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Working Memory Storage Is Intrinsically Domain Specific

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A longstanding debate in working memory (WM) is whether information is maintained in a central, capacity-limited storage system or whether there are domain-specific stores for different modalities. This question is typically addressed by determining whether concurrent storage of 2 different memory arrays produces interference. Prior studies using this approach have shown at least some cost to maintaining 2 memory arrays that differed in perceptual modalities. However, it is not clear whether these WM costs resulted from competition for a central, capacity-limited store or from other potential sources of dual-task interference, such as task preparation and coordination, overlap in representational content (e.g., object vs. space based), or cognitive strategies (e.g., verbalization, chunking of the stimulus material in a higher order structure). In the present study we assess dual-task costs during the concurrent performance of a visuospatial WM task and an auditory object WM task when such sources of interference are minimized. The results show that performance of these 2 WM tasks are independent from each another, even at high WM load. Only when we introduced a common representational format (spatial information) to both WM tasks did dual-task performance begin to suffer. These results are inconsistent with the notion of a domain-independent storage system, and suggest instead that WM is constrained by multiple domain-specific stores and central executive processes. Evidently, there is nothing intrinsic about the functional architecture of the human mind that prevents it from storing 2 distinct representations in WM, as long as these representations do not overlap in any functional domain.

Keywords: working memory

Whenever we have to jot down a phone number, solve a complex math problem, or engage in lengthy conversations, we rely on our capability to store information in a highly active and accessible state for use by other cognitive processes (Baddeley & Hitch, 1974). Yet, although such working memory (WM) is critically important in our day-to-day lives, its capacity is surprisingly limited. People struggle to store more than a handful of representations, and often fail to detect rather salient changes between two displays separated by a short temporal interval (Cowan, 2001; Cowan, Chen, & Rouder, 2004; Henderson, 1972; Hollingworth, 2004; Irwin, 1992; Luck & Vogel, 1997; Miller, 1956; Pashler, 1988; Rensink, 2000, 2002). Despite these limitations, nearly every major cognitive function is linked to working memory. For example, attentional control, problem solving, language, reasoning, and consciousness are just some of the cognitive functions with close links to working memory (Baddeley, 1986; Baddeley & Hitch, 1974; Duncan, 1995; Engle, Tuholski, Laughlin, & Conway, 1999; Hasher & Zacks, 1988; Kane & Engle, 2002; Kane et al., 2004; Roberts, Hager, & Heron, 1994; Unsworth, Schrock, & Engle, 2004). Performance in working memory tasks also is strongly correlated with important measures of behavioral traits such as general intelligence (Alloway & Alloway, 2010; Cowan et al., 2005; Fukuda, Vogel, Mayr, & Awh, 2010; Kyllonen & Christal, 1990). Thus, working memory is generally considered to play a broad and central role in cognitive ability.

Despite decades of research, the source(s) of the severe capacity limits of WM storage are still under intense debate (Baddeley, 1986; Cowan, 2001, 2006). Of particular interest is the representational content of working memory and how this relates to its limited capacity. Some researchers have suggested that working memory representations are tied to a particular domain (e.g., visual, auditory) and that limitations in memory arise from competition in domain-specific stores (e.g., Baddeley & Logie, 1999). Other researchers have suggested that the main limitation is a domain-independent process that allows items to be stored in working memory regardless of content or modality (e.g., Cowan, 2006). Thus, the debate centers on the degree to which limits arise from interference in content-specific stores or from a capacity-limited process that operates over items regardless of content. Determining an answer to this question has broad implications for understanding working memory. Without understanding the representational format of its contents, it is difficult to make progress in other lines of inquiry about the nature of working memory

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(Suchow, Fougnie, Brady, & Alvarez, 2014) or to interpret the meaning of differences in WM measures across conditions or people. This question also has implications for understanding cognition more broadly: The strong links between working memory and other cognitive processes—such as reasoning and attention—raise the possibility that these processes could also be confronted with the same fundamental issue about the domain generality and specificity of their contents.

One popular approach for assessing the degree to which WM is domain independent or domain specific has been to require participants to concurrently store two WM loads of distinct content and assess the degree to which they interfere. Such studies have typically used WM tasks involving items presented in distinct sensory modalities, particularly the auditory and visual modalities. The findings of such cross-modal WM studies suggest that when a visual WM task is paired with a small auditory WM load, WM task performance is unaffected (Fougnie & Marois, 2006; Luck & Vogel, 1997; Morey & Cowan, 2004; Woodman, Vogel, & Luck, 2001). However, when the dual-task load is high, significant dual-task costs arise (Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002; Fougnie & Marois, 2006; Morey & Cowan, 2004, 2005; Saults & Cowan, 2007; Scarborough, 1972). The emerging view from these studies is that working memory is constrained by both domain-general and domain-specific sources (Baddeley, 2000; Fougnie & Marois, 2006; Morey & Cowan, 2004). Neuroimaging data is consistent with the idea of multiple constraints. Distinct neural correlates appear to be involved in maintenance of different content (Gruber & von Cramon, 2001, 2003; Kirschen, Chen, & Desmond, 2010; Rämä & Courtney, 2005; Romanski & Goldman-Rakic, 2002; Schumacher et al., 1996; Smith et al., 1995; Todd & Marois, 2004; Tresch, Sinnamon, & Seamon, 1993; Ungerleider, Courtney, & Haxby, 1998). However, there also may be brain regions, such as the left parietal cortex, that are involved in storing multimodal information (Cowan et al., 2011).

Here we present evidence that clashes with the consensus view of both domain-general and domain-independent constraints on working memory. As noted earlier, all previous dual-task studies have found at least some cost between the two tasks, and this finding has provided strong support for the dual-constraints view. However, an issue with past studies is that there are many potential causes of interference aside from competition for a domain-general store. After controlling for potential overlap in representational content, or interference from nonmnemonic aspects of the task, here we found no interference between concurrent storage of auditory and visual items. This surprising result was found in seven separate studies under a variety of experimental conditions. These findings are problematic for the view that a capacity-limited domain-general process constrains working memory. In contrast, the results support a view where competition between items in working memory arises not from a process that operates regardless of modality, but one that is intrinsically linked to the stored content, and that interference can be minimized or even eliminated if the stored contents are sufficiently distinct from one another.

Minimizing Nonmnemonic Sources of Dual-Task Interference

Compared to a single-task condition, a dual-task setting makes additional demands on task preparation, coordination, encoding, and response processes. Just the need to coordinate performance for two tasks could load on the central executive, particularly if the task order is unpredictable (De Jong & Sweet, 1994). In addition, tasks that require maintaining bound featural information in WM are more likely to interfere with one another (Fougnie & Marois, 2011). Moreover, two stimulus arrays that differ in sensory modalities may nevertheless overlap in the format in which these representations are maintained, and it may be this overlap in representational format rather than the existence of a supramodal WM store that could be the source of dual-task interference. For example, a participant might encode an object in a visual display in propositional form as "green square on the right" and this may interfere with concurrent maintenance of verbal stimuli. Indeed, studies have found evidence for shared representational content across modalities (Postle, Desposito, & Corkin, 2005; Zhou, Ardestani, Fuster, 2007), and tasks interfere with another much more when they share representational content compared to when they do not (Awh & Jonides, 1998; 2001). Therefore, convincing evidence for a domain-independent store in WM would be provided by dual-task studies that used stimuli with as little overlap in the representational content as possible. It is unfortunate that previous studies typically had participants encode and store object properties of auditory and/or visual stimuli. A much stronger test would be to pair maintenance of auditory object features with maintenance of visuospatial locations—as there is evidence that our WM system may have distinct capacities and neural correlates for object and spatial features (Logie, 1995; Logie & Marchetti, 1991; Postle et al., 2005; Smith et al., 1995; Tresch et al., 1993; Ungerleider et al., 1998; Ventre-Dominey et al., 2005).

Thus, to determine whether there is a source of domain-independent storage in WM, the present study assessed the dual-task costs for concurrent maintenance of visuospatial and auditory arrays while minimizing nonmnemonic sources of interference. The visuospatial working memory (VWM) task required participants to remember a single feature, namely the spatial position of one to five circles presented on a computer screen (Figure 1A). The task was designed such that the higher order structure formed by the circles—a line—was constant across trials and therefore not informative. We also minimized grouping by physical proximity by not allowing the sample stimuli to occupy adjacent positions along the line; meaning that there was always a positional gap between the stimuli on a particular trial. Participants were given a single probe stimulus to test memory, and a nonmatching probe stimulus was always adjacent to one of the sample stimuli (Figure 1A). This method of probe presentation meant that remembering the general location of clusters of items was not informative, thereby encouraging participants to remember the exact spatial position of each item. This spatial WM task was paired with an auditory working memory (AWM) task for digit identity, as this stimulus type should have minimal overlap with processing of the visuospatial array.

To minimize differences in executive demands between single- and dual-task conditions we presented two samples and required two responses on all trials (Figure 1B). In addition, the task order was constant across trials to minimize changes in preparation across conditions (De Jong & Sweet, 1994). If costs for concurrently maintaining spatial and auditory arrays are still observed under these task conditions, this will provide strong evidence for a domain-independent source of WM capacity.

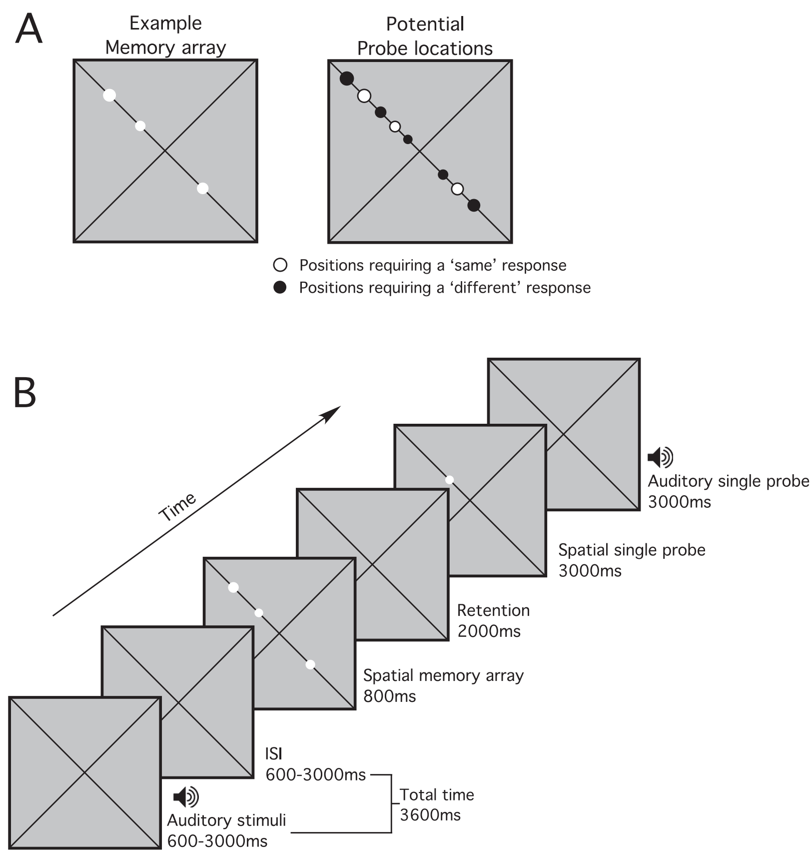

Figure 1. A: Example visuospatial working memory (VWM) display (left) and potential probe locations (right) in the corresponding VWM probe display. B: Trial timeline of a dual-task condition in Experiment 1. ISI = interstimulus interval.

