli.

We observed significant main effects of each factor ($\eta^2_p=.25$ for task, .58 for

presentation condition, and .69 for serial position), but these were qualified by a

significant 3-way interaction between task, presentation condition, and serial position ($F(12,396)=1.97$, $MSE=.02$, $\eta^2_p=.06$, $p<.05$). This relationship is depicted in Figure 3, which is strikingly similar to the pattern uncovered in Experiment 1. For spatial order reconstruction, the detrimental effect of encoding and maintaining a verbal list is present throughout the lists. However for verbal order reconstruction, the memory for the final items in the list is not significantly impaired by simultaneously maintaining a spatial list. To understand this interaction, we carried out separate ANOVAs for each task with presentation condition and serial position as factors, simplified by collapsing over the first 6 serial positions as in Experiment 1. Again, we observed a significant presentation condition by serial position interaction for verbal reconstruction ($F(2,66)=9.11$, $MSE=.01$, $\eta^2_p=.22$, $p<.001$), but no such interaction for spatial reconstruction ($F(2,66)=2.82$, $\eta^2_p=.08$, $p>.06$). The same pattern of inference appears even if only the cued and uncued presentations conditions are considered (verbal reconstruction, presentation by serial position interaction $\eta^2_p=.36$, $p<.001$; for spatial reconstruction $\eta^2_p=.08$, $p>.09$). Thus as in Experiment 1, it appears that the final verbal item is preserved from cross-domain interference, whereas there is no evidence that the final spatial item is preserved.

Discussion

Despite measuring memory for nonwords instead of nouns, Experiment 2 closely replicated the results of Experiment 1. As in Experiment 1, we consistently observed a cross-domain dual-task cost to both verbal and spatial serial reconstruction performance. We also replicated our finding from Experiment 1 of differing effects of concurrent maintenance on end-of-list items for verbal versus spatial stimuli. For spatial stimuli,

concurrently maintaining verbal stimuli is detrimental throughout the list but for verbal stimuli, final items may be concurrently encoded and maintained while presumably also maintaining a spatial sequence, or at least shifting attention toward another stimulus. We therefore cannot strongly support the notion that the asymmetric preservation from cross-domain interference observed in Experiment 1 is attributable to superior support for verbal information from long-term memory.

With Experiment 3, we test another hypothesis to explain why verbal but not spatial lists exhibited this preservation from interference for the final item. Possibly, verbal information has access to a specialized store or rehearsal mechanism, and perhaps there is no equivalent structure for nonverbal information. This hypothesis is consistent with the reasoning of Camos et al. (2009; see also Barrouillet & Camos, 2010). Using a similar design and procedure as in Experiments 1 and 2, we added sensory suffixes after the presentation of the final memoranda. Even though our task called for serial reconstruction beginning with the first item remembered, we consistently observed recency effects in both tasks, and in the verbal task, no dual-task cost for the last item. If the mental representation of the last verbal item is maintained in a domain-specific sensory store, then the imposition of a sensory mask should induce a dual-task cost for the final item in the verbal list, making the effect of a concurrent task on verbal memory the same as it is to spatial memory. Such a pattern would suggest that the differences observed between interference with verbal and spatial serial reconstruction are attributable to differences in the availability or robustness of domain-specific short-term storage resources.

Experiment 3

Method

Participants. Thirty-seven students from the University of Groningen participated as part of their course requirements. One participant's data were removed due to near chance performance in the 4-item single-task conditions, leaving a final sample of 36 (27 women, 9 men, age ranged 19-31 years, *M*=21.22 years, *SD*=2.50). None of these participants took part in Experiments 1 or 2.

Apparatus, Stimuli, Design, and Procedure. The spatial memoranda were created and selected in the same manner as in Experiments 1 and 2. We selected verbal memoranda from the nonword list used in Experiment 2, because the proportions correct for nonwords were most similar to the proportions correct for spatial locations at the beginning and end of the 7-item lists in Experiment 2. We added auditory and visual suffixes after presentation of the to-be-remembered lists. The visual suffix was designed to occupy the entire area of the screen where spatial memoranda could have appeared, and consisted of a 675 x 525 pixel checkerboard-like image of black and white squares (75 x 75 pixels). The auditory suffix included all non-words presented during the current trial played back at the same time. In the cued and uncued conditions, both suffixes were presented simultaneously 500 ms after the offset of the last item. During single-task conditions, only the domain-specific suffix was presented, also 500 ms after the offset of the final list item. In all cases, presentation of the suffix lasted 1000 ms.

The experimental design was similar to that in Experiment 2. Four factors were manipulated within-subjects: task domain (verbal or spatial), presentation condition (single-presentation, cued, uncued), presentation order (square then nonword, or nonword

then square), and list length (4 or 7). Combinations of these factors were presented randomly, for a total of 96 trials. Unlike in Experiment 2, in which we needed more 7-item trials to make up for the inclusion of an extra factor (i.e., words versus non-words), we were able to run an equivalent number of 4- and 7-item list trials, and included this factor in our analysis of overall number of correct responses per trial, in order to have an additional way to assess whether cross-domain costs were similar across presentation conditions and task domains.

