Research Article

Distinct Capacity Limits for Attention and Working Memory

Evidence From Attentive Tracking and Visual Working Memory Paradigms

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ABSTRACT—*A hallmark of both visual attention and working memory is their severe capacity limit: People can attentively track only about four objects in a multiple object tracking (MOT) task and can hold only up to four objects in visual working memory (VWM). It has been proposed that attention underlies the capacity limit of VWM. We tested this hypothesis by determining the effect of varying the load of a MOT task performed during the retention interval of a VWM task and comparing the resulting dual-task costs with those observed when a VWM task was performed concurrently with another VWM task or with a verbal working memory task. Instead of supporting the view that the capacity limit of VWM is solely attention based, the results indicate that VWM capacity is set by the interaction of visuospatial attentional, central amodal, and local task-specific sources of processing.*

A key characteristic shared by both visual attention and working memory is their severe capacity limit. The amount of visual information that can be actively held in visual working memory (VWM) is limited to about four objects (Irwin & Gordon, 1998; Pashler, 1988; Sperling, 1960; Vogel, Woodman, & Luck, 2001). Attention is similarly constrained: People's ability to attentively track a number of randomly moving objects among like distractors is limited to four or five items (Cavanagh & Alvarez, 2005; Culham, Cavanagh, & Kanwisher, 2001; Oksama & Hyönä, 2004; Pylyshyn & Storm, 1988; Scholl, 2001; Sears & Pylyshyn, 2000).

The similarity in the number of objects that can be held in mind and attentively tracked has led researchers to suggest that these two abilities rely on a common capacity-limited process (e.g., Cowan, 1998, 2001). Studies consistent with this proposal have demonstrated that visuospatial attention and VWM can interfere with each other (Awh, Jonides, & Reuter-Lorenz, 1998; Oh & Kim, 2004; Woodman & Luck, 2004). Because visuospatial working memory depends on an attention-based rehearsal mechanism (Awh et al., 1998), the shared process may be none other than attention. Indeed, it has been proposed that attention is the capacity-limited process that constrains VWM capacity (Cowan, 2001; Rensink, 2000a, 2000b, 2002). However, the fact that attention and working memory interact need not imply that the capacity limit of VWM is reducible to that of attention. The capacity limit of VWM may result from content-specific stages of information processing rather than from a monolithic attentional capacity (Luck & Vecera, 2002), or it may be a product of the interaction between capacity-limited attentional processes and the independent capacity of distinct feature stores (Delvenne & Bruyer, 2004; Wheeler & Treisman, 2002).

In the present dual-task study, we tested the hypothesis that attention underlies the capacity limit of VWM. The basic experimental design consisted of inserting an attention-demanding multiple object tracking (MOT) task during the maintenance period of a VWM task (Fig. 1) and assessing the effect of varying the load of the attention task. If VWM capacity is constrained solely by attention, then not only should increasing attentional load decrease VWM performance, but it should do so to the same extent as a second concurrently executed working memory task would.

EXPERIMENT 1

The first experiment assessed whether a VWM change-detection task (Todd & Marois, 2004; Vogel et al., 2001) and a MOT task (Pylyshyn & Storm, 1988) interfere with each other in a load-dependent manner when they are executed concurrently.

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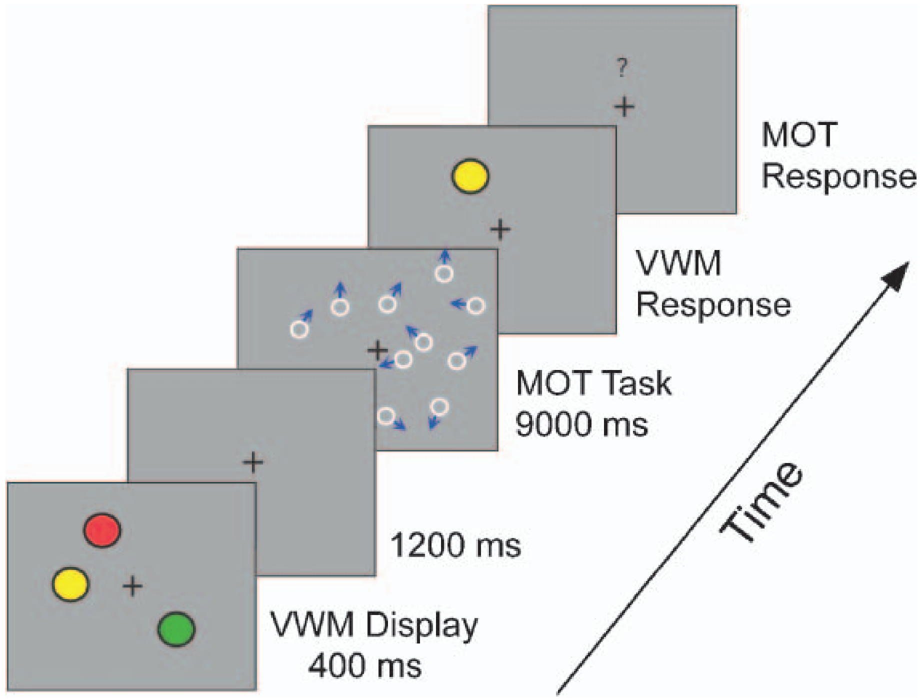

Fig. 1. Trial design for the dual-task condition of Experiment 1, which involved a visual working memory (VWM) task and a multiple object tracking (MOT) task. In the VWM task, participants memorized the colors and locations of three briefly presented circles. During the MOT task, participants tracked a subset of randomly moving discs (either one or three). Participants then responded to the VWM task (indicating whether a VWM probe item matched the color and location of a circle in the original VWM display) and the MOT task (indicating whether the item selected during the probe phase of the tracking task was a MOT target). See the text for details.