Experiment 1

Method

Participants. Seventeen young adults (11 women) between the ages of 18 and 27 (*M* age 20.5years) participated for course credit or monetary reward ($10 per hour).[1] All participants had normal hearing and normal or corrected-to-normal visual acuity. Informed consent was obtained at the beginning of each experiment.

Design. Participants performed single-task AWM (20% of trials), single-task VWM (20% of trials), and dual-task trials (60% of trials) randomly intermixed within four blocks of 60 trials. For each task, there were three manipulations of set size. There were 16 trials per condition for each combination of dual-task and single-task load. To keep task order constant across trials we embedded the VWM task within the retention interval of the AWM task (Figure 1B). Trials were separated by a 1,000-ms intertrial interval.

Participants were given bonus pay of 0 to $10 based on their performance in the task. For each single-task trial that participants answered correctly, and for each dual-task trial with both responses correct, the amount of bonus pay that a participant would receive increased by $.05. Participants were instructed to maintain fixation throughout each trial, and to emphasize the two tasks equally. During practice blocks, participants were given response accuracy feedback during the 1,000-ms intertrial interval.

VWM task. The VWM display consisted of one, three, or five white dots appearing along one of two black diagonal lines that crossed the screen to form an *X* (Figure 1A). The use of two diagonal lines also served to create a fixation point at the center of the screen where the lines crossed. The stimuli always appeared on the same line within a block and were presented for 800 ms.[2] Whether the stimuli appeared on the line that runs from top-left to bottom-right, or vice versa, changed between blocks. Participants were instructed to memorize the spatial positions indicated by the white dots. A dot could occupy one of 12 possible positions on a line, with the restriction that two dots could not occupy adjacent positions. The spacing of positions was not constant but increased with increased distance from fixation to account for the lower

[1] The number of participants was not set prior to testing but was determined by the number of individuals who volunteered for the study during a week of testing. Changes in the availability of the participant pool are responsible for the varying numbers of participants across experiments. Data was not analyzed until the data from all participants were collected to prevent *p* hacking (Simmons, Nelson, & Simonsohn, 2011).

[2] A pilot study on nine participants found that memory accuracy was better with an 800-ms than a 400-ms encoding duration ($p < .05$) but was not further improved with a 1,600-ms encoding duration ($p = .4$).

spatial resolution of vision with increased eccentricity: The two positions closest to fixation were separated by .5°. With each step from fixation the spacing increased by 33% such that the spacing for the farthest adjacent dots was 2.77°. This spacing produced nearly equivalent WM performance at all positions in a pilot study with eight participants. The size of the dots also increased with increased distance from fixation (.15° diameter near fixation to .3° diameter at the point farthest from fixation).

After a 2,000-ms retention interval the VWM probe appeared. The probe consisted of a single dot presented at the same position as one of the sample dots, or at a position adjacent to a sample dot (50% probability). Participants made one of two key presses with their left hand to indicate whether the probe was the same as or different from the sample dot positions. Participants had 3,000 ms to respond before the display cleared and an incorrect response was registered. The VWM probe remained onscreen for 3,000 ms even if participants responded within that interval. Thus, the total duration of the VWM task was 5,800 ms.

AWM task. The AWM task consisted of the presentation via headphones of two, six, or 10 consonants spoken by a female voice. In pilot testing we found that this set size produced similar levels of performance to that of the VWM task for set sizes one, three, and five, respectively. The stimuli were presented sequentially at a rate of 300 ms per consonant. Note that the duration of auditory stimulus presentation ranged from 600 ms (Set Size 2) to 3,000 ms (Set Size 10). To equate for total AWM retention time across set sizes (as AWM retention begins immediately after the presentation of the first auditory stimulus), the interval between the offset of the last AWM stimulus and the onset of the VWM sample ranged from 600 ms (Set Size 10) to 3,000 ms (Set Size 2), for a total duration of 3,600 ms for the auditory presentation phase. This phase was followed by the AWM retention phase proper (5,800 ms), during which the VWM task displays were presented. The AWM probe followed the VWM probe and involved the presentation for 300 ms of a consonant that was the same or different from the auditory sample (50% probability). Participants made one of two key presses with their right hand to indicate whether the probe was the same as or different from the sample. Participants had 3,000 ms to respond before an incorrect response was registered.

Single- versus dual-task conditions. In dual-task trials, the VWM task was presented during the retention period of the AWM task, as described earlier (Figure 1B). We strove to minimize differences in sensory stimulation and motor responses between single- and dual-task conditions by still presenting stimuli and requiring a motor response for the irrelevant task on single-task trials. In particular, in the AWM single-task trials, the VWM display consisted of black dots at every potential location, regardless of set size. The presence of these dots informed the participants to ignore the VWM task. Following a 2,000-ms period, the VWM probe display—which also consisted of black dots at every potential location—appeared and participants were instructed to respond by pressing either of the two response keys. In the VWM single-task trials, the auditory sample consisted of the singular presentation of the vowel *E* for 300 ms to indicate to the participants that there was no AWM load. This sound also was used during the AWM probe phase of VWM single-task trials to instruct participants to press either of the two response keys.

Measuring WM capacity. To measure capacity for the spatial WM task, change detection accuracy was entered into Cowan's (2001) *K* formula ($K = [\text{hit rate} - \text{false alarm rate}]\,N$; Cowan, 2001; Cowan, Johnson, & Saults, 2003; Pashler, 1988). This formula for estimating *K* is appropriate when a probed item can be compared with a specific target item.

To measure capacity for the auditory WM task, change detection accuracy was entered into a "reverse Pashler" *K* formula ($K = [(\text{hit rate} - \text{false alarm rate})/\text{hit rate}]\,N$; Cowan, Blume, & Saults, 2013). This formula is appropriate when a probe item has to be compared to all targets.

Results and Discussion

To minimize confusion, we reserve the term *set size* to refer the number of stimuli for the currently analyzed task and the term *load* for the other task. For example, for VWM performance, we discuss the impact of VWM *set size* and AWM *load*. The analyses in the following are on the capacity (*K*) data. Note that there were no qualitative differences in the outcomes of the analyses of variance (ANOVA) performed on the *K* and change detection accuracy data for Experiments 1 through 7. The advantage of examining *K* values is that it allows us to determine whether the single-task set sizes tested were sufficient to exhaust capacity. The *K* results for the first six experiments are shown in Figure 2. The percentage correct results for these studies are shown in Figure 3. Responses were considered incorrect if not made within the 3,000-ms response time.

Single-task performance. Single-task *K* values for intermediate set sizes were higher than for low set sizes in both conditions, paired *t* tests: VWM task, $t(16) = 3.02$, $p < .01$, Cohen's $d = 0.73$; AWM task, $t(16) = 17.6$, $p < .001$, Cohen's $d = 2.6$ (Figure 2A), suggesting that the low set size was insufficient to exhaust WM capacity. More important, there was no difference in *K* scores between high and intermediate set sizes, VWM task, $t(16) = .80$, $p = .43$, Cohen's $d = 0.01$; AWM task, $t(16) = 1.27$, $p = .22$, Cohen's $d = 0.3$, suggesting that participant's auditory and spatial WM capacity was exhausted at intermediate and high set sizes. Thus, a failure to find dual-task costs cannot be attributable to insufficient task demands.

Dual-task performance. *K* values for the VWM task (Figure 2A top panel) were analyzed with a 4 (AWM load) × 3 (VWM set size) within-subjects ANOVA. There was a main effect of VWM set size, $F(2, 32) = 3.41$, $p < .05$, $\eta_p^2 = .17$; no main effect of AWM load, $F(3, 48) = .93$, $p = .43$, $\eta_p^2 = .07$; and a marginal interaction, $F(6, 96) = 2.06$, $p = .06$, $\eta_p^2 = .11$. *K* values for the AWM task (Figure 2A bottom panel) were analyzed with a 4 (VWM load) × 3 (AWM set size) within-subjects ANOVA. There was a main effect of AWM set size, $F(2, 32) = 8.28$, $p = .001$, $\eta_p^2 = .30$; no main effect of VWM load, $F(3, 48) = .30$, $p = .83$, $\eta_p^2 = .01$; and no interaction, $F(6, 96) = .09$, $p = .99$, $\eta_p^2 = .006$.[3]

[3] Even though the task was not speeded, we also recorded reaction time (RT) data (only 2% of trials had timed-out responses). For both AWM and SWM responses, RTs increased with increased set size ($ps > .001$), but there were no load effects ($ps > .2$). Thus, RTs showed the same pattern as the accuracy and capacity measures, suggesting that our paradigm does not introduce a speed–accuracy trade-off. Given these results and the limited value of RT data in nonspeeded tasks, RTs will not be further considered in this study.