Results

Whole list Accuracy. We carried out a 3-way ANOVA with task domain, presentation condition, and list length as factors. Descriptive statistics can be found in Table 3. We uncovered a main effect of task domain ($F(1,35)=28.38$, $MSE=1.84$, $\eta^2_p=.45$, $p<.001$), showing that more correct responses were given for spatial ($M=3.48$, $SEM=.12$) than verbal ($M=2.79$, $SEM=.10$) serial reconstruction. Presentation condition also produced a significant main effect ($F(2,70)=89.41$, $MSE=.32$, $\eta^2_p=.72$, $p<.001$), with the uncued condition ($M=2.62$, $SEM=.10$) resulting in fewer correct responses per trial than the cued ($M=3.35$, $SEM=.09$) and single-presentation conditions ($M=3.43$, $SEM=.10$), which did not significantly differ ($p>.20$). The effect of list length was nonsignificant ($p=.09$).

Each interaction, including the 3-way interaction between task domain, presentation condition, and list length was statistically significant (3-way: $F(2,70)=4.20$, $MSE=.26$, $\eta^2_p=.11$, $p<.02$; 2-way η^2_ps from .09-.31, ps$<.05$). This 3-way interaction was driven by differences in sizes of the effects of presentation condition on short and long verbal and spatial lists, not changes in directions of effects. We carried out separate

ANOVAs for the verbal and spatial data, to better explain the significant 3-way

interaction. For spatial lists, the cost of simultaneously maintaining a verbal list increased

with list length, as evidenced by a significant 2-way interaction between list length and

presentation condition for the separate ANOVA on spatial reconstruction performance

($F(2,70)=7.06$, $MSE=.32$, $\eta^2_p=.17$, $p<.003$). For verbal lists, there was no interaction

between list length and presentation condition ($p=.89$), and thus no evidence of an

additional increase in cost as list length increased. These interactions show that both

adding a concurrent task and increasing the number of to-be-remembered items impacts

spatial memory more than verbal memory.

Serial Position Accuracy. As in Experiments 1 and 2, with auditory and visual

suffixes a consistent effect of presentation condition was apparent, such that maintaining

two lists simultaneously reduced performance compared to maintaining only one list. In

Experiments 1 and 2, the final verbal items in each list, unlike the final spatial items,

were preserved from interference. We considered whether an auditory suffix was

sufficient to reveal a dual-task cost for verbal items at the end of lists.

We ran a 3-way ANOVA on mean proportions correct with presentation

condition, task domain, and serial position as factors. In order to best isolate changes in

our results due to the addition of sensory masks, we included 7-item lists from the

stimulus presentation order in which the mask occurred directly after the final to-be-

recalled stimulus; for the spatial reconstruction task, these were the lists in which a

location was the final item prior to the mask and for the verbal task, these were the lists in

which a nonword occurred just before the mask. This analysis is depicted in Figure 4.

The critical 3-way interaction from our previous experiments was nonsignificant

($F(12,420)=1.13$, $\eta^2_p=.03$, $p>.33$). The 2-way interaction between presentation condition and serial position was also nonsignificant ($F(12,420)=.70$, $\eta^2_p=.02$, $p>.75$), providing no support for the hypothesis that end-of-list items differed from early-list items in the impact of cross-domain interference. We also observed main effects of presentation condition ($F(2,70)=33.21$, $MSE=.14$, $\eta^2_p=.49$, $p<.001$), task domain ($F(1,35)=23.97$, $MSE=.32$, $\eta^2_p=.41$, $p<.001$), and serial position ($F(6,210)=37.33$, $MSE=.07$, $\eta^2_p=.52$, $p<.001$), and an interaction between task domain and serial position ($F(6,210)=3.34$, $MSE=.03$, $\eta^2_p=.09$, $p<.02$). Other interactions were nonsignificant (ps>.09). Follow-up Bonferroni-correct comparisons confirmed that for both verbal and spatial serial reconstruction, performance in the uncued condition was significantly worse than performance in the cued or single-task conditions (ps<.03), which did not significantly differ (ps>.64)

Inter-task Correlations, Experiments 2 and 3. The consistent decrease in performance in the uncued conditions suggests that verbal and spatial serial memory share some resource. Another way we might examine this is by comparing patterns of correlations between verbal and spatial single-task performance and performance in the dual-presentation conditions. To do this, we calculated the average number of correct responses within 7-item lists for each participant in each presentation condition for the nonword and spatial location lists of Experiments 2 and 3. In the single-task conditions, these values may be considered estimates of verbal and spatial memory span, and we correlated these estimates with estimates from each of the dual-presentation conditions. Correlations are given in Table 4, where values below the diagonal are raw correlations, and those above the diagonal are partial correlations controlling for variance from the

verbal or spatial single task conditions respectively. Consistent with the suggestion that some resources are shared between these tasks, verbal and spatial single-task performance correlated significantly. Though this relationship was statistically significant, the magnitude of the correlation (r=.32) does not suggest that these two tasks measure a single unique construct, so we calculated partial correlations between dual-presentation and single-presentation conditions, controlling for unique variance in verbal and spatial single-presentation performance. When variance with verbal serial memory was partialled out, spatial single-presentation performance still correlated significantly with verbal performance in the uncued dual-task condition. However, verbal single-presentation performance only correlated significantly with verbal dual-task performance after variations in spatial memory were controlled for.