Method

Twenty-three undergraduate students at Vanderbilt University participated for course credit or monetary reward.

VWM Task

On each trial of the VWM task, three colored circles (each 0.78°) were presented for 400 ms, with each circle located in one of six possible locations along an imaginary ring (3.3° radius from fixation). The colors of the circles were selected from a pool of 11 colors (light blue, dark green, red, black, white, light green, brown, pink, blue, yellow, and purple). Participants memorized both the color and the location of each circle. After a retention period of 10.2 s, a probe display containing one colored circle from the sample display was shown. On half of the trials, this circle was at the same location as in the sample display, and on the other half of the trials, it was at the location previously occupied by one of the other two circles. Participants indicated by button press whether the colored circle was in the correct location. The probe display remained present until response collection.

MOT Task

A MOT movie selected out of a pool of 40 was shown during the retention interval of each VWM trial, beginning 1.2 s after the offset of the VWM sample display. MOT stimuli were hollow white discs (0.50°) that moved around within an 8.5° × 8.5° area centered at fixation. The speed of each disc varied from 0.00215°/ms to 0.0195°/ms, and the disc's direction of movement had a 10% chance of changing at every refresh (13.3 ms). The discs bounced off the boundaries of the MOT display, other MOT discs, and the six possible locations of the VWM stimuli.

Each 9-s MOT movie had three phases: marker, tracking, and probe phases, lasting 3, 4.5, and 1.5 s, respectively. During the *marker* phase, target discs were surrounded by hollow black squares (0.50°). Half of the trials contained one target (low load), and the other half contained three targets (high load). During the *tracking* phase, the markers disappeared, rendering the targets indistinguishable from other discs. During the *probe* phase, a single disc was marked, with 50% probability that this disc corresponded to a target. Following the VWM response, a question mark appeared above fixation, notifying participants to indicate by button press whether the MOT probe item corresponded to a target.

Articulatory Suppression Task

To minimize contamination with verbal working memory (verbal WM), we instructed participants to perform an articulatory suppression task by repeating the word *the* at a 2-Hz rate, starting 1 s prior to the VWM stimulus display and ending after