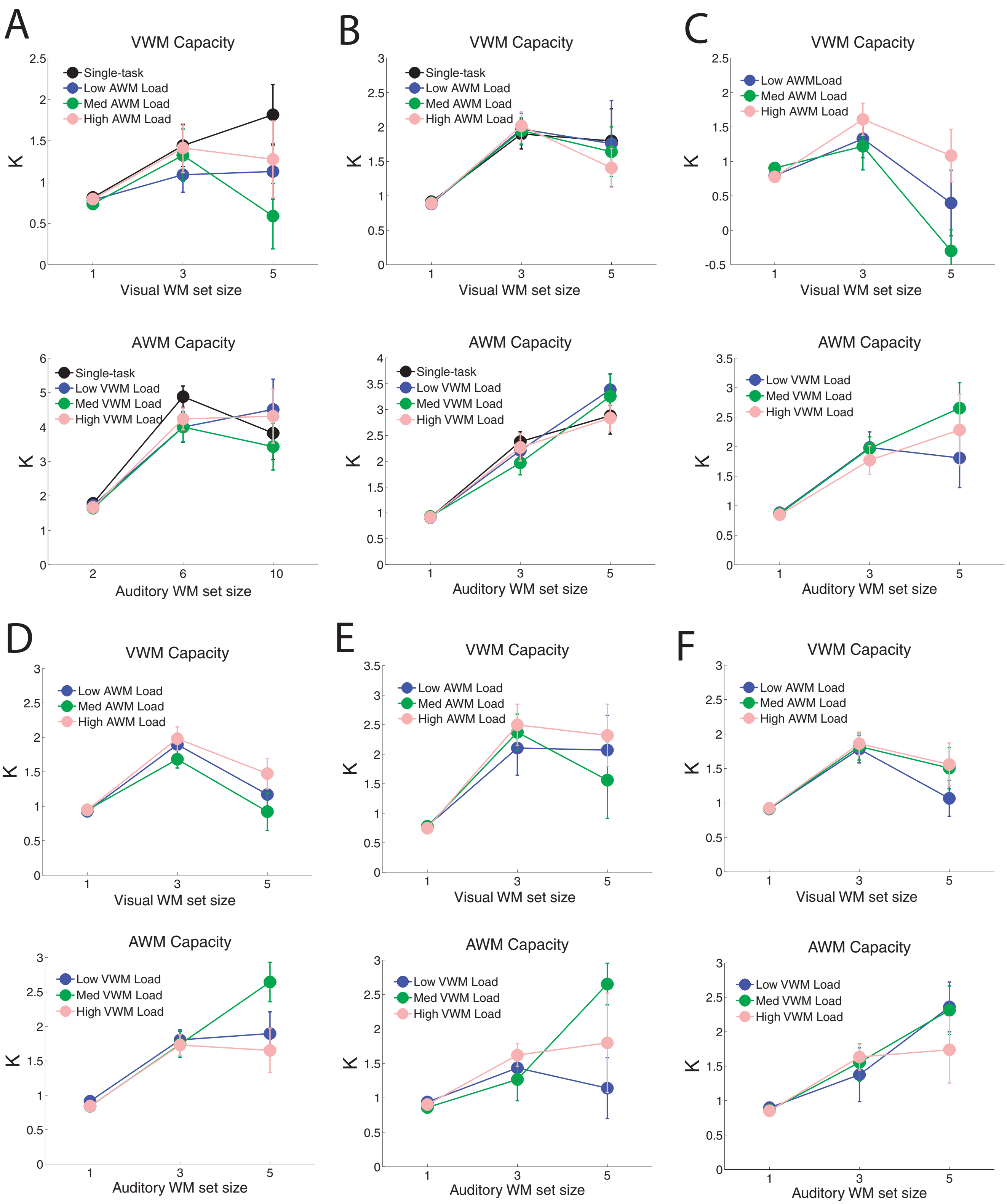

Figure 2. Capacity (*K*) data for the auditory working memory (AWM; above) and visuospatial working memory (VWM; below) tasks for Experiments 1 through 6 (panels A–F, respectively) as a function of task set size and secondary task load. Error bars represent between subject standard error of the mean. WM = working memory. See the online article for the color version of this figure.

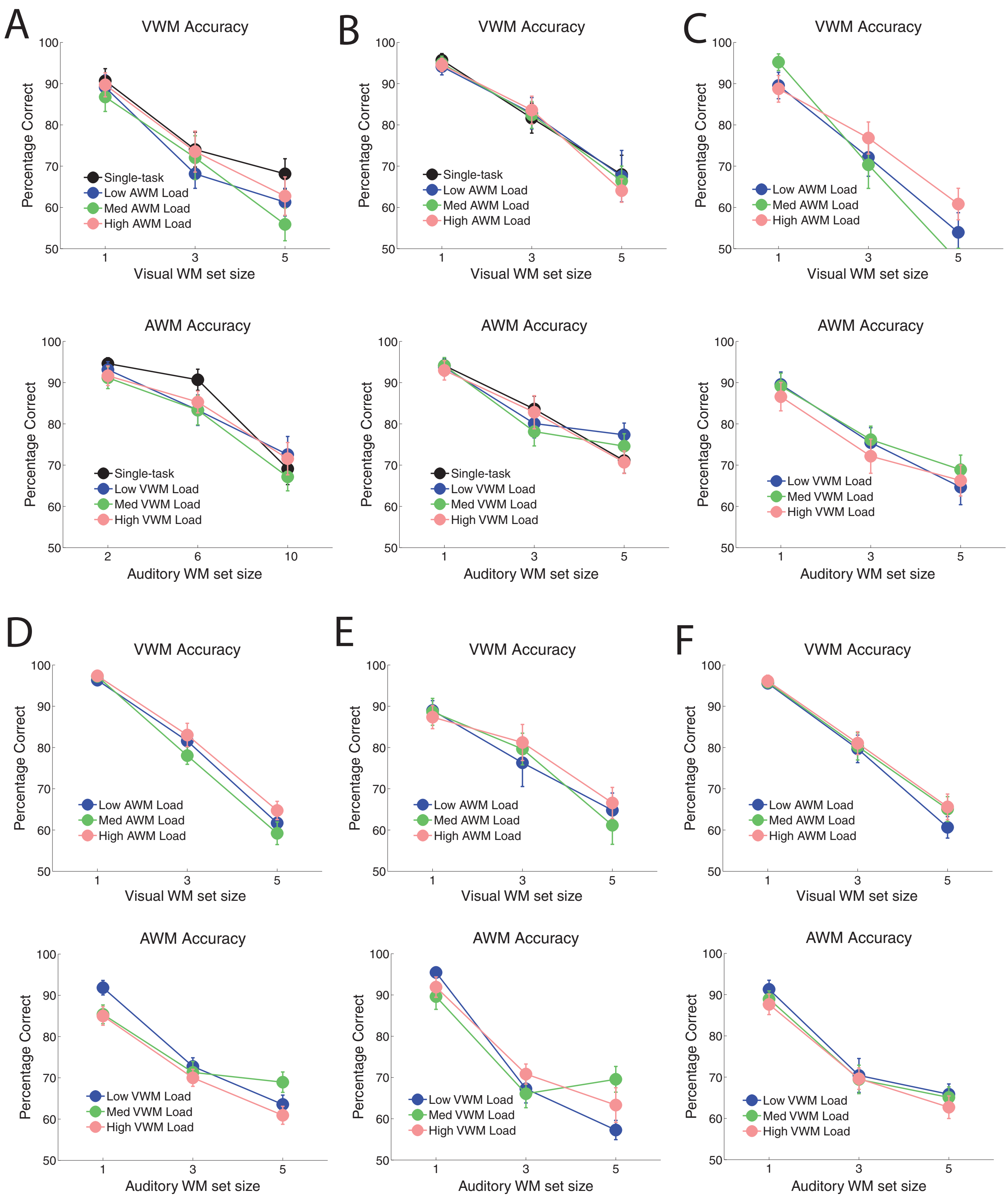

Figure 3. Percentage correct for the auditory working memory (AWM; above) and visuospatial working memory (VWM; below) tasks for Experiments 1 through 6 (panels A–F, respectively) as a function of task set size and secondary task load. Error bars represent between-subject standard error of the mean. WM = working memory. See the online article for the color version of this figure.

For both AWM and VWM, *K* values were strongly affected by task set size, suggesting that the tasks were sufficiently demanding to exhaust processing capacity. However, there was no evidence of dual-task costs for either task. Even at the highest secondary task load, WM performance is similar to that in the single-task condition. These results differ from previous studies that found significant costs when auditory and visual tasks are paired at high load (Cocchini et al., 2002; Fougnie & Marois, 2006; Scarborough, 1972). The results also seem at odds with the notion of a domain-independent store capable of holding several items in WM (Cowan, 2001). However, several concerns need to be addressed before we can claim strong evidence against a domain-independent source to WM capacity:

1. Do these findings generalize for different auditory WM stimuli?

2. Does the lack of interference effects occur even if an additional task ties up participants' articulatory loop (i.e., ability to subvocally rehearse stimuli)?

3. Can these results be explained by long-lasting sensory traces of the stimuli instead of by the need for storage in WM (Saults & Cowan, 2007)?

The following studies address these concerns and show that the lack of costs between auditory and spatial stimuli is highly replicable in this paradigm.

Experiment 2

A possible explanation for the lack of dual-task costs in Experiment 1 could be that the use of a verbal WM load allowed participants to rehearse the AWM stimuli using the articulatory loop proposed by Baddeley (1986). In others, the auditory WM task may not have interfered with the visual WM task because the auditory information was retained by subvocally rehearsing the stimuli rather than by maintaining them in a central WM store. Hence, in Experiment 2 we asked whether stimuli that cannot be maintained in the articulatory loop would show evidence of dual-task costs.

Experiment 2 combined the VWM task of Experiment 1 with an AWM task for synthesized sounds. The 12 sounds were designed to be uncommon, very difficult to verbalize, and as distinct from each other as possible (the sounds can be found at: http://sites.google.com/site/darylfougnie/audwmexamples). In a pilot study on 10 participants we found that set sizes of one, three, and five sounds produced the same pattern of *K* as set sizes of two, six, and 10 for verbal WM in Experiment 1.

Method

Participants. Sixteen young adults (7 women) between the ages of 18 and 25 years (*M* age 19.9 years) participated for course credit or monetary reward. All participants had normal hearing and normal or corrected-to-normal visual acuity.

AWM task. An AWM task for one, three, or five nonverbalizable sounds (out of 12) replaced the verbal WM task in Experiment 1. The sounds lasted 300 ms in duration and were presented at a rate of 500 ms per item. Total stimulus presentation time lasted between 500 ms (Set Size 1) and 2,500 ms (Set Size 5), and was followed by an interval (duration between offset of auditory presentation and onset of VWM sample) that varied between 2,000 ms (Set Size 5) and 4,000 ms (Set Size 1) such that the VWM sample was always presented 4,500 ms after AWM sample onset. During the AWM task probe, a single sound was presented and participants indicated by key press whether the probe was one of the sample items. Participants completed five blocks of 60 trials for a total of 20 trials per condition (up from 16 in Experiment 1). All other aspects of the study were unchanged from Experiment 1.

Results

Single-task performance. Single-task *K* values for intermediate set sizes were higher than for low set sizes in both conditions, VWM task, $t(15) = 4.64$, $p < .001$, Cohen's $d = 1.16$; AWM task, $t(15) = 8.26$, $p < .001$, Cohen's $d = 2.07$ (Figure 2B). However, there were no differences in *K* values between intermediate and high set sizes, VWM task, $t(15) = .25$, $p = .80$, Cohen's $d = 0.06$; AWM task, $t(15) = 1.62$, $p = .13$, Cohen's $d = 0.40$. This suggests that the task loads used were sufficiently demanding to exhaust single-task capacity.