Discussion

In light of the results of Experiments 1 and 2, the results of Experiment 3 suggest that verbal and spatial short-term memory differ in the availability of short-term storage resources. In each experiment we carried out, concurrently maintaining a verbal sequence interfered with memory for a spatial sequence and vice versa. At both list lengths we chose, we observed dual-task costs. Thus, throughout this project we have observed statistically significant dual-task costs for all but 3-item verbal lists.

This dual-task cost was present throughout the serial positions in the spatial reconstruction task. In an auditory-verbal version of the same serial reconstruction task, although memory was in general reduced by concurrent maintenance of a spatial list, the final item in the verbal list seemed to be unaffected by a concurrent spatial memory task in Experiments 1 and 2. Imposing an auditory suffix after the presentation of the final

item ruined this preservation. We interpret this finding to indicate that recently presented

verbal information is preserved in a short-term store in addition to the domain-general

resource believed to underlie serial order memory, while visual-spatial information is not

preserved in a comparable domain-specific store, or at least not for as long.

General Discussion

Although much research on immediate memory considers whether auditory-

verbal and visual-spatial representations interfere with each other, this literature is full of

conflicting evidence, varying from impressive examples of cross-domain multi-tasking

(e.g., Cocchini, Logie, della Sala, MacPherson, & Baddeley, 2002; Logie et al., 1990) to

evidence of strong cross-domain competition for storage resources (Depoorter &

Vandierendonck, 2009; Saults & Cowan, 2007; Vergauwe, Barrouillet, & Camos, 2010)

or equivalent interference from rehearsal suppression tasks designed to selectively engage

domain-specific processes (Jones, et al., 1995). We chose to address this question by

comparing performance on verbal and spatial serial order reconstruction tasks under

single-task and cross-domain dual-task conditions.

Across three experiments, we consistently observed cross-domain interference

between verbal and spatial serial reconstruction tasks when circumstances called for

simultaneous maintenance of the two stimulus sets. We always observed dual-task costs

for both verbal and spatial serial memory, except for in the shortest verbal lists. This

confirms that verbal and spatial serial order memory tasks conflict substantially with each

other, as previously observed (Depoorter & Vandierendonck, 2009). We add to previous

findings by confirming that two cross-domain order tasks provoke an asymmetric pattern

of interference, and testing the source of this asymmetry. Despite similar task demands,

verbal order memory is less affected by concurrent memory of a spatial list than spatial memory is by a concurrently maintained verbal list. We learned that this asymmetry appears only for the final verbal list items, suggesting that verbal memory might be supported by a separate, domain-specific resource. Consistently with this idea, verbal list memory shows the same pattern of cross-domain interference from a concurrently held spatial list when an auditory suffix, which presumably disrupts the contents of an auditory sensory memory store, is imposed. This pattern of results is consistent with the possibility of a domain-specific verbal memory store but offers no support for a comparable domain-specific spatial memory store.

Our work is consistent with key elements of previous research supporting cross-domain sharing between verbal and spatial serial memory (Depoorter & Vandierendonck, 2009; Guérard & Tremblay, 2008; Jones et al., 1995) and helps to clarify discrepancies between these studies and others showing little or no cross-domain interference (e.g., Meiser & Klauer, 1999). Like Jones et al., we found evidence for shared resources between verbal and spatial short-term memory, but our evidence comes from concurrent verbal and spatial memory tasks rather than concurrent rehearsal suppression and memory tasks. Their clear effects of both verbal and motor suppression on verbal and spatial serial memory tasks have not clearly replicated (see Guérard & Tremblay, 2008), but if there were actually separate stores for verbal and spatial serial memory (separate even for maintaining order information, as Smyth and Scholey (1996) argued) one would not expect to observe substantial dual-task costs for concurrent maintenance of verbal and spatial lists, as we and others (Depoorter & Vandierendonck, 2009) have observed. Our data produced typical bowed serial position curves for verbal and spatial order

reconstruction, as Guérard and Tremblay observed using similar tasks (see also Smyth, Hay, Hitch, & Hornton, 2005, who found typical serial position functions for faces), also consistent with the assumption of commonality across stimulus domains.

Although we have confirmed that interference occurs during simultaneous maintenance of verbal and spatial sequences, we cannot declare with certainty that simultaneous maintenance itself was the reason for dual-task impairment. Maintenance requires not only consolidation of the incoming memory items, but attending to them and encoding them, and in our design, switching attention quickly from encoding stimuli encountered aurally to stimuli encountered visually. We did not observe consistent dual-task costs in conditions in which verbal and spatial lists were both presented, but one dimension was cued prior to presentation. This makes it difficult to argue that processes involved in selective attending contribute much to the dual-task costs we observed. However, we cannot yet be sure whether encoding or consolidating the incoming stimuli is more responsible for the dual-task costs we observed. Prior research suggests that processes involved in simultaneously maintaining cross-domain stimuli, not simultaneously encoding stimuli provoke dual-task costs (Cowan & Morey, 2007), but judgments which do not require maintenance, such as those typically required by the processing task components of complex span tasks (e.g., Vergauwe et al., 2010), also seem to interfere with memory storage. Research from many cognitive paradigms suggests that interference from multiple sources can occur during the retention period in which a memory is consolidated or refreshed (e.g., Dewar, della Sala, Beschin, & Cowan, 2010; Morey & Cowan, 2005; Stevanovski & Jolicoeur, 2007).