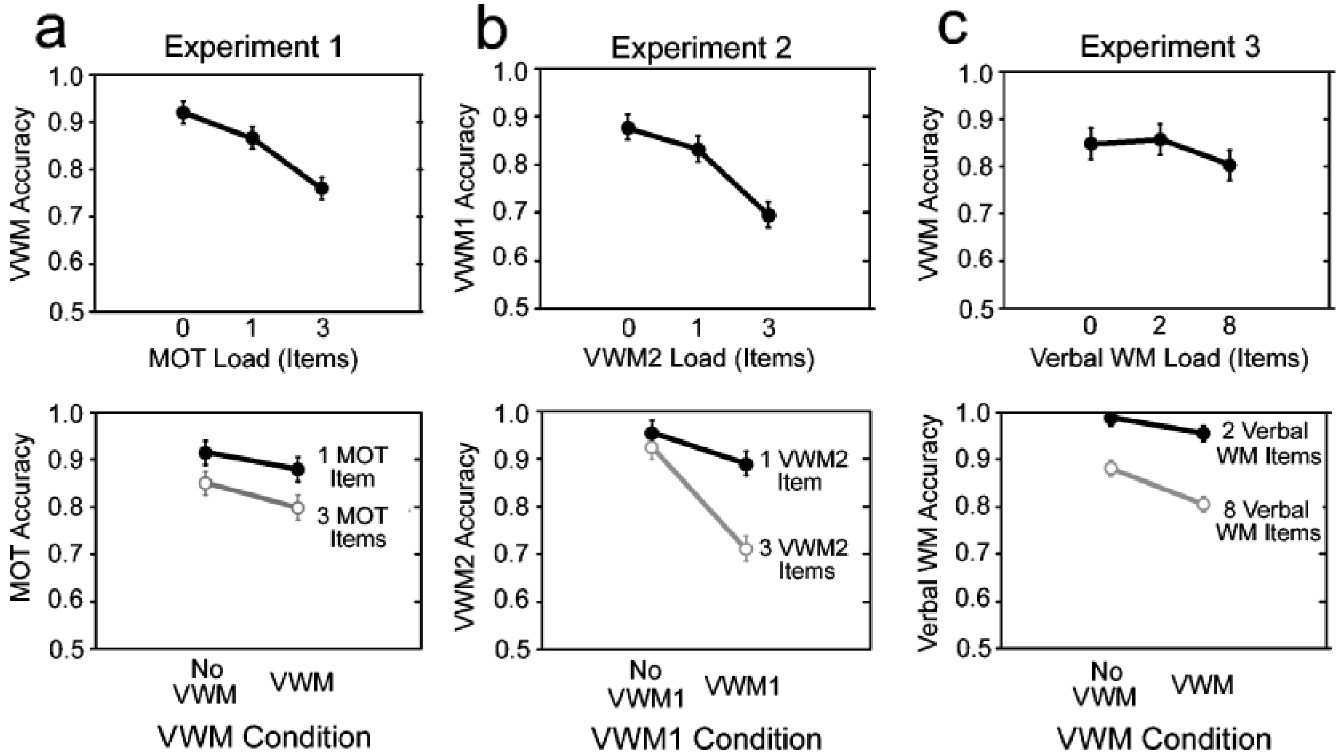

Fig. 2. Accuracy data for Task 1 (top panels) and Task 2 (bottom panels) of Experiments 1, 2, and 3. In Experiment 1 (a), Task 1 was a visual working memory (VWM) task, and Task 2 was a multiple object tracking (MOT) task. In Experiment 2 (b), both tasks were VWM tasks (VWM1 and VWM2). In Experiment 3 (c), Task 1 was a VWM task, and Task 2 was a verbal working memory (verbal WM) task. Error bars represent within-subjects errors of the mean.

responses for both tasks were collected. Performance of this task was monitored by the experimenter via speakers.

Design and Procedure

Forty-two percent of all trials contained both the VWM and MOT tasks. In the remaining trials, subjects performed either the VWM or the MOT task; this allowed us to assess performance in each task independently. To control for sensory and motor demands across all trial types, we designed each single-task condition to involve visual presentation and a motor response for the other task. Thus, for the VWM-only trials (25% of trials), a MOT movie with no targets replaced the normal MOT task. For the MOT-only trials (33% of trials: 16.5% for each MOT load), the VWM display was replaced by a screen with six black triangles (0.78° each), one at each possible VWM position. For both these kinds of trials, the probe display contained an ampersand above fixation, indicating that the participants should press the space bar.

All trial types were randomly intermixed within two blocks of 48 trials. Participants were instructed to maintain fixation throughout each trial, and to emphasize the two tasks equally.

Results and Discussion

A one-way within-subjects analysis of variance (ANOVA) across MOT conditions (no, low, or high load) revealed that VWM performance was impaired by the MOT task, $F(2, 21) = 24.9$, $p < .0001$,[1] $\omega^2 = .25$ (Fig. 2a, top panel). Planned comparisons using paired t tests showed that accuracy was different across the three load conditions (ps $< .05$). In addition, a 2 (MOT load: low or high) × 2 (VWM condition: task or no task) within-subjects ANOVA revealed that MOT accuracy was reduced with high MOT load, $F(1, 22) = 14.08$, $p < .001$, $\omega^2 = .17$. More important, MOT accuracy was lower when performed with than without the VWM task, $F(1, 22) = 5.11, p < .005, \omega^2 = .09$ (Fig. 2a, bottom panel).

Thus, the MOT and VWM tasks interfered with each other: Performing a MOT task reduced VWM accuracy, and vice versa. Furthermore, this interference was load-dependent, as VWM performance decreased as the number of MOT targets increased.

To test whether these drops in accuracy in dual-task conditions translate into fewer objects stored or tracked, we used Cowan's (2001) K formula: $K = [\text{hit rate} + \text{correct rejection rate} - 1]N$, where K is the estimated number of objects stored or tracked and N is the number of objects or targets presented. Specifically, we compared the observed dual-task capacity (measured by summing the K estimates for the two tasks in the dual-task condition) with the expected dual-task capacity assuming independent task capacities (measured by summing

[1]A significant result ($p < .05$) corresponds to a probability of replication (p_{rep}) of .917 or higher (Killeen, 2005).