Dual-task performance. *K* values for the VWM task (Figure 2B top panel) were analyzed with a 4 (AWM load) × 3 (VWM set size) within-subjects ANOVA. There was a main effect of VWM set size, $F(2, 30) = 8.99$, $p < .001$, $\eta_p^2 = .40$; no main effect of AWM load, $F(3, 45) = 0.16$, $p = .93$, $\eta_p^2 = .01$; and no interaction, $F(6, 90) = 0.34$, $p = .92$, $\eta_p^2 = .02$. *K* values for the AWM task (Figure 2B bottom panel) were analyzed with a 4 (VWM load) × 3 (AWM set size) within-subjects ANOVA. There was a main effect of AWM set size, $F(2, 30) = 61.87$, $p < .001$, $\eta_p^2 = .78$; no main effect of VWM load, $F(3, 45) = 0.57$, $p = .64$, $\eta_p^2 = .02$; and no interaction, $F(6, 90) = 1.52$, $p = .18$, $\eta_p^2 = .09$. One concern is that the null effect of VWM load might have been driven by performance in the AWM single-task condition, which is low compared to Experiment 1. Perhaps by mixing single- and dual-task conditions within blocks, the single-task trials (which were less common) were more difficult because they were unexpected. However, there was still no effect of VWM load if single-task trials were excluded, $F(2, 30) = 1.16$, $p = .33$, and no interaction, $F(6, 90) = 1.71$, $p = .13$. Indeed, an analysis of dual-task performance at the highest AWM set size still found no effect of VWM load ($p = .14$).

Experiment 3

No evidence of dual-task costs was observed in the previous study even with nonverbal AWM stimuli. Although the sounds for Experiment 2 were difficult to verbalize, participants may have associated the sounds with conceptual labels that they could articulate. To further minimize the possibility that the lack of dual-task costs between auditory and visual WM are due to participants being able to rehearse the auditory stimuli using a verbal or preverbal strategy, the AWM task for Experiment 3 used a set of stimuli drawn from a single category; difficult-to-identify birdcalls from birds not endemic to the United States (to listen to these sounds visit http://sites.google.com/site/darylfougnie/audwmexamples). During debriefing all participants were asked whether they recognized the birdcalls. No participant reported that they associated a birdcall with a specific bird. Thus, performance on this task likely depended on participants memorizing sound characteristics rather than memorizing a category label.

Method

Ten young adults (7 women) between the ages of 19 and 27 years (*M* age 20.7 years) participated for course credit or monetary reward. The AWM task was changed to memorizing one, three, or five birdcalls (350-ms duration, presented every 500 ms) selected from a set of 12 possible birdcalls. In addition, single-task trials were removed from the design so that participants performed two tasks on all trials. This was done to address concerns that the single-task conditions were more difficult than dual-task conditions due to the relatively rare occurrence of single-task trials. Participants performed six blocks of 36 trials for a total of 24 trials per condition.

Results and Discussion

Dual-task performance at low load. In Experiment 3 there are no single-task conditions. Therefore, to test whether the tasks used were sufficient to exhaust WM capacity we compared *K* values as a function of task set size during low load. *K* values for intermediate set sizes were higher than for low set sizes in both conditions, VWM task, $t(9) = 2.23$, $p = .05$, Cohen's $d = 0.71$; AWM task, $t(9) = 4.62$, $p < .005$, Cohen's $d = 1.46$ (Figure 2C). A comparison of differences in *K* values between intermediate and high set sizes revealed no difference for the AWM task, $t(9) = .29$, $p = .78$, Cohen's $d = 0.09$, and a trend toward lower capacity at high than intermediate set sizes for the VWM, $t(9) = -2.0$, $p = .08$, Cohen's $d = 0.65$. This is consistent with previous studies that have found smaller *K* values at high than low set sizes (e.g., Rouder et al., 2008). There have been several proposals to account for why *K* may decline at large set sizes. Rouder et al. (2008) suggested that participants may feel intimidated by large set sizes. On the other hand, performance could be limited, in part, by mutually suppressive interactions between WM representations (Johnson, Spencer, Luck, & Schöner, 2009) where mutual inhibition increases at higher set sizes. Regardless of why VWM *K*s decline at the highest set size, the results suggest that the task loads used were sufficiently demanding to exhaust capacity.

Effect of load on dual-task performance. *K* values for the VWM task (Figure 2C top panel) were analyzed with a 3 (AWM load) × 3 (VWM set size) within-subjects ANOVA. There was a main effect of VWM set size, $F(2, 18) = 7.1$, $p < .005$, $\eta_p^2 = .50$; a main effect of AWM load, $F(2, 18) = 15.91$, $p < .005$, $\eta_p^2 = .24$; and an interaction, $F(4, 36) = 3.6$, $p = .01$, $\eta_p^2 = .29$. Thus, unlike the previous studies, the present study finds evidence that AWM load influences VWM *K* values. However, this result is inconsistent with competition for a shared capacity, as that theory predicts lower VWM *K* values as AWM load is increased. Contrary to this prediction, a linear contrast analysis found that VWM *K*s were greater during high AWM load than low AWM load, $t(9) = 2.55$, $p = .03$ (paired *t* tests).

K values for the AWM task (Figure 2C bottom panel) were analyzed with a 3 (VWM load) × 3 (AWM set size) within-subjects ANOVA. There was a main effect of AWM set size, $F(2, 18) = 16.53$, $p < .001$, $\eta_p^2 = .49$; no main effect of VWM load, $F(2, 18) = .84$, $p = .45$, $\eta_p^2 = .04$, and no interaction, $F(4, 36) = .74$, $p = .57$, $\eta_p^2 = .08$. Thus, there is no evidence that VWM load interferes with AWM *K* values.

Experiment 4

To further eliminate the possibility that the lack of interference between the auditory and VWM tasks was due to verbalization of the auditory stimuli, Experiment 4 required participants to overtly repeat the word *the* at a rate of 4 Hz (the verbalizations were monitored remotely by an experimenter). This articulatory suppression task should reduce participants' ability to verbalize stimuli (Allen, Hitch & Baddeley, 2009; Logie, Brockmole & Jaswal, 2011).

Method

Twenty young adults (11 women) between the ages of 18 and 28 years (*M* age 20.5 years) participated for course credit or monetary reward. All participants had normal hearing and normal or corrected-to-normal visual acuity. One participant's data were not included in the analysis because they were not performing the articulatory suppression task on all trials, leaving 19 participants for analysis. This experiment was similar to Experiment 3 except that participants were instructed to perform articulatory suppression while the VWM lines were shown on screen. Between trials, the VWM lines were removed for a 1,000-ms intertribal interval (ITI) and appeared 1,000 ms prior to the AWM sample.

Results and Discussion

Dual-task performance at low load. To test whether the tasks used were sufficient to exhaust WM capacity, we compared *K* values as a function of task set size during low load. *K* values for intermediate set sizes were higher than for low set sizes in both conditions, VWM task, $t(18) = 6.57$, $p < .001$, Cohen's $d = 1.51$; AWM task, $t(18) = 6.27$, $p < .001$, Cohen's $d = 1.44$. A comparison of differences in *K* values between intermediate and high set sizes revealed no differences for the AWM task, $t(18) = 0.24$, $p = . 81$, Cohen's $d = 0.06$, and evidence for lower capacity at high versus intermediate set sizes for the VWM task, $t(18) = -2.75$, $p = .02$, Cohen's $d = 0.63$. This suggests that the task loads used were sufficiently demanding to exhaust capacity.

Effect of load on dual-task performance. *K* values for the VWM task (Figure 2D top panel) were analyzed with a 3 (AWM load) × 3 (VWM set size) within-subjects ANOVA. There was a main effect of VWM set size, $F(2, 36) = 25.73$, $p < .001$, $\eta_p^2 = .45$; a main effect of AWM load, $F(2, 36) = 3.27$, $p = .05$, $\eta_p^2 = .07$; but no interaction, $F(4, 72) = 0.88$, $p = .48$, $\eta_p^2 = .04$. Because we found a significant effect of AWM load, a linear contrast analysis was run to determine whether VWM *K*s were greater during low AWM load than high AWM load, as would be expected of a central WM store. Contrary to this expectation, the results showed a nonsignificant trend of greater VWM *K*s at higher secondary (AWM) task load, $t(18) = -1.11$, $p = .27$. *K* values for the AWM task (Figure 2D bottom panel) were analyzed with a 3 (VWM load) × 3 (AWM set size) within-subjects ANOVA. There was a main effect of AWM set size, $F(2, 36) = 25.47$, $p < .001$, $\eta_p^2 = .48$; a marginal effect of VWM load, $F(2, 36) = 2.50$, $p = .10$, $\eta_p^2 = .05$; and a significant interaction, $F(4, 72) = 2.68$, $p =$

.04, $\eta_p^2 = .14$. A linear contrast analysis found that AWM *K*s were not greater during low VWM load than high VWM load, $t(18) = 1.5$, $p = .14$. Thus, for both tasks, there is little evidence that increased secondary task load interferes with WM capacity.

Experiment 5

The first four experiments revealed no interference between VWM and AWM tasks. This finding generalized across several classes of auditory stimuli held in WM, and was independent of whether participants engaged in articulatory suppression. A key assumption to accept these results is that both the auditory and visual stimuli taxed working memory. Saults and Cowan (2007) argued that performance in some WM studies may be assisted by long-lasting sensory memory for auditory and visual stimuli. *Sensory memory*, which is distinct from WM, refers to the temporary persistence of sensory information after a stimulus has ceased. It is characterized as having an extremely large capacity but a brief duration. Typical estimates of the duration of sensory memory for visual information (iconic memory; 200–300 ms) or auditory information (echoic memory; 1–2 s) are too brief to assist performance in typical WM tasks (Averbach & Coriell, 1961; Broadbent, 1958; Crowder, 1982; Crowder & Morton, 1969; Rostron, 1974; Sperling, 1960). However, Cowan (1988, 1995) argued that there were two phases of sensory storage: an initial transient phase with unlimited capacity, and a capacity-limited phase lasting several seconds. If there is a long-lasting component of sensory memory, it would inflate WM performance for each modality and could conceal central WM costs in dual-task settings because these sensory memories are by definition modality specific. This possibility was addressed in Experiments 5 and 6. In Experiment 5, the retention interval for the VWM task (during which participants were also storing the AWM sample) was increased from 2,000 ms to 9,000 ms such that it would exceed even the longer estimates of sensory memory proposed by Cowan (1988, 1995). Hence, we can be reasonably certain that the two tasks will be competing at the stage of working memory rather than sensory memory.

Method

Eleven young adults (8 women) between the ages of 18 and 27 years (*M* age 20.6 years) participated for course credit or monetary reward. All participants had normal hearing and normal or corrected-to-normal visual acuity. This experiment was similar to Experiment 2 except that the retention duration for the VWM task was increased from 2,000 ms to 9,000 ms. As in Experiment 3 single-task trials were removed and participants performed six blocks of 36 trials for a total of 24 trials per condition.