We thus confirm several previous findings and observe a predicted asymmetrical pattern of interference, which could help to reconcile conflicting claims regarding resource sharing in working memory. Although we observed cross-domain interference, there are aspects of our data that cannot be elegantly explained by simply supposing that verbal and spatial materials strictly compete for a common storage resource. The asymmetries we observed prevent such a clear decision. Moreover, no model of working memory satisfactorily predicts and explains these asymmetries. Below, we describe how several prominent working models may accommodate this pattern.

Implications for models of working memory

The multi-component model of Baddeley (2007) proposes independent stores for auditory-verbal and visual-spatial information along with domain-general resources. Both of these stores are believed to benefit from the deployment of the domain-general episodic buffer and central executive, the latter of which is specifically presumed to support activities of the buffers during demanding tasks (Logie, 2011). Assuming that cross-domain interference occurs in this system because of competition for the domain-general components only, there is currently no reason to expect asymmetric patterns of cross-domain interference, as both verbal and visual-spatial representations are believed to benefit from the domain-general components. The multi-component model might account for the asymmetric patterns we observed by supposing that relationships between general attention resources and the domain-specific stores are not equivalent, perhaps explicitly hypothesizing that visual memory is more dependent on these general resources than verbal memory is. For example, one might suppose that rehearsal or refreshing of the contents of a visual-spatial buffer must take place more frequently than rehearsal or

refreshing of the contents of a comparable domain-specific verbal store, thus frequently hogging the central executive's limited resources. More drastically, one might suppose a model with multiple components, but no specific visual-spatial store, as Phillips and Christie (1977) proposed. In our studies, the time between presentation and recall of any particular item would have been many seconds; it is thus perhaps most cautious to suppose that any domain-specific spatial representations could not be maintained without sustained attention during so long a period. However, in support of the Phillips and Christie hypothesis, we observed cross-domain interference at all list lengths in the spatial serial reconstruction task, not only the demanding levels for which the central executive would presumably be recruited.

Alternatively, one might also suppose a preference for attending to verbal stimuli, honed by life-long practice (Logie, Cocchini, della Sala, & Baddeley, 2004), but this assumption can be adopted much more parsimoniously within a perceptual-gestural account of memory (e.g., Hughes, Marsh, & Jones, 2009), which might explain greater verbal-list independence from cross-domain interference on account of the availability of speech-based motor processes. Speech-based motor processes may be arguably more practiced and distinct than the motor movements that distinguish several spatial locations all situated within a limited visual field, which might require a greater share of attention to initiate. However, one weakness of these possibilities is that they would suppose that cross-domain dual-task costs should be smaller for verbal serial memory than for spatial serial memory throughout a list, whereas we find clear differences in the size of cross-domain costs only for the final items in a list.

Embedded models of working memory and attention (e.g., Cowan, 1995; 2005; Oberauer, 2002; Oberauer & Kliegl, 2006) posit that working memory is a subset of long-term memory, characterized by unusually strong activation. The most strongly activated objects occupy the focus of attention, whose capacity is constant regardless of the stimulus modality of its contents. Other, less highly activated information might be retrieved into the focus of attention over the course of some cognitive activity. Emphasizing common structures for memory representation across domains, these models are more parsimonious than Baddeley's (2007) multi-component model, but do not clearly explain why dual-task performance is sometimes so resistant to interference. Embedded models do not necessarily predict the asymmetric pattern we observed, but could explain it by supposing that auditory-verbal information remains activated longer than visual-spatial information, and is therefore more likely to be accessible by the focus of attention even after a delay.

Like the embedded models, the Time-Based Resource Sharing (TBRS) model of Barrouillet, Bernardin, and Camos (2004) posits a single attentional resource that must be shared between multiple mental operations. The TBRS model posits that the focus of attention might be briefly deployed to refresh activated representations in between operations of a task. Interference is then determined by the cognitive demand of a concurrent task: if a task requires the constant application of the focus of attention, then previously activated information will become weakened and less likely to be retrieved. Similarly to the embedded models, TBRS could explain our asymmetric interference by supposing that visual-spatial representations are more susceptible to time-based decay than auditory-verbal ones, and thus require more frequent application of attentional

resources to maintain activation. Recent proposals also suggest that a resource capable of verbal rehearsal could be supposed in addition to the standard TBRS account (Barrouillet & Camos, 2010; Camos, et al., 2009), which would be consistent with our results. However, an account of how these two resources might interact is not yet thoroughly described.