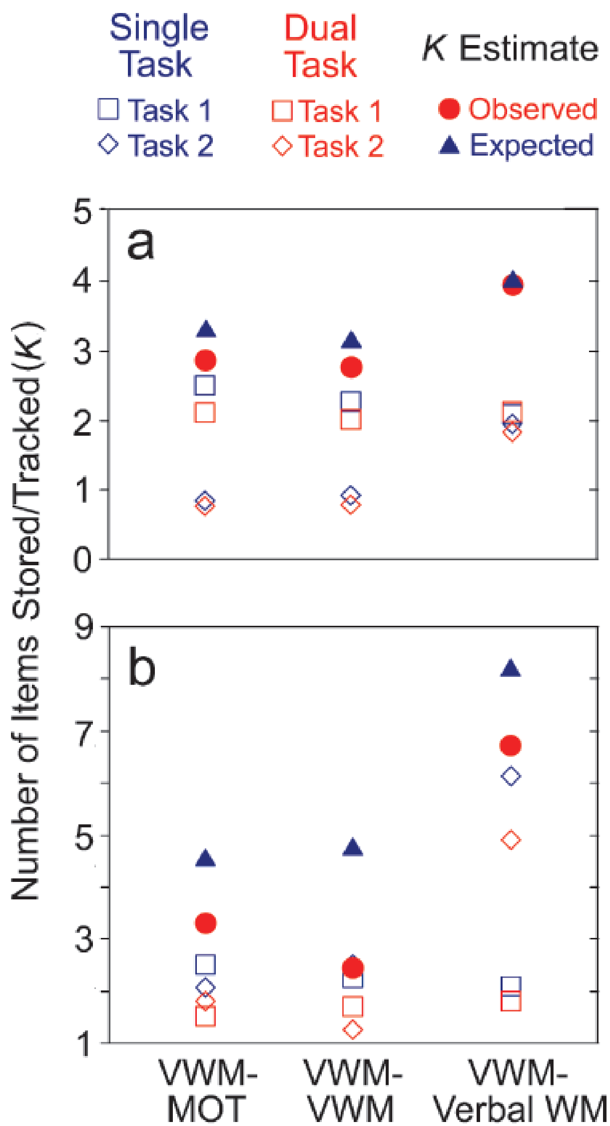

Fig. 3. Observed versus expected dual-task performance in Experiments 1, 2, and 3. Observed dual-task *K* is the sum of the *K* estimates for the two tasks under dual-task conditions; expected *K* corresponds to the sum of the *K* estimates for the two tasks under single-task conditions. The load of the second task was either low (a) or high (b). A visual working memory (VWM) task was paired with a multiple object tracking (MOT) task in Experiment 1, with a second VWM task in Experiment 2, and with a verbal working memory (verbal WM) task in Experiment 3.

K estimates for the two tasks in the single-task condition). This analysis was performed separately for each MOT load.

For the low MOT load, observed dual-task capacity was lower than the expected dual-task capacity, $t(22) = 3.764$, $p < .001$, $d = 0.79$ (Fig. 3a), indicating that fewer objects were stored or tracked under dual-task conditions than under single-task conditions. Because similar results at high MOT load could simply be due to a carryover of the difference at low load, the latter interference was subtracted out in the analysis of the high-load condition. Nevertheless, the observed dual-task capacity at high load was still lower than the expected dual-task capacity, $t(22) = 4.254$, $p < .001$, $d = 0.89$ (Fig. 3b), indicating that increasing MOT load from one to three objects led to a further decrease in the number of objects that could be stored or tracked under dual-task conditions relative to single-task conditions. Thus, the *K* and accuracy data both indicate that MOT and VWM interfere with each other in a load-dependent manner.

EXPERIMENT 2

Experiment 2 assessed how the MOT-VWM dual-task costs compare with those obtained when the two tasks performed concurrently are both VWM tasks, the dual-task condition that should provide maximal VWM interference. If MOT taps into the same capacity-limited process as VWM, then a VWM-VWM dual task should yield interference costs comparable to those obtained in Experiment 1 at both low and high loads.

Method

This experiment, which involved 21 participants, was identical to Experiment 1 except that the MOT task was replaced by a second VWM task, so that there were two VWM tasks (VWM1 and VWM2). We used set sizes of 0, 1, and 3 for VWM2 because they yielded single-task performance similar to that for the MOT task.

The shapes (circles or squares), colors, and locations of the stimuli were distinct for the two VWM tasks. For each trial, each of two color sets (light blue, dark green, red, white, and purple vs. light green, brown, pink, blue, and yellow) was randomly assigned to either VWM1 or VWM2. The three VWM1 circles could appear at any of the four locations 3.3° from fixation on the horizontal and vertical axes, whereas the VWM2 squares could appear at the corresponding locations of the two 45° diagonal axes. The VWM2 sample display appeared for 400 ms, starting 1.2 s after the offset of the VWM1 sample display. After a retention interval of 9 s, participants responded first to the VWM1 probe display and then to the VWM2 probe display, indicating in each case whether the single colored probe matched a sample item in both its color and its location. A match occurred in 50% of the trials. For the VWM2 task, the probe for nonmatch trials was a new color or a new location for set size 1, and either a new color or location or an incorrect pairing of a sample color and location for set size 3. For trials with no VWM1 (25%) or VWM2 (33%) task, four black triangles (0.78°) replaced the color stimuli at the four locations.

Results and Discussion

VWM1 task performance was impaired by the VWM2 task, $F(2, 19) = 31.12$, $p < .0001$, $\omega^2 = .33$ (Fig. 2b, top panel). VWM1 accuracy dropped across the three VWM2 load conditions ($ps < .05$). VWM2 accuracy was reduced by increasing VWM2 load, $F(1, 20) = 58.73$, $p < .0001$, $\omega^2 = .47$, and VWM2 accuracy was lower in dual-task than in single-task trials, $F(1, 20) =$

61.32, $p < .0001$, $\omega^2 = .49$ (Fig. 2b, bottom panel). The interaction between VWM2 load and VWM1 condition, $F(1, 20) = 16.43$, $p < .001$, indicates that VWM2 performance suffered mostly under high load and dual-task conditions. Finally, observed dual-task capacity was lower than expected dual-task capacity for both low load, $t(20) = 2.57$, $p < .05$, $d = 0.57$, and high load, $t(20) = 7.44$, $p < .001$, $d = 1.6$ (Fig. 3). Thus, the accuracy and *K* results indicate that two concurrently executed VWM tasks interfere with each other in a load-dependent manner.