Results

Dual-task performance at low load. To test whether the tasks exhausted WM capacity, we compared *K* values as a function of task set size during low load. VWM *K* values for intermediate VWM set sizes were higher than for low VWM set sizes, $t(10) = 3.01$, $p = .01$, $d = 0.91$ (Figure 2E, top panel). Likewise, AWM *K* values for intermediate AWM set sizes were marginally higher than for low AWM set sizes, $t(10) = 2.00$, $p = .07$, Cohen's $d = 0.61$ (Figure 2E, bottom panel). A comparison of differences in *K* values between intermediate and high set sizes revealed no differences for both tasks, VWM task, $t(10) = 1.80$, $p = .11$, Cohen's $d = 0.03$; AWM task, $t(10) = 0.86$, $p = .41$, Cohen's $d = 0.26$. This suggests that the task loads used were sufficiently demanding to exhaust capacity.

Effect of load on dual-task performance. *K* values for the VWM task (Figure 2E top panel) were analyzed with a 3 (AWM load) × 3 (VWM set size) within-subjects ANOVA. There was a main effect of VWM set size, $F(2, 20) = 9.03$, $p = .002$, $\eta_p^2 = .75$; no main effect of AWM load, $F(2, 20) = 1.45$, $p = .26$, $\eta_p^2 = .09$; and no interaction, $F(4, 40) = 1.88$, $p = .13$, $\eta_p^2 = .16$. Thus, there is no evidence of AWM load interfering with VWM capacity. *K* values for the AWM task (Figure 2E bottom panel) were analyzed with a 3 (VWM load) × 3 (AWM set size) within-subjects ANOVA. There was a main effect of AWM set size, $F(2, 20) = 9.44$, $p < .005$, $\eta_p^2 = .25$; no main effect of VWM load, $F(2, 20) = 1.17$, $p = .33$, $\eta_p^2 = .06$; and a marginal interaction, $F(4, 40) = 2.22$, $p = .08$, $\eta_p^2 = .18$). This interaction appears to be driven by the unusual *K* pattern across set size in the medium VWM load condition. If this level of load is removed, the interaction between AWM set size and VWM load is not close to significant ($p = .41$). The present data provide no clear evidence that VWM load interferes with AWM capacity.

Experiment 6

With its very long retention interval, Experiment 5 provides evidence against the possibility that the lack of interference between the auditory and visual tasks could be due to participants relying on sensory memory rather than WM to perform the tasks. However, Saults and Cowan (2007) indicated that an effective means of discarding sensory memory contributions to WM tasks is with the use of sensory masks, as the masks will disrupt any echoic or iconic sensory traces of the sample displays. Experiment 6 aimed at determining whether AWM and VWM would still fail to interfere with each other even when sensory masks are introduced after the sample displays. The other utility of Experiment 6 is that it can assess whether the unusual *K* pattern across AWM set size in the medium VWM load condition of Experiment 5 can be replicated in another experiment that rules out sensory memory contributions.

Method

Fifteen young adults (9 women) between the ages of 18 and 26 years (*M* age 20.3 years) participated for course credit or monetary reward. All participants had normal hearing and normal or corrected-to-normal visual acuity.

This experiment was similar to Experiment 3 except that auditory and visual sensory masks were presented during the VWM retention interval to eliminate sensory traces of the auditory and VWM samples. The masks were presented 1,000 ms after the offset of the VWM display. The VWM mask consisted of the presentation of white dots at each potential stimulus location (12 dots on each line) for 1,000 ms. For the AWM mask the 12 possible auditory stimuli were combined into one sound (350 ms) that was played twice (with an interstimulus interval [ISI] of 300 ms) during the 1,000-ms mask interval. A 2,000-ms retention interval separated mask presentation and the presentation of the VWM probe.

Results and Discussion

Dual-task performance at low load. To test whether the tasks used were sufficient to exhaust WM capacity, we compared *K* values as a function of task set size during low load. For the VWM task, *K* values were higher for intermediate than low set sizes, $t(14) = 4.77$, $p < .001$, $d = 1.23$, and higher for intermediate than high set sizes, $t(14) = 3.97$, $p = .001$, $d = 1.03$ (Figure 2F top panel). For the AWM task, surprisingly, *K* values were no higher for the intermediate than low AWM set sizes, $t(14) = 1.28$, $p = .2$, $d = 0.33$, while there was a difference between intermediate and high set sizes, $t(14) = 2.25$, $p = .04$, $d = 0.58$ (Figure 2F bottom panel). Thus, we cannot conclude that the intermediate task load was sufficient to exhaust capacity. However, because this is the same task used in previous studies it is likely that capacity was exhausted by the highest task load because the other studies found that intermediate loads were sufficient to tax performance. Indeed, capacity at Set Size 5 in this study was comparable to Experiments 2 through 5 ($ps > .64$).

Effect of load on dual-task performance. *K* values for the VWM task (Figure 2F top panel) were analyzed with a 3 (AWM load) × 3 (VWM set size) within-subjects ANOVA. There was a main effect of VWM set size, $F(2, 28) = 12.02$, $p < .001$, $\eta_p^2 = .53$; no main effect of AWM load, $F(2, 28) = 1.67$, $p = .21$, $\eta_p^2 = .06$; and no interaction, $F(4, 56) = 1.12$, $p = .36$, $\eta_p^2 = .07$. Thus, there is no evidence of AWM load interfering with VWM capacity. *K* values for the AWM task (Figure 2F bottom panel) were analyzed with a 3 (VWM load) × 3 (AWM set size) within-subjects ANOVA. There was a main effect of AWM set size, $F(2, 28) = 12.41$, $p < .001$, $\eta_p^2 = .49$; no main effect of VWM load, $F(2, 28) = 0.67$, $p = .67$, $\eta_p^2 = .02$; and no interaction, $F(4, 56) = 1.24$, $p = .30$, $\eta_p^2 = .08$ (the unusual *K* pattern in Experiment 5 was not observed here). Thus, the data also provide no evidence that VWM load interferes with AWM capacity.

Experiments 5 and 6 tested the possibility that the lack of interference between AWM and VWM task was due to the use of sensory memory. In Experiment 5, the retention interval was increased to be longer than the most generous estimates of the duration of sensory memory. In Experiment 6, sensory masks were presented to disrupt information from the sample stored in sensory buffers. Neither study found evidence for interference between AWM and VWM. Thus, the lack of interference between the two tasks cannot be explained by a role of sensory memory.

Experiment 7

In Experiments 1 through 6 the experimental conditions were intermixed within blocks. It is conceivable that under such conditions, participants cannot dynamically adjust their task settings on a trial-by-trial basis, instead adopting a worst-case scenario setting (e.g., preparing for five visual items and five auditory items) for all trials. As a result, performance in the single-task trials may be underestimated as participants were a priori allocating their resources to both tasks. Underestimation of single-task performance (or of performance at low dual-task load) could in turn "mask" dual-task costs (at high loads) to which they are compared. It is therefore possible that a domain-general storage system exists, but that this system may be divided among audition and vision in an inflexible manner when single- and dual-task trials are intermixed.

To test this "cognitive inflexibility" hypothesis we separated each load condition (e.g., five visual items and one auditory item) into distinct blocks of trials. Under such experimental conditions, the cognitive inflexibility hypothesis predicts that dual-task costs relative to single-task performance will emerge as participants can now adopt the optimal task setting for each blocked condition (such as allocating all resources to the single-task). More important, participants were informed, before each block, of the number of items they were required to remember for each task.

An additional goal of Experiment 7 was to determine whether the lack of dual-task costs in the previous experiments was specific to the task order employed. In all previous experiments, the auditory stimuli were presented first, followed by the visual stimuli. In Experiment 7 we reversed the order of the two tasks. If no dual-task costs are observed under this condition, this would suggest that task order plays no role in eliminating the costs between the two tasks.

Method

Twelve young adults (6 women) between the ages of 18 and 30 years (*M* age 21.75 years) participated for course credit or monetary reward. All participants had normal hearing and normal or corrected-to-normal visual acuity.

This experiment was similar to Experiment 3 but with two major changes.

Task order. The order of the two tasks was switched. The trial began with presentation of the VWM display (800 ms) followed by a 1,500 ms ISI, followed by presentation of the AWM task, which ranged in duration between 500 ms (Set Size 1) and 2,500 ms (Set Size 5). Stimulus presentation was followed by a retention interval that lasted between 1,500 ms (Set Size 5) and 3,500 ms (Set Size 1) before the AWM probe. The variable retention interval length meant that 4,000 ms separated the onset of the AWM stimuli and the AWM probe regardless of AWM set size. The AWM was presented for 3,000 ms and was followed by the VWM probe (also presented for 3,000 ms).

Blocked conditions. We presented conditions in separate blocks, rather than intermixed within blocks. There were nine types of dual-task blocks (formed by crossing the three levels of load for each task) and six single-task blocks (three for each task). Each block type occurred twice for a total of 30 blocks of eight trials each. To minimize confusion between single- and dual-task blocks, the two block types were not intermixed. The first and last blocks of the experiment were single-task blocks. The middle 18 blocks were the dual-task blocks chosen in a random order. We found no performance differences between single-task blocks presented at the beginning or end of the study ($p > .6$), suggesting that block order did not strongly influence the data. Before the start of each block, a screen was presented telling the participants the number of auditory and spatial items that would be presented in all trials of that block. This screen remained until the participant pressed the spacebar.

Results and Discussion

Single-task performance. Single-task *K* values (Figure 4A) for intermediate set sizes were higher than for low set sizes in both conditions, VWM task, $t(11) = 7.55$, $p < .001$, Cohen's $d = 2.18$; AWM task, $t(11) = 7.84$, $p < .001$, Cohen's $d = 2.26$ (Figure 2B).