We believe that the assumptions of the extended TBRS account merit further theorizing and testing; particularly, further study is needed to better specify this hypothesis. Currently, it is difficult to determine whether the extended TBRS account and a truncated version of Baddeley's (2007) multi-component model would make unique predictions. One prediction upon which they may differ is in the total amount of information that can be concurrently maintained. The extended TBRS account, as delineated by Camos et al. (2009), conceives of the extra verbal resource as a rehearsal mechanism that acts upon stored information, not a separate store, whereas in Baddeley's (2007) account, domain-specific and domain-general stores are both proposed, and perhaps may be simultaneously used. These two conceptions could lead to differing predictions about the total amount of information stored at any one time. Ultimately, a system with fewer modules than the multi-component model but incorporating embedded attention and storage components may explain divergent dual-task data better than the currently proposed frameworks, but more hypothesis testing is necessary before we can declare precisely how such a framework ought to be specified.

Conclusions

These studies help to clarify previous research about interference between verbal and spatial serial memory, which has varied so much that some researchers endorse

complete sharing between verbal and spatial memory while others insist on nearly independent verbal and spatial systems. Although clear effects of interference were observed between verbal and spatial serial memory tasks, our results also indicate that verbal and spatial storage differ in their reliance on domain-general resources. These findings endorse emerging assumptions for models of working memory that may ultimately produce a compromise between models that focus on domain-specificity and models that stress domain-general resources.

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Appendix

Experiment 1 Words	Experiment 2 Words	Experiment 2 & 3 Nonwords
belt	anchor	bagans
cage	basket	catter
chess	battle	covart
clay	butter	dachel
cream	button	dector
drum	carpet	dublip
egg	cellar	erdest
farm	cherry	flogan
fork	circle	fluing
fruit	closet	germed
gate	coffee	gidled
ghost	corner	grager
gift	dancer	griple
golf	dinner	herped
hill	doctor	hilder
map	dollar	lacket
myth	engine	latten
road	figure	lerman
room	forest	mecamp
sand	garden	menant
seat	hammer	migwig
shirt	kettle	minger
shoe	lawyer	mising
snail	letter	mogleg
soap	locker	ounwit
stone	nickel	outrin
tea	office	partar
tire	orange	pliver
trash	palace	prewap
trend	pencil	rapimt
wave	pillow	rostal
wing	pocket	seword
wood	powder	slared
year	shower	slosed
	sister	soners
	supper	spavel
	tennis	stimed
	ticket	talmid
	valley	tartle
	window	toplin
	yellow	unhort

Table 1: Experiment 1 accuracy, by task domain, presentation condition, and list length

	Spatial Task			Verbal Task		
	3	5	7	3	5	7
Word-Square Order (*N*=34)						
Single	2.92(.26)	4.31(.70)	4.82(1.15)	2.97(.12)	4.39(.54)	4.54(.94)
Cued	2.94(.21)	4.29(.78)	4.42(1.44)	2.97(.15)	4.32(.48)	4.36(.96)
Uncued	2.76(.35)	3.94(.90)	3.51(1.09)	2.94(.17)	3.97(.65)	3.19(1.13)
Square-Word Order (*N*=30)						
Single	2.87(.36)	4.11(.84)	4.11(1.48)	2.95(.17)	4.40(.58)	4.57(1.08)
Cued	2.90(.22)	3.95(.97)	4.15(1.31)	2.93(.18)	4.46(.50)	4.16(1.12)
Uncued	2.82(.30)	3.45(1.10)	2.99(1.26)	2.97(.13)	3.99(.70)	3.86(.87)

Note. Mean number correct per list (with standard deviations).

Table 2: Experiment 2, effects of cueing on word and nonword list memory

	Spatial Task		Verbal Task	
	Words	Nonwords	Words	Nonwords
Single	3.94 (1.03)		4.37 (1.32)	3.33 (0.92)
Cued	3.83 (1.12)	3.82 (1.10)	4.05 (1.09)	3.29 (0.89)
Uncued	2.83 (1.07)	2.93 (1.09)	3.23 (0.89)	2.55 (0.91)

Note. Mean number correct per 7-item lists (with standard deviations). *N*=34.

Table 3: Experiment 3 accuracy, by task domain, presentation condition, and list length

	Spatial Task		Verbal Task	
	4	7	4	7
Single	3.64(.46)	4.06(1.30)	3.20(.61)	2.84(.95)
Cued	3.60(.50)	3.87(1.09)	3.19(.56)	2.74(1.03)
Uncued	2.99(.82)	2.74(1.05)	2.59(.70)	2.17(.84)

Note. Mean number correct per list (with standard deviations). *N*=36.

Table 4: Correlations between tasks and presentation conditions, Experiments 2 and 3

Measure	1	2	3	4	5	6
Single-presentation conditions						
1. Spatial			.68*	.10	.63*	.24*
2. Verbal	.32*		-.16	.74*	.16	.53*
Dual-presentation conditions:						
3. Cued Spatial	.68*	.10				
4. Cued Verbal	.31*	.77*	.18			
5. Uncued Spatial	.67*	.32*	.59*	.25*		
6. Uncued Verbal	.37*	.58*	.20	.46*	.35*	