The *K* scores cannot be directly used to compare dual-task costs between Experiments 1 and 2 because *K* units may not equate to the same demands across tasks. That is, the *K* capacity under single-task conditions may not be identical for the VWM and MOT tasks. We therefore developed a normalized *K* score, which expressed for each task the dual-task costs relative to the *K* in the single-task condition. This proportional measure of dual-task cost was calculated separately for each of the two tasks of a given experiment and then summed across the two tasks to provide a combined measure of interference that is robust to performance trade-offs. These computations were carried out separately for the low-load and high-load conditions. Thus, ΔK_{low} assessed the extent to which the number of objects stored or tracked in tasks *i* and *j* decreased under dual-task, low-load conditions relative to their respective single-task, low-load conditions:

$$\Delta K_{\text{low}} = \left(\frac{K_{\text{low(single}_i)} - K_{\text{low(dual}_i)}}{K_{\text{low(single}_i)}}\right) + \left(\frac{K_{\text{low}\left(\text{single}_j\right)} - K_{\text{low}\left(\text{dual}_j\right)}}{K_{\text{low}\left(\text{single}_j\right)}}\right) \quad (1)$$

ΔK_{high} assessed whether increasing task load resulted in interference additional to that observed at low load:

$$\Delta K_{\text{high}} = \left[\left(\frac{K_{\text{high(single}_i)} - K_{\text{high(dual}_i)}}{K_{\text{high(single}_i)}}\right) - \left(\frac{K_{\text{low(single}_i)} - K_{\text{low(dual}_i)}}{K_{\text{low(single}_i)}}\right)\right] + \left[\left(\frac{K_{\text{high}\left(\text{single}_j\right)} - K_{\text{high}\left(\text{dual}_j\right)}}{K_{\text{high}\left(\text{single}_j\right)}}\right) - \left(\frac{K_{\text{low}\left(\text{single}_j\right)} - K_{\text{low}\left(\text{dual}_j\right)}}{K_{\text{low}\left(\text{single}_j\right)}}\right)\right] \quad (2)$$

Figure 4 shows that although the combined dual-task costs are equivalent for Experiments 1 (VWM-MOT) and 2 (VWM-VWM) at low load, $t < 1$, they are much higher for Experiment 2 than for Experiment 1 at high load, $t(41) = 2.71$, $d = 0.82$. These results suggest that under low-load conditions, VWM performance is equally affected by concurrently performing another VWM task or a MOT task, but that when the load is increased, VWM performance is much more affected by another VWM task than by a MOT task. Thus, although VWM and MOT interfere with each other in a load-dependent manner, this interference is smaller than the interference observed under VWM-VWM dual-task conditions.

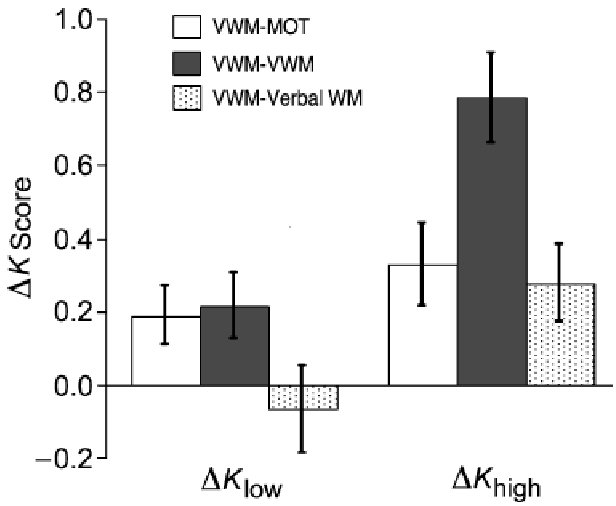

Fig. 4. ΔK scores in Experiments 1, 2, and 3. Larger ΔK scores imply greater dual-task interference. The load of the second task was either low (left) or high (right). In each experiment, a visual working memory (VWM) task was paired with a multiple object tracking (MOT) task, a second VWM task, or a verbal working memory (verbal WM) task. Error bars represent between-subjects errors of the mean.

EXPERIMENT 3

Even though MOT and VWM tasks do not interfere with each other to the same extent that two VWM tasks do, concurrent performance of a MOT task and a VWM task still instilled substantial and load-dependent dual-task costs. Did these costs arise from interference in visuospatial attention, or did they originate from central sources of dual-task limitations? Experiment 3 addressed this issue by determining whether verbal WM, generally considered to be independent from visuospatial attention and VWM (Baddeley, 1986; Logan, 1979; Vogel et al., 2001), would interfere with VWM to the same extent as a MOT task. If so, this would provide evidence for a central, amodal source for the VWM-MOT interference.