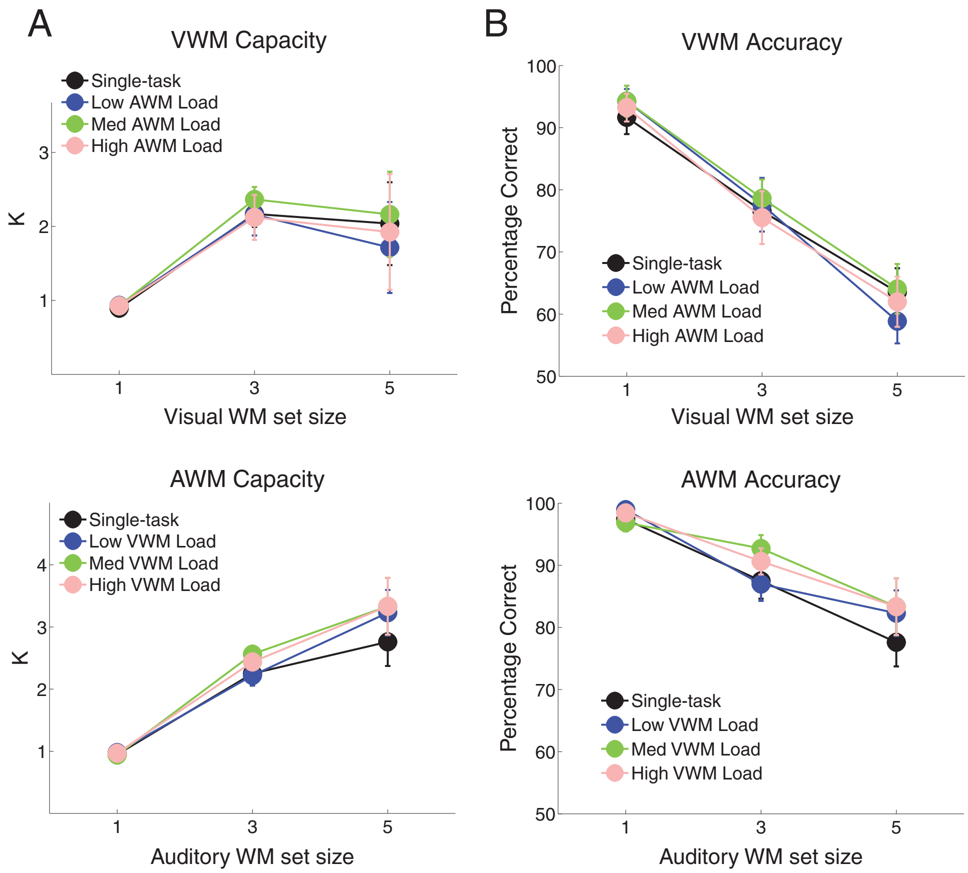

Figure 4. A: Capacity measures (*K*) for the visuospatial working memory (VWM; above) and auditory working memory (AWM; below) for Experiment 7 as a function of task set size and secondary task load. B: Percentage correct for the VWM (above) and AWM (below) tasks for Experiment 7 as a function of task set size and secondary task load. Error bars represent between-subject standard error of the mean. WM = working memory. See the online article for the color version of this figure.

However, there were no differences in *K* values between intermediate and high set sizes, VWM task, $t(11) = -0.22$, $p = .83$, Cohen's $d = 0.07$; AWM task, $t(15) = 1.45$, $p = .17$, Cohen's $d = 0.42$. This suggests that the task loads used were sufficiently demanding to exhaust single-task capacity.

Effect of load on dual-task performance. *K* values for the VWM task (Figure 4B top panel) were analyzed with a 4 (AWM load) × 3 (VWM set size) within-subjects ANOVA. There was a main effect of VWM set size, $F(2, 22) = 8.51$, $p < .005$, $\eta_p^2 = .34$; no main effect of AWM load, $F(3, 33) = 0.22$, $p = .89$, $\eta_p^2 = .01$; and no interaction, $F(6, 66) = 0.1$, $p = 1.0$, $\eta_p^2 = .01$. Thus, there is no evidence of AWM load interfering with VWM capacity. *K* values for the AWM task (Figure 4B bottom panel) were analyzed with a 4 (VWM load) × 3 (AWM set size) within-subjects ANOVA. There was a main effect of AWM set size, $F(2, 22) = 59.88$, $p < .001$, $\eta_p^2 = .12$; a main effect of VWM load, $F(3, 33) = 3.37$, $p = .03$, $\eta_p^2 = .11$; but no significant interaction, $F(6, 66) = 1.40$, $p = .23$, $\eta_p^2 = .12$. The main effect of VWM load appears to be driven by performance in the single-task conditions. When single-task blocks are removed a main effect of VWM load is no longer observed, $F(2, 22) = 1.02$, $p = .38$, $\eta_p^2 = .03$. Note that the effect of VWM load mediated by the single-task condition is opposite to what is predicted by a common storage system; as such a system would have predicted increased AWM capacity under single-task relative to dual-task conditions. As such, the present data provide no clear evidence that VWM load interferes with AWM capacity.

The results of Experiment 7 rule out two important concerns about our previous findings. First, they rule out the possibility that the lack of dual-task costs is tied to a specific task order, as dual-task costs were also absent when the presentation order of the AWM and VWM tasks was switched. Second, they rule out the concern that single-task and low load dual-task performance were underestimated because participants adopted a default high load dual-task set in which the storage resources are split across modalities instead of pooled in one modality under single-task conditions. Were this to be the case, single-task (or low load dual-task) performance should have been greater than (high load) dual-task performance when conditions were presented in separate blocks of trials, as participants are now free to optimize the domain-general store for each condition. Contrary to this expectation, blocking the trial conditions led to the same results as those obtained with intermixed trial conditions. Thus, a lack of dual-task costs in our experiments is not explained by cognitive inflexibility.

It is worth noting that task performance in this and our previous experiments are often low, even in single-task conditions, relative to previous studies (e.g., Fougnie & Marois, 2006; Saults & Cowan, 2007). It is likely a result of task difficulty. The visuospatial WM task required participants to discriminate spatial positions from adjacent foil locations, whereas the auditory WM task required participants to discriminate birdcalls or synthesized sounds from a set of items with high similarity. The level of precision demanded by these tasks may require more memory resources per stored item (Alvarez & Cavanagh, 2004) or may involve performance limitations stemming from imprecise memories (Bays & Husain, 2008; Wilken & Ma, 2004; Zhang & Luck, 2008). Consistent with these suggestions, WM performance for one item was below ceiling for most participants. More important, however, these demands were consistent across experimental conditions and cannot explain the lack of dual-task costs.

Pooling the Data Across the Seven Studies

In six studies we found no evidence of dual-task costs between AWM and VWM. May these studies have lacked the power to detect small but significant interference between tasks? To provide the most sensitive test for interference, we pooled the results of the 100 participants in Experiments 1 through 7 and examined the effect of secondary task load on task performance. Because Experiments 3 through 6 did not include single-task trials, single-task conditions were not included. In addition, although average accuracy for low, medium, and high set size conditions was relatively equivalent across conditions, *K* values, which scale with set size, can vary considerably. For example, in Experiment 1 the AWM set sizes of two, six, and 10 were twice those of other studies, and the *K* values were considerably higher. Hence, we restricted the pooled analyses to measures of accuracy.

VWM accuracy of the pooled data (Figure 5, left) was analyzed with a 3 (AWM load) × 3 (VWM set size) between-subjects ANOVA. There was a main effect of VWM set size, $F(2, 198) = 496.72$, $p < .001$, $\eta_p^2 = .81$; no main effect of AWM load, $F(2, 198) = 1.06$, $p = .35$, $\eta_p^2 = .01$; and no interaction, $F(4, 396) = 0.78$, $p = .54$, $\eta_p^2 = .01$. Thus, pooling across all studies, there is still no evidence of AWM load interfering with VWM capacity. AWM accuracy (Figure 4, right) was analyzed with a 3 (VWM load) × 3 (AWM set size) between-subjects ANOVA. There was a main effect of AWM set size, $F(2, 198) = 207.29$, $p < .001$, $\eta_p^2 = .69$; and no main effect of VWM load, $F(2, 198) = 0.99$, $p = .37$, $\eta_p^2 = .00$. There was a significant interaction between AWM set size and VWM load, $F(4, 396) = 2.89$, $p = .02$, $\eta_p^2 = .03$. Exploration of this interaction revealed that it was driven by small differences at the lowest set size. We performed linear contrasts to examine the effect of load at each set size level and found a significant effect of load at the lowest set size, $t(99) = 3.53$, $p < .001$, but not for the larger set sizes (ts < 1, ps $> .33$) where interference would have been expected to be maximal. Therefore, as with VWM performance, pooling across all six studies provided little evidence of VWM load interfering with AWM capacity.

Bayesian tests for accepting or rejecting the null hypothesis. None of the six studies we conducted, nor the pooled data from those experiments, revealed convincing evidence of competition between auditory and spatial WM loads. These results are difficult to reconcile with the existence of a domain-independent WM store (Baddeley, 2000; Cowan, 1995, 2001, 2006; Fougnie & Marois, 2006; Saults & Cowan, 2007). However, the evidence against such a store is a failure to reject the null hypothesis that auditory and spatial loads do not interfere. Traditional statistical tests using *t* tests and *F* tests do not allow for the statement of evidence for the null hypothesis. Fortunately, an alternative statistical test has been developed using Bayes factor analysis that allows one to state a preference for the null hypothesis or for the alternative (Rouder, Speckman, Sun, Morey, Iverson, 2009). However, use of the Bayes factor is not straightforward in a factorial design. To provide the strongest case for the alternative hypothesis (i.e., that secondary task load affects primary task performance), we consider whether there is an effect of load (comparing low and high load) on performance at the highest set size. The *t* value for the effect of VWM load on AWM performance ($t = .75$) corresponds to a Bayes Factor of 9.50, suggesting that the null hypothesis was nearly 10 times more probable than the alternative

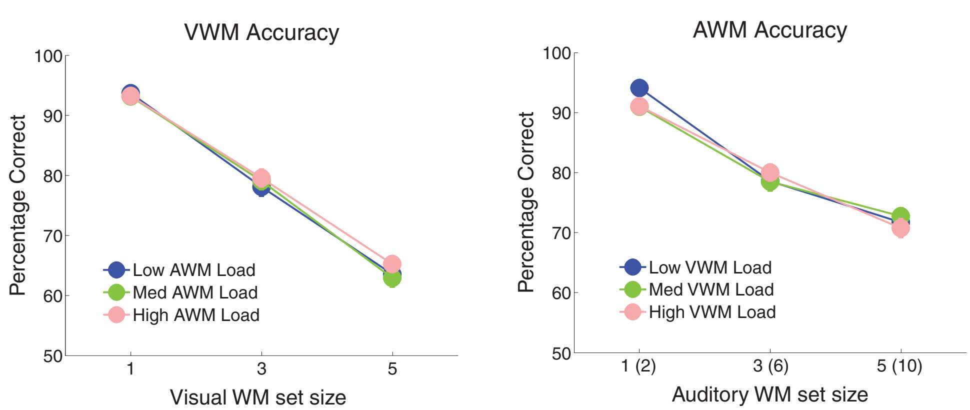

Figure 5. Task accuracy for the visuospatial working memory (VWM; left) and auditory working memory (AWM; right) tasks pooled across Experiments 1 through 7 ($n = 100$). Auditory set sizes for Experiment 1 were two, six, and 10, and are in parenthesis for the x-axis of the right panel. The between-subject error bars are not visible for many of the data points because they do not extend beyond the markers. WM = working memory. See the online article for the color version of this figure.

hypothesis. Likewise, the *t* value for the effect of AWM load on VWM performance ($t = -1.10$) corresponds to a Bayes factor of 6.98. Similar results are found if all set sizes are included, or if only intermediate and high set sizes are included. Overall, these findings provide strong support for the null hypothesis.