Note. Below the diagonal, raw Pearson 2-tailed correlations. Above the diagonal, partial correlations controlling for verbal (first row) and spatial (second row) performance in the single-list presentation conditions. * indicates $p<.05$. $N=70$.
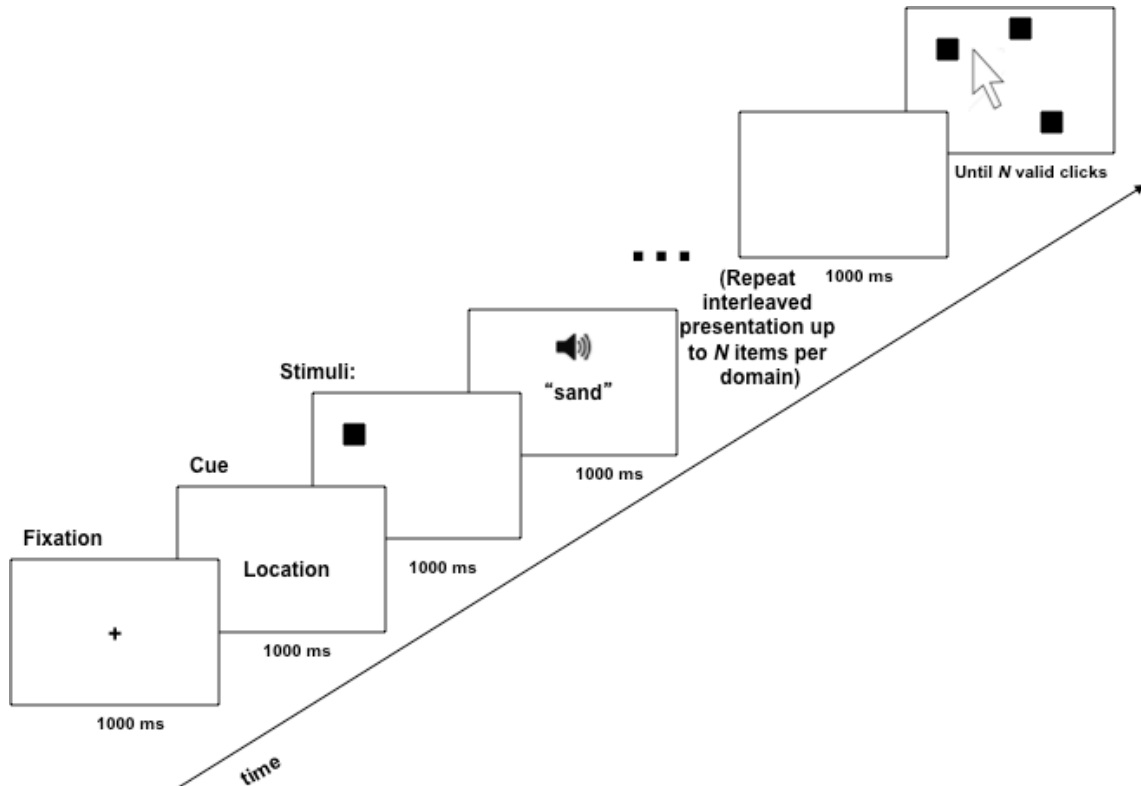
Figure 1

Figure 1. Depiction of trial events, Experiment 1. In this example, a cued 3-item location

trial is shown. Locations or words could be cued for recall with equal probability. In the

uncued presentation condition, a question mark appeared in place of a cue word. Stimulus

presentation could begin with presentation of a word or presentation of a square, and

alternated thereafter. *N* equals the number of items per list, and was always equal for each

stimulus domain. In single-presentation trials, the periods occupied by the other stimulus