Method

Experiment 3, which involved 22 participants, was identical to Experiment 1 except that a verbal WM task replaced the MOT task. The verbal WM task began 1.2 s after the offset of the VWM display, with presentation of either two (low load) or eight (high load) spoken consonants over headphones. Each consonant stimulus was presented for 360 ms and separated from the next consonant by a 400-ms interstimulus interval. For each trial, the consonants were chosen randomly with no repeats from the following set: *F*, *G*, *K*, *N*, *P*, *Q*, *R*, *S*, *T*, *X*, *Y*, or *Z*. Participants repeated the stimuli aloud at a 2-Hz rate for 8.4 s, after which a spoken probe consonant was presented for 360 ms, followed 600 ms later by the VWM probe. Following response to that probe, a question mark above fixation instructed the participants to indicate by key press whether the spoken probe matched a consonant from the sample set (50% of the trials were match trials). In the 25% of the trials with no verbal WM task, the second probe screen contained an ampersand, indicating that the participants should press the space bar. Participants performed articulatory suppression only in those trials.

Results and Discussion

VWM accuracy was not affected by the verbal WM task, $F(2, 20) = 1.66, p > .2, \omega^2 = .014$ (Fig. 2c, top panel). VWM performance did not differ between the conditions with no and low verbal WM load ($p = .81$), and there was a marginal difference in VWM performance between the conditions with low and high verbal WM load ($p = .07$). However, verbal WM accuracy was reduced not only by increased verbal load, $F(1, 21) = 63.8, p < .001, \omega^2 = .55$ (Fig. 2c, bottom panel), but also by concurrent performance of the VWM task, $F(1, 21) = 18.75, p < .005, \omega^2 = .21$.

Subjects' observed and expected dual-task capacities were comparable under low verbal WM load, $t(21) = 0.02, p = .85, d = 0.07$ (Fig. 3a). Furthermore, ΔK_{low} for the verbal task was not only lower than ΔK_{low} for the MOT task, $t(37) = 2.177, p < .05, d = 0.58$, but was also indistinguishable from 0, $t < 1$ (Fig. 4). These results suggest that verbal WM and VWM did not interfere with each other under low verbal WM load.

By contrast, the observed K was lower than the expected K under high verbal WM load, $t(21) = 3.53, p < .005, d = 0.75$ (Fig. 3b). Furthermore, under high-load conditions, the verbal WM-VWM costs were just as large as the VWM-MOT costs in Experiment 1, $t < 1$ (Fig. 4), although they were smaller than the VWM-VWM costs in Experiment 2, $t(39) = 3.13, p < .005, d = 0.72$. Thus, whereas the low-load results reveal that VWM and MOT share a process that is not accessed by verbal WM, the high-load results suggest that the increased interference between the VWM and MOT tasks relative to the low-load results may be accounted for by central sources of dual-task interference.

EXPERIMENTS 4 THROUGH 7

We carried out additional experiments to investigate the source of the interference between the attention and working memory tasks. The first two examined the importance of featural overlap between the MOT and VWM tasks. The MOT task involved monitoring the motion of colorless objects, whereas the VWM task required holding in mind the location of colored objects. We reasoned that perhaps greater interference would be obtained if the two tasks overlapped more in task-relevant attributes.

In Experiment 4, which involved 20 participants, we assessed whether VWM-MOT interference would increase if both tasks involved monitoring colored stimuli. The experiment was identical to Experiment 1, except that the MOT discs were colored. Distinct color sets were used for the two tasks, as in Experiment 2. In trials with one MOT target, the target shared a color with three distractors, and two sets of four distractors shared other colors. In trials with three targets, each target had a distinct color shared with three distractors. Both matching and nonmatching probes were the same color as a target. The resulting ΔK scores ($\Delta K_{low} = .236, SE = .119$; $\Delta K_{high} = .195, SE = .125$) were indistinguishable from the ΔK scores in Experiment 1 ($ps > .5$). Additionally, ΔK_{high} was still lower than in Experiment 2 ($p < .01$). These results suggest that interference between the MOT and VWM tasks is not strongly affected by whether or not both tasks involve color processing.

Given that interference between attention and VWM tasks depends on whether they both require visuospatial information (e.g., Awh et al., 1998; Oh & Kim, 2004; Woodman & Luck, 2004; Woodman, Vogel, & Luck, 2001), Experiment 5 examined whether a purely spatial VWM task could produce greater dual-task interference between VWM and MOT tasks, because the latter task involves tracking objects moving in space. This experiment, which involved 17 participants, was identical to Experiment 1 except that the VWM task consisted of the sequential presentation of four black discs (0.78°) that marked four spatial positions along an imaginary circle (3.3° radius). Each disc was presented for 200 ms and followed by a 200-ms gap. After the retention interval, participants indicated whether the probe disc occupied one of the memorized locations (50% of trials were match trials). Not only were dual-task costs ($\Delta K_{low} = .253, SE = .103$; $\Delta K_{high} = .01, SE = .188$) statistically indistinguishable from those in Experiment 1 (both $ps > .1$), but more important, the ΔK score was still lower than in Experiment 2 (VWM-VWM; $p < .01$).