Experiment 8

Our results so far provide evidence against domain-independent stores of working memory as virtually no interference was observed when the representational contents (i.e., spatial or object form) of the two tasks were distinct. Do our methods allow us to detect dual-task costs when we would expect interference? We predicted that when the contents of working memory do overlap in representational format, interference among the two tasks would emerge. We tested this hypothesis in Experiment 8 by having participants perform two WM tasks that overlapped in spatial representation.

Method

Twenty-one young adults (12 women) between the ages of 18 and 34 years (*M* age 23.3 years) participated for course credit or monetary reward. All participants had normal hearing and normal or corrected-to-normal visual acuity. Participants performed between four and six runs of 36 trials.

This experiment only included dual-task (AWM and VWM) trials. As in Experiments 1 through 6, the AWM task was presented first and responded to second, with the VWM task sandwiched in the middle (see Figure 6).

We used Cowan's *K* instead of "reverse Pashler *K*" to estimate capacity in the AWM task because the AWM probe was to be compared with a specific probe item.

VWM task. Participants viewed a serial presentation of one, three, or five colored circles (2° of visual angle) presented at 5° of eccentricity to either the left or right side of a fixation dot. If the set

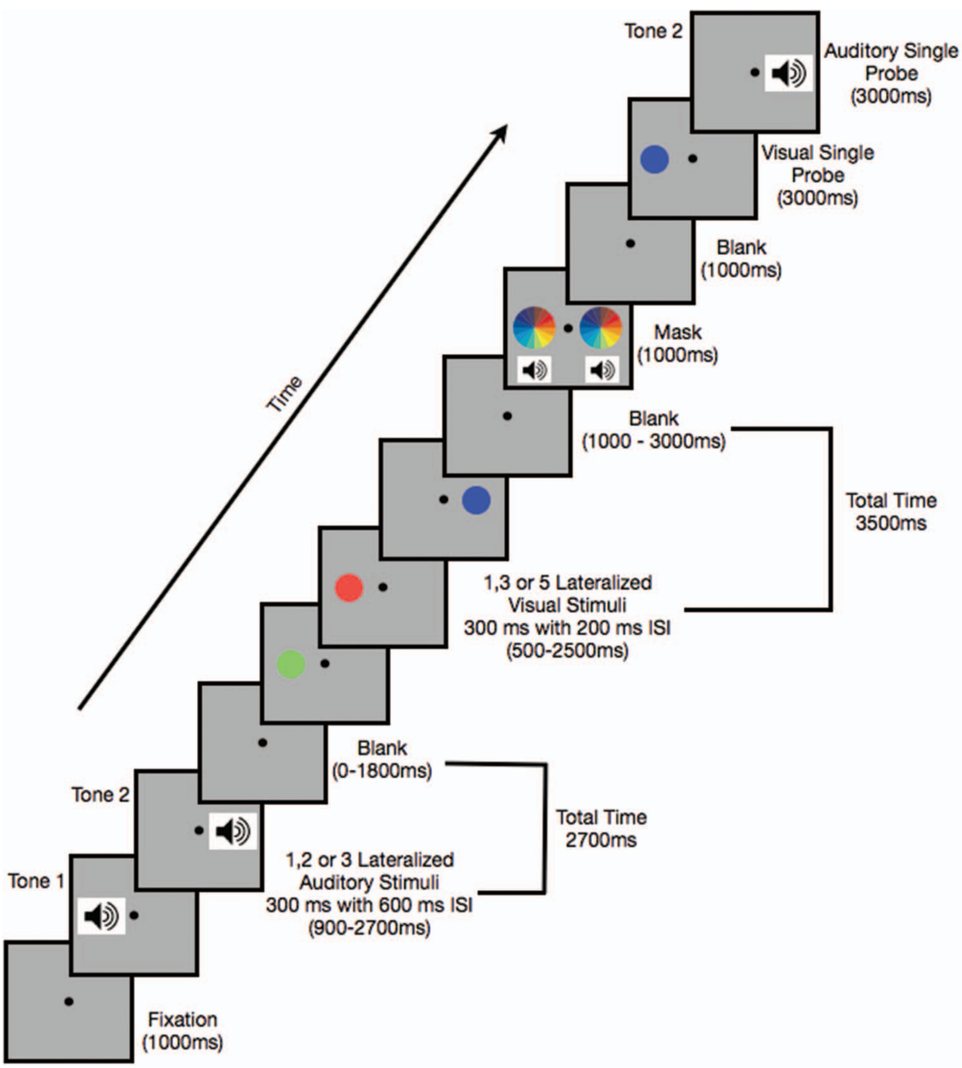

Figure 6. Trial outline for Experiment 8. Participants performed an auditory working memory and visuospatial working memory task on each trial. Each task required memory of both object identity and spatial location. ISI = interstimulus interval. See the online article for the color version of this figure.

size was greater than one, at least one circle appeared on each side. Each circle was presented for 300 ms with a 200-ms ISI. To equate for total retention time across set sizes the interval between the offset of the last stimulus and a subsequent mask ranged from 1,000 ms (Set Size 5) to 3,000 ms (Set Size 1), for a total duration of 3,500 ms. Each circle was assigned one of 11 equiluminant colors, without replacement, evenly distributed along a circle in the CIE $L^*a^*b^*$ color space (centered at L = 54, a = 18, b = −8, with a radius of 59°). Participants were instructed to remember both the colors and locations (which side of fixation) of the items that appeared in the stream while maintaining fixation. One second after the visual presentation, a visual mask consisting of two circular, colored pinwheels (all 11 possible colors; 5° of visual angle) appeared on the left and right sides lasting 1,000 ms. One second after the offset of the visual mask, a colored, circular probe (2° of visual angle) appeared on the left or right side of the display. Participants reported via key press whether the probe's color and location matched any of the circles from the remembered sample. The visual probe could either match both the color and location of one of the previous remembered colors (match; 50% probability), match only the color of a sample item but not its position by presenting it on the opposite side (location nonmatch; 25% probability), or match the location but not the color of one of the items (color nonmatch; 25% probability). This last trial type was intended to prevent participants from only attending to the spatial location in Set Size 1 trials. The visual probe was displayed for 3,000 ms and participants were required to respond during this time window.

AWM task. In line with the VWM task, the auditory working memory task consisted of one, two, or three auditory items (bird calls) presented sequentially to the left or right ear. If the set size was greater than one, at least one tone was played in each ear. Each tone lasted 300 ms with a 600-ms ISI and was chosen from one of 11 bird calls (without replacement). To equate for total retention time across set sizes the interval between the offset of the last stimulus and the start of the VWM task ranged from 0 ms (Set Size 3) to 1,800 ms (Set Size 1), for a total duration of 2,700 ms between the onset of the first tone and the VWM sample. The auditory mask began at the same time as the visual mask and was identical to the one used in Experiment 6 (except created from 11 rather than 12 sounds). The auditory probe was initiated 3,000 ms after the onset of the visual probe. This probe was a single tone played in the left or right ear. The probe could be one of the tones played during the auditory sample and in the same ear (match; 50% probability), in the opposite ear (location nonmatch; 25% probability) or a new tone (identity nonmatch; 25% probability). Participants had 3,000 ms to respond to the auditory probe.

Results and Discussion

Dual-task performance at low load. *K* values (Figure 7B) for intermediate set sizes were higher than for low set sizes in both conditions, AWM task, $t(20) = 2.26$, $p = .04$, $d = 0.49$; VWM task, $t(20) = 5.05$, $p < .001$, $d = 1.1$. Neither task showed significant difference in *K* values between intermediate and high set sizes, AWM task, $t(20) = 0.42$, $p = .68$, $d = 0.09$; VWM task, $t(20) = 1.57$, $p = .13$, $d = 0.34$. This suggests the task loads used were sufficient in exhausting capacity.

Effect of load on dual-task performance. Capacities for both tasks were analyzed using a 3 (set size) × 3 (load) within-subjects ANOVA. For the VWM task, there was a main effect of visual set size, $F(2, 40) = 8.44$, $p < .001$, $\eta_p^2 = .26$; no main effect of auditory load, $F(2, 40) = 0.20$, $p = .82$, $\eta_p^2 = .01$; and no interaction, $F(4, 80) = 1.50$, $p = .21$, $\eta_p^2 = .07$. For the AWM task, there was a main effect of visual load on auditory capacity, $F(2, 40) = 14.02$, $p < .001$, $\eta_p^2 = .28$; no main effect of auditory set size,[4] $F(2, 40) = 0.71$, $p = .50$, $\eta_p^2 = .03$; and a marginal interaction $F(4, 80) = 2.10$, $p = .09$, $\eta_p^2 = .09$. In addition, to show that the changes to the task resulted in greater load effects relative to previous studies, we conducted an ANOVA with AWM capacity to compare the load effect found in the first seven experiments (pooled data) to Experiment 8. We found a greater effect of load in Experiment 8 relative to previous studies (interaction between load and experiment type), $F(7, 833) = 23.01$, $p < .001$.

Thus, Experiment 8, unlike all previous experiments, revealed clear evidence for interference between two working memory tasks, suggesting that interference can arise across tasks under certain conditions. Because the main change between this experiment and the previous ones was that both tasks required memory for object properties at specific spatial locations, this is likely to be the source of interference observed in Experiment 8. We find it interesting that the interference only affected AWM capacity and not VWM capacity. Participants preferring one task to the other and therefore expending more effort/resources on the VWM task likely explain this asymmetry.

These results are noteworthy not only because they support the hypothesis that two WM tasks interference with one another when they overlap in representational content, but also because they suggest that our methods had enough sensitivity to detect interference between two tasks in the previous experiments had there been any.

General Discussion

Working memory is of central importance to our daily lives and yet we can only hold in mind a very limited amount of information. A considerable amount of research has explored the nature and cause of this limit in working memory storage. Of particular interest is the degree to which we have multiple stores for different types of information (such as auditory or visual information; i.e., domain specific) or the degree to which storage is mediated by a single process that operates on information regardless of its content (domain general). Studies employing a dual-task method have largely found evidence for both domain-specific and domain-general sources. When auditory and visual information are required to be maintained concurrently, the costs are much less than if two sets of objects from the same modality are to be stored (Cocchini et al., 2002; Fougnie & Marois, 2006, 2011; Morey & Cowan, 2004, 2005; Scarborough, 1972). However, these studies also found that combining high auditory and visual loads has a cost, even if that cost is less than you would expect from a purely domain-general viewpoint. These findings have led to the view that working memory is constrained both by domain-general and domain-specific sources (e.g., Baddeley 2000; Cocchini et al., 2002; Fougnie & Marois, 2006).