presentation in dual-presentation trials were unfilled pauses. Depiction is not to scale.
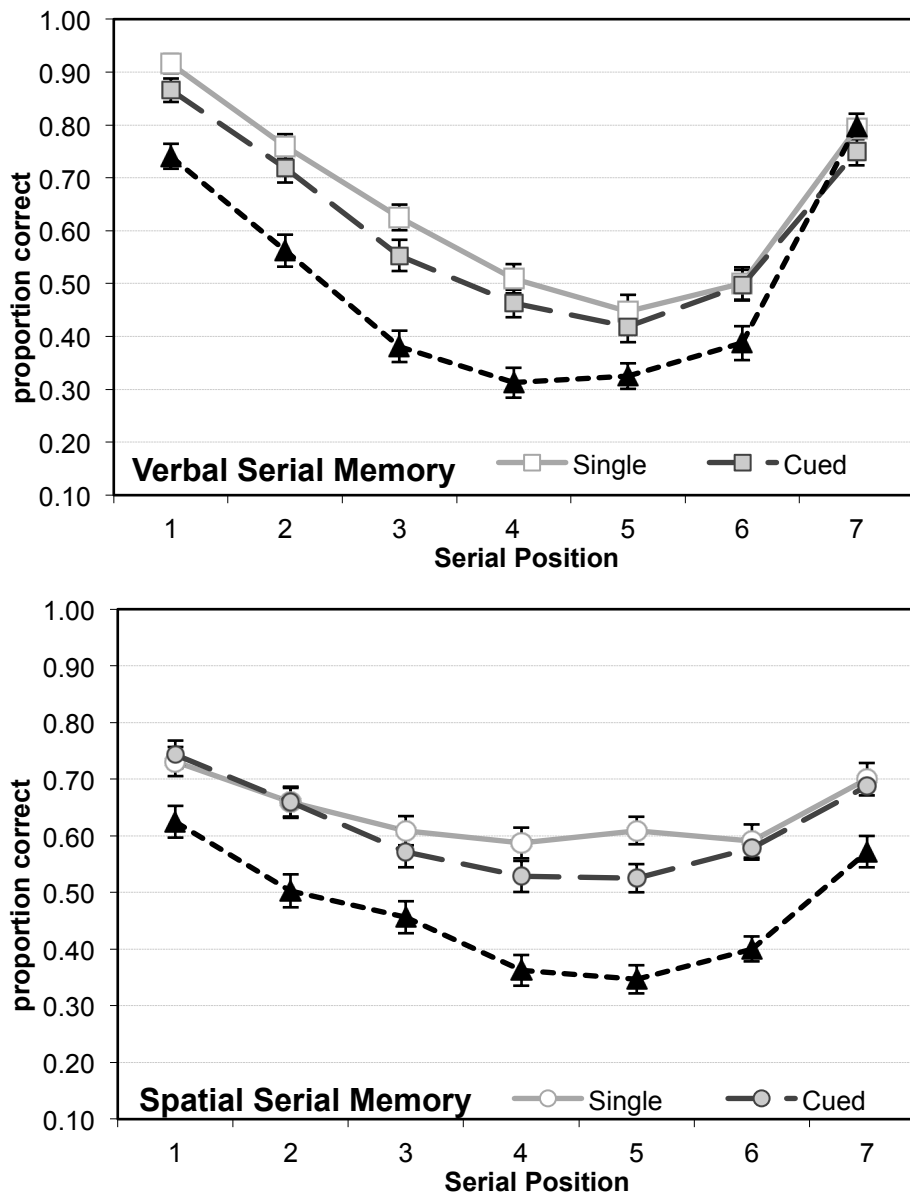
Figure 2

Figure 2. Serial reconstruction accuracy as a function of serial position for verbal

sequences (upper panel) and spatial sequences (lower panel), 7-item lists, Experiment 1.

Error bars are within-subjects standard errors of the mean (Cousineau, 2005) with
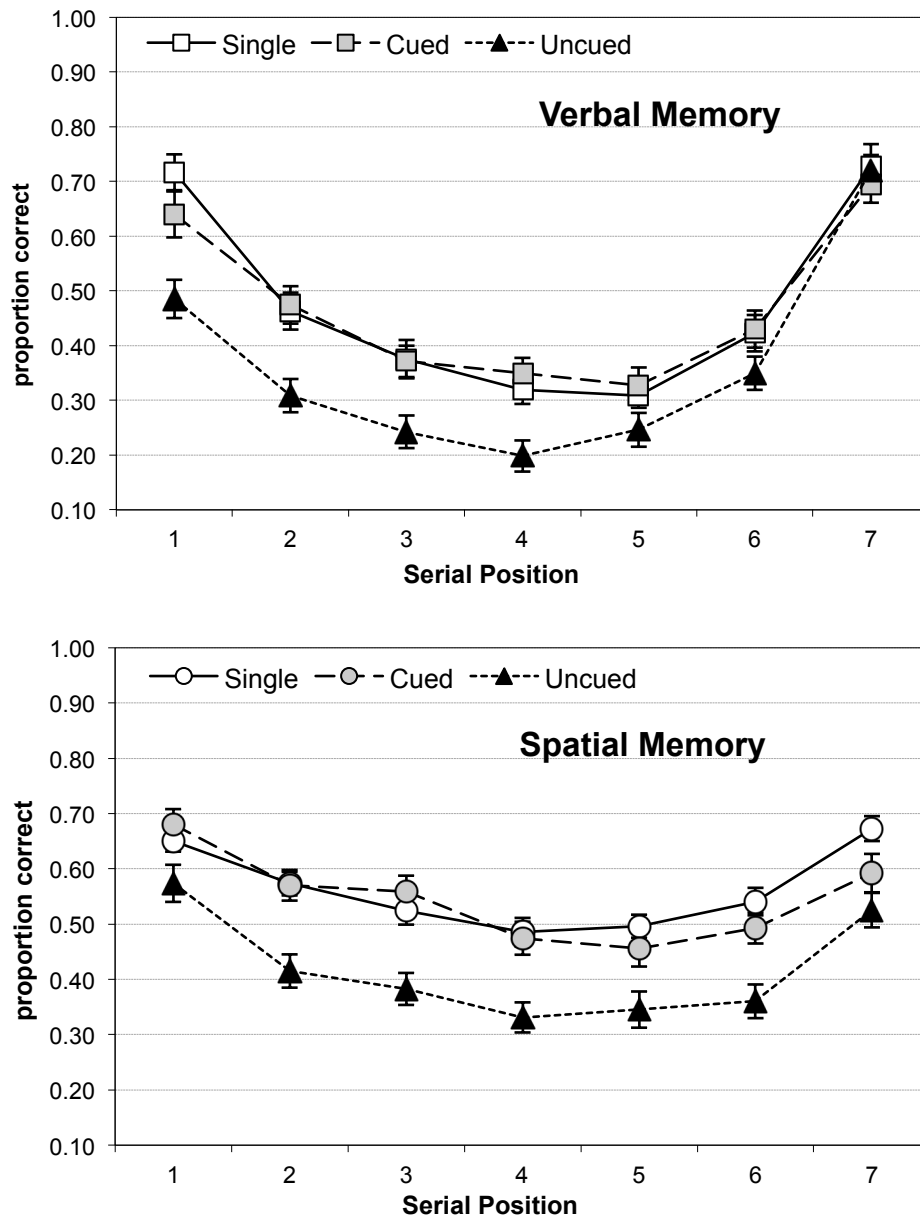
Morey's (2008) correction.