Nearly identical dual-task costs were also obtained in Experiment 6 ($n = 18$), which was identical to Experiment 1 except that the VWM task did not require spatial working memory because probe items were presented at fixation. Thus, manipulations that affected the spatial demands of the VWM task failed to increase the MOT-VWM costs to the level obtained under VWM-VWM conditions. More generally, these spatial experiments, together with the color experiment, suggest that the difference in dual-task costs between MOT-VWM and VWM-VWM conditions does not likely originate at the featural level.

Last, Experiment 7, which involved 17 participants, assessed whether the source of the MOT-VWM interference is common to other visual attention tasks. Specifically, we paired the VWM task of Experiment 1 with a target detection task involving multiple rapid serial visual presentation (RSVP) streams (Fig. 5). The attentional load of the RSVP task was manipulated by varying the number of streams to be attended (one or three). Thus, whereas K estimated the number of objects tracked successfully in the MOT task, in the RSVP task K estimated the number of streams attended successfully. A pilot experiment ($n = 15$) established that in single-task conditions, participants' monitoring capacity leveled off at three to four RSVP streams.

The VWM task was the same as in Experiment 1, except that the stimuli were colored diamonds (pink, dark green, light blue,

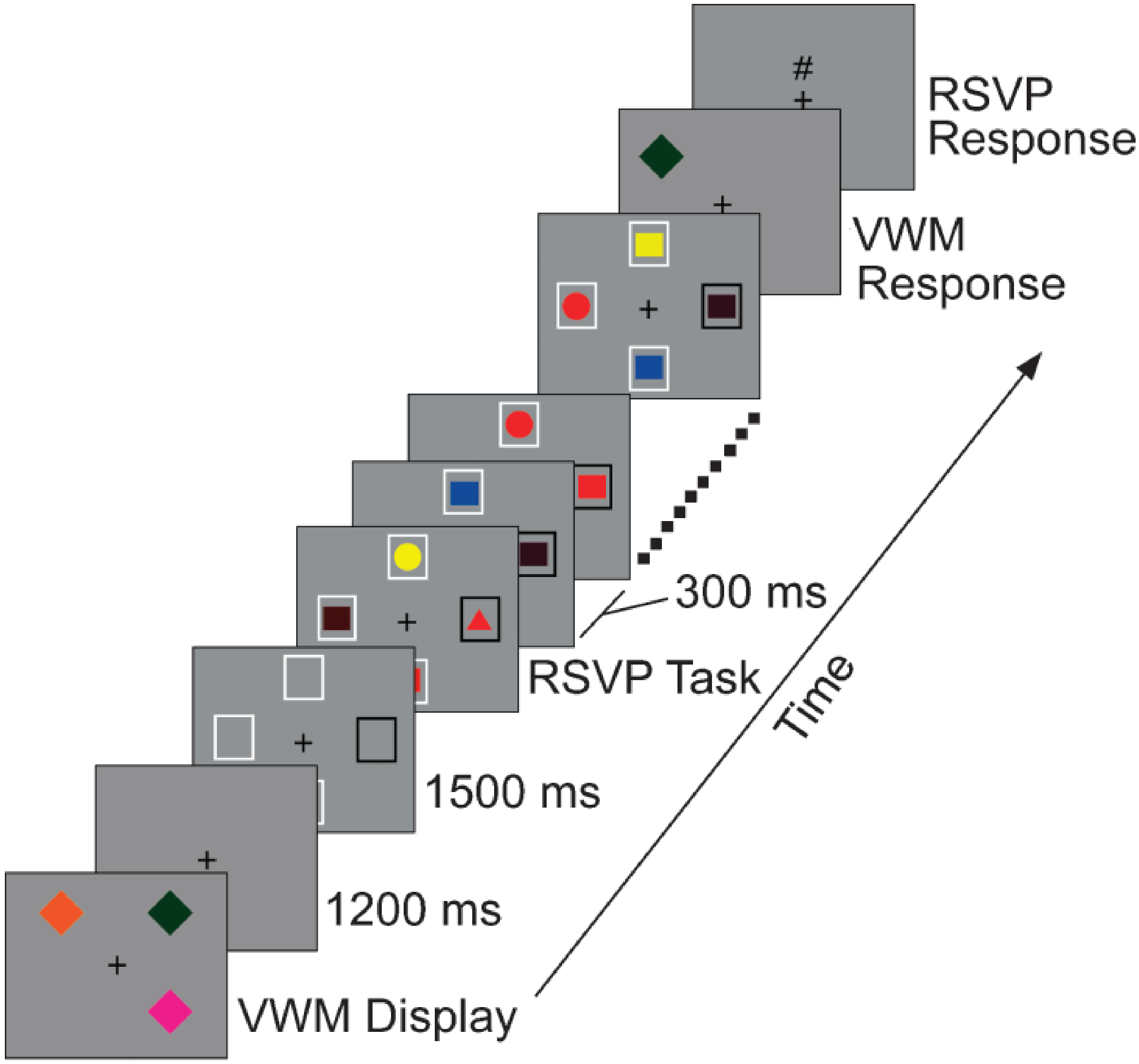

Fig. 5. Dual-task trial design for Experiment 7, which paired a visual working memory (VWM) task with a rapid serial visual presentation (RSVP) task. The VWM task involved memorizing the color and location of three briefly presented diamonds. During the RSVP task, participants monitored one or three locations for the appearance of target items (red squares). Participants then responded to the VWM task (indicating whether a VWM probe item matched the color and location of a diamond in the original VWM display) and the RSVP task (indicating the number of targets that appeared).