[4] The lack of a set size effect reflects the fact that *K* measures were near ceiling with one item. Auditory performance was strongly affected by the number of auditory items to remember. If we perform the ANOVA using percentage correct rather than *K* values we find strong effects of both AWM set size ($F = 67.45$) and VWM load ($F = 18.20$). This is the only result in all eight experiments in which the qualitative result differs if using percentage correct rather than *K* as the dependent measure.

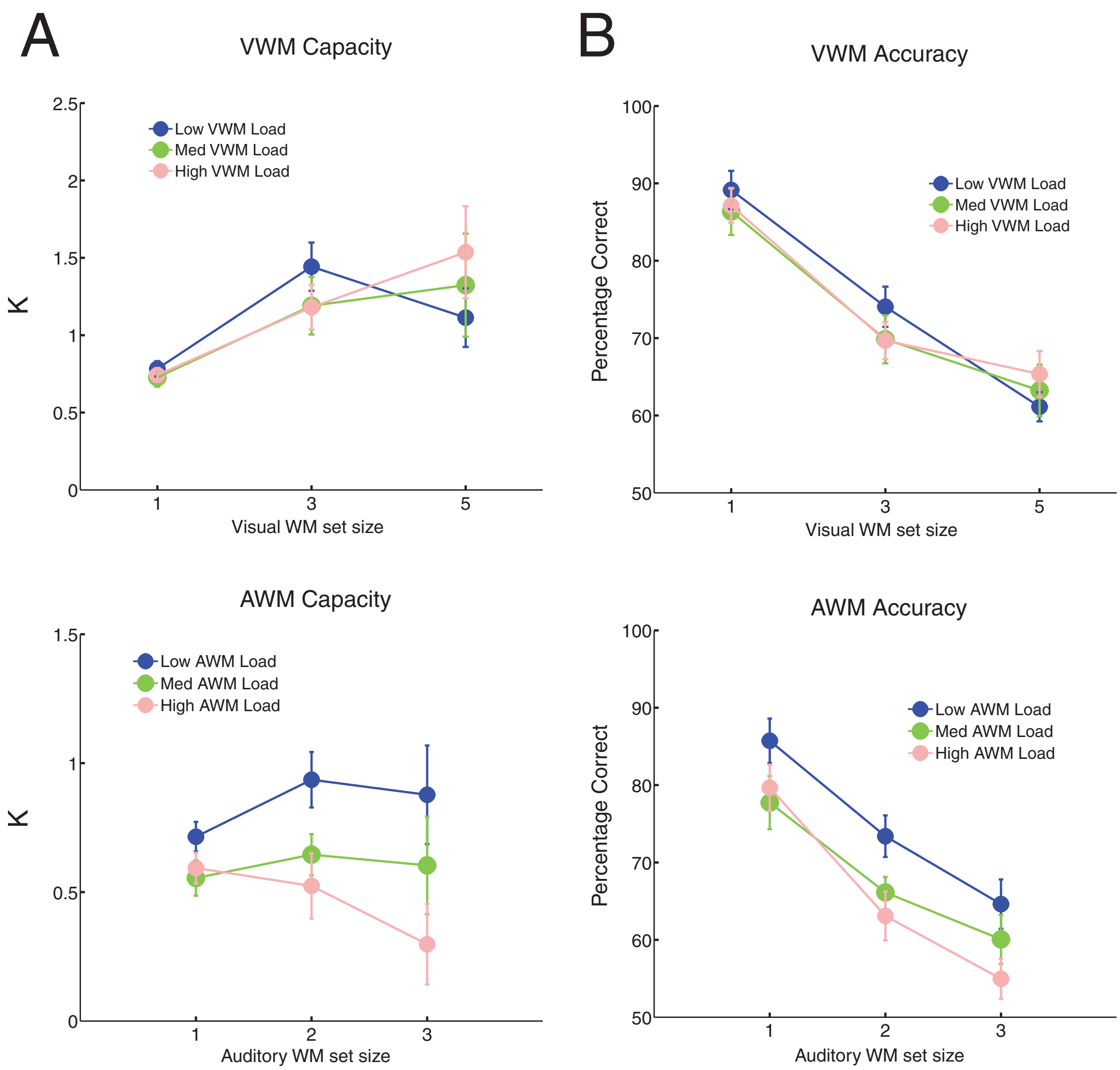

Figure 7. A: Capacity measures (*K*) for the visuospatial working memory (VWM; above) and auditory working memory (AWM; below) for Experiment 8 as a function of task set size and secondary task load. B: Percentage correct for the VWM (above) and AWM (below) tasks for Experiment 8 as a function of task set size and secondary task load. Error bars represent between-subject standard error of the mean. WM = working memory. See the online article for the color version of this figure.

It is possible, however, that the costs between auditory and visual information in previous dual-task studies may have arisen for reasons other than competition for a domain-general store, such as an inability to effectively coordinate two tasks (Cocchini et al., 2002), the requirement to maintain bound feature representations in WM (Fougnie & Marois, 2011), or an overlap in the representational content between the two stimulus displays (Postle et al., 2005). The goal of the current study was to measure the amount of costs with a dual-task WM paradigm in which these alternate sources of costs were minimized.

To reduce the possibility of interference in representational codes between tasks, we used a VWM task that required participants to encode and store visuospatial locations unbound with any other featural information, and an auditory task that was devoid of spatial information. Secondary verbal and semantic tasks have been shown to interfere less with spatial VWM than object VWM (Postle et al., 2005). In addition, neuroimaging studies have shown separate neural correlates for object and spatial object properties (Smith et al., 1995; Tresch et al., 1993; Ungerleider et al., 1998; Ventre-Dominey et al., 2005). Therefore, a strong test of a domain-independent WM store is to require concurrent maintenance of visuospatial location and auditory object identity. To ensure that participants were not chunking several visual dots into a higher order structure (such as an object shape), the shape formed by the dots was invariant across trials, and therefore uninformative. In addition, to prevent knowledge of the general layout of the VWM display from assisting task performance, sample dot positions had open adjacent spots that could be occupied by a probe in "different" response trials. Thus, performance of the task required encoding a detailed representation of the display and discouraged simply encoding the visuospatial gist of that display. In addition, dual-task presentation was designed to minimize differences in task preparation or executive load across conditions. A potential source of executive load is the attentional control required to react to an unpredictable task order (De Jong & Sweet, 1994). Therefore, in the current studies, the task order was consistent in all trials. To further eliminate differences in executive load across conditions, the single-task conditions were not included in Experiments 3 through 7. Finally, to ensure that all trials included sensory information and motor responses, dummy sample and probe displays replaced the nonrelevant task in single-task trials in Experiments 1 and 2.

In the first seven studies reported here we found no evidence that auditory and visuospatial stimuli compete for shared WM storage capacity. Indeed, the pooled results (see Figure 5) show virtually identical WM performance regardless of secondary task load. This occurred even when the task loads were greater than what could be held in working memory. Therefore, we did not find evidence of a domain-general source even when domain-specific sources of WM were overloaded. Furthermore, the lack of dual-task costs occurred under a variety of experimental conditions, demonstrating its resilience to slight changes in methodology. More important, when we introduced a common representational format (location information) to both tasks in Experiment 8, dual-task interference now surfaced, suggesting that our analytical approach had the sensitivity to detect dual-task costs in the previous experiments had there been some.

The present results diverge from previous dual-task WM studies reporting cross-modal costs at high load (Cocchini et al., 2002; Fougnie & Marois, 2006; Saults & Cowan, 2007; Scarborough, 1972). Our efforts to minimize sources of dual-task interference not attributable to a domain-independent store likely account for this discrepancy, as none of the previous studies simultaneously controlled for all potential sources of interference such as task preparation and coordination, overlap in representational format (e.g., space-based), and use of cognitive strategies (e.g., verbalization or higher order chunking). In particular, the dual-task conditions in Saults and Cowan (2007) and Scarborough (1972) added increased preparation costs relative to single-task conditions (e.g., increased uncertainty in the type of probe stimulus), the visual and auditory tasks of Fougnie and Marois (2006) both required maintaining spatial information, and the visuospatial stimuli in Cocchini et al. (2002) contained higher order structure that may have been encoded in an object and/or verbal format that competed with the verbal task information.

Our results support the idea that we have separate WM stores for auditory and visual stimuli (Baddeley, 1986; Baddeley & Logie, 1999). At the same time, these results also suggest that the absence of interference between auditory and visual WM may only occur under fairly specific experimental conditions, and may not usually occur for the type of objects we interact with in our everyday lives. Perfect sharing between auditory and visual stimuli may be the exception, rather than the rule. However, knowing how to minimize interference between two tasks has practical implications for ergonomic design. In addition, the fact that costs can be completely eliminated under certain conditions has important theoretical implications about the nature of working memory capacity. In particular, the results are problematic for theories that posit a storage system or process that operates regardless of content. If a domain-general store played a significant role in constraining memory, than loading this store with twice as many stimuli under dual visual and auditory WM conditions should have lead to performance costs. It is, of course, not possible to completely rule out the potential existence of a domain-general store. However, our results indicate that were such store to exist, its capacity would either be so small as to go undetected in the current study even under conditions in which domain-specific sources were overloaded, or that it is not accessible or strategically adaptable to certain experimental conditions. Thus, at the very least, the present findings challenge the scope and importance of a domain-general store and strongly constrain its potential role in working memory capacity.

We propose, however, that it may no longer be fruitful to conceive of working memory capacity as controlled by either a set of independent memory stores or a single domain-general store. Moving beyond the dichotomous nature of the domain-specific versus domain-general debate, we suggest that the amount of interference between two sets of objects may scale with the amount of representational overlap between the two sets (similar to the idea of functional distance in dual-task interference, Kinsbourne & Hicks, 1978). Given the richness of our representational systems, it seems likely that the interference between sets of items in memory is determined by more than the perceptual modality of the stimuli, and that multiple levels of representation interact in determining the amount of overlap (Wood, 2009, 2011). For example, aside from perceptual modality, another important representational format may correspond to spatial versus nonspatial attributes). Neuroimaging studies have shown distinct neural correlates for object and spatial properties (Smith et al., 1995; Tresch et al., 1993; Ungerleider et al., 1998; Ventre-Dominey et al., 2005), suggesting that a combination of spatial and nonspatial attributes may be necessary to minimize overlap in WM capacity.

In conclusion, our finding that auditory and spatial WM loads can be performed in parallel is surprising. This study began under the assumption that there was a domain-independent source of WM capacity and that the neural correlates of this store could be identified using fMRI. However, the evidence from eight behavioral experiments leads us to reject this hypothesis. When a dual-task is designed to minimize sources of interference not due to domain-independent storage, auditory and spatial arrays can be concurrently held in WM with no discernible interference.

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