Figure 3

Figure 3. Serial reconstruction accuracy as a function of serial position for verbal

sequences (upper panel) and spatial sequences (lower panel), for non-word lists only,

Experiment 2. Error bars are within-subjects standard errors of the mean (Cousineau,
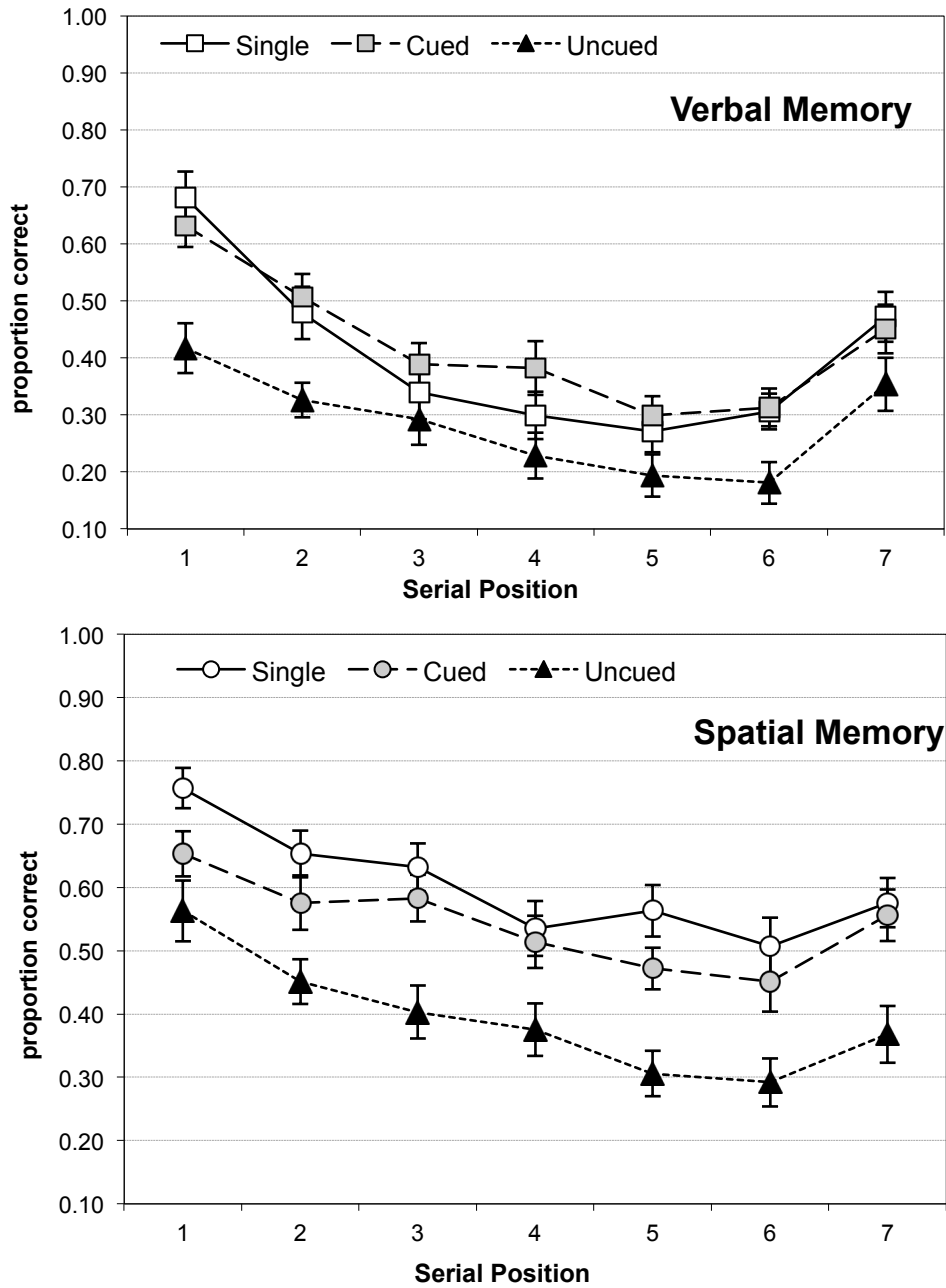
2005) with Morey's (2008) correction.

Figure 4

Figure 4. Serial reconstruction accuracy as a function of serial position for verbal

sequences (upper panel) and spatial sequences (lower panel), Experiment 3. Error bars

are within-subjects standard errors of the mean (Cousineau, 2005) with Morey's (2008)

correction.