or orange) that appeared at any of the four locations 2.5° from fixation along the two 45° diagonal axes. Starting 1.2 s after the offset of the VWM display, white or black boxes (0.7°) appeared at four locations 2.5° from fixation along the vertical and horizontal axes, remaining present for the 7.5-s duration of the RSVP streams. Black boxes indicated the streams to be attended for targets, and white boxes indicated the streams to be ignored. Trials without the RSVP task contained four white boxes that informed participants not to perform the search task. The RSVP streams started 1.5 s after the appearance of the boxes and consisted of the synchronous presentations of colored shapes (0.5°) in all four boxes every 300 ms (each shape was presented for 200 ms and followed by a 100-ms blank). Because stimuli included the target (red square), red distractors (circle, triangle, cross, hexagon), and nonred square distractors (blue, brown, yellow, purple), the task required subjects to attend to both color and shape at the cued streams. There were zero, one, or two targets per trial, with the targets appearing only in cued streams. After the response to the VWM task (see Experiment 1), a number sign indicated that the participants should press a key to indicate the number of targets seen in the RSVP task. For the 25% of trials with no RSVP task, an ampersand, rather than a number sign, appeared, and participants pressed the space bar in response. Only zero- and one-target trials were used for analysis because attention may not have been engaged for the entire RSVP sequence in two-target trials.

The results revealed not only that ΔK scores for the low-load ($\Delta K = .362$, $SE = .153$, $p = .6$) and high-load ($\Delta K = .272$, $SE =$

.137, $p = .86$) conditions were indistinguishable from ΔK scores in Experiment 1 (VWM-MOT), but also that ΔK_{high} was still lower than in Experiment 2 (VWM-VWM; $p < .05$). Thus, even though the RSVP and MOT tasks are very distinct attentional tasks, they yielded comparable dual-task costs when paired with a VWM task. These results strongly suggest that the interference between MOT and VWM generalizes across other visual attention tasks. Furthermore, given that the RSVP and VWM tasks involved substantial featural overlap (the RSVP task requiring attention to location, color, and shape, and the VWM task requiring attention to location and color) and yet yielded much less dual-task interference than the VWM-VWM condition, these results provide further evidence against the possibility that the difference between MOT-VWM and VWM-VWM dual-task costs is primarily due to differences in task-relevant features.

GENERAL DISCUSSION

Although our results suggest that attention and VWM are intertwined cognitive operations, they are not consistent with the view that the capacity limit of VWM is reducible to that of attention (e.g., Cowan, 2001; Rensink, 2000a), because the dual-task costs in the MOT-VWM condition (Experiment 1) and the VWM-VWM condition (Experiment 2) were not comparable. However, the data also suggest that VWM storage capacity is not a property that is entirely specific to this cognitive subsystem, because we observed interference between verbal WM and VWM, much as did Morey and Cowan (2004, 2005). Thus, our results are consistent with VWM capacity being a product of three cognitive operations: visuospatial attention; a central, amodal supervisory process; and local stage-specific operations.

The dual-task costs observed under low-load conditions corroborate previous findings of an interaction between visuospatial attention and VWM (Awh & Jonides, 2001; Awh et al., 1998; Oh & Kim, 2004; Woodman & Luck, 2004), but not between verbal WM and VWM (Todd & Marois, 2004; Vogel et al., 2001). The interference between the MOT and RSVP tasks and the VWM task may have originated from the common use of visuospatial attention. Focused attention to the VWM positions may have been necessary either to maintain spatial location information during the retention interval (Awh & Jonides, 2001) or to bind featural information in memory (Wheeler & Treisman, 2002). Because execution of the MOT task necessitated shifts of visuospatial attention (e.g., Culham et al., 2001), attention may have been withdrawn from the “tagged” sites, thereby disrupting the memory.

Two principal conclusions can be drawn from the dual-task costs observed under high load. The first is that attention and verbal WM tasks produce comparable dual-task interference with VWM. The most parsimonious account of this finding is that the interference arises from a shared capacity-limited process that impedes the concurrent execution of two distinct cognitive tasks under high demands. Although this process remains to be fully characterized (Baddeley, Chincotta, & Adlam, 2001; Morey & Cowan, 2004, 2005; Ruthruff & Pashler, 2001; Tombu & Jolicoeur, 2003), it is evidently of central, amodal origin, and may correspond to a supervisory attentional system responsible for goal and task setting (Norman & Shallice, 1986).

The second important conclusion from the high-load results is that dual-task costs are much higher when two VWM tasks are performed concurrently than when a VWM task is paired with an attentional or verbal task. These results are consistent with the hypothesis that VWM involves stage-specific capacity-limited processes (Luck & Vecera, 2002). Indeed, VWM may contain several distinct subprocesses, each with its own processing capacities, just as MOT likely taps into its own content-specific processes. Evidently, it is through the complex interactions between these local processes and global attentional processes that the vivid but constrained mental representations of the visual world emerge.

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