Atten Percept Psychophys (2011) 73:420–439
DOI 10.3758/s13414-010-0048-8

When do spatial and visual working memory interact?

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Abstract This study examined how spatial working memory and visual (object) working memory interact, focusing on two related questions: First, can these systems function independently from one another? Second, under what conditions do they operate together? In a dual-task paradigm, participants attempted to remember locations in a spatial working memory task and colored objects in a visual working memory task. Memory for the locations and objects was subject to independent working memory storage limits, which indicates that spatial and visual working memory can function independently from one another. However, additional experiments revealed that spatial working memory and visual working memory interact in three memory contexts: when retaining (1) shapes, (2) integrated color-shape objects, and (3) colored objects at specific locations. These results suggest that spatial working memory is needed to bind colors and shapes into integrated object representations in visual working memory. Further, this study reveals a set of conditions in which spatial and visual working memory can be isolated from one another.

Keywords Spatial working memory · Visual working memory · Memory binding · Feature integration · Short-term memory

How do people retain visual representations of the environment? Previous studies provide evidence that working memory can be divided into separate systems for retaining location information and object information (i.e., colors, shapes). These systems are commonly referred to as ‘spatial working memory’ (SWM) and ‘visual working memory’ (VWM), respectively; there is also evidence for specialized working memory systems for retaining verbal information (Baddeley, 1986) and spatiotemporal information (i.e., observed movement information; Wood, 2007, in press).

Evidence for the dissociation between SWM and VWM comes from three main findings. First, brain damage can impair object memory or spatial memory without impairing the other type of memory (e.g., Carlesimo, Perri, Turriziani, Tomaiuolo, & Caltagirone, 2001; Farah, Hammond, Levine, & Calvanio, 1988; Hanley, Young, & Pearson, 1991; Owen, Iddon, Hodges, Summers, & Robbins, 1997; Postle, Jonides, Smith, Corkin, & Growdon, 1997). Second, object memory tasks activate different neural substrates than spatial memory tasks (e.g., Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998; McCarthy et al., 1996; Smith et al., 1995). For example, posterior dorsal frontal cortex is preferentially involved during the maintenance of spatial information, whereas posterior ventral frontal cortex is preferentially involved during the maintenance of non-spatial information (e.g., Sala & Courtney, 2007). Third, there is less interference between an object memory task and a spatial memory task than between two object memory tasks or between two spatial memory tasks (e.g., Klauer & Zhao, 2004; Logie, 1986; Logie & Marchetti, 1991; Logie & Pearson, 1997; Smyth & Scholey, 1994). Despite this wealth of evidence, however, it is unclear under what conditions VWM requires resources from SWM in order to retain object information. What type of object units can VWM retain independent of contributions from SWM?

Some researchers argue that VWM stores information in the form of integrated object representations (e.g., Luck & Vogel, 1997). These ‘object-based’ models therefore predict that memory for features (e.g., "red" and "square"), and

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memory for how features were organized as objects (e.g., "red square") are one and the same. For object-based models, SWM does not play a necessary role in retaining information about how individual features were organized as objects in VWM. In contrast, other researchers argue that VWM stores feature values from different feature dimensions[1] in separate feature-specific memory stores, and requires SWM and attention to keep those features organized as integrated object representations in memory (e.g., Wheeler & Treisman, 2002). These 'feature-based' models therefore predict that memory for features and memory for feature organization are supported by separate mechanisms, with SWM playing a necessary role in retaining information about how features were organized as objects in VWM.

A second open question concerns whether VWM and SWM can function independently from one another in *any* context. Specifically, when observers retain objects in VWM they also store information about the spatial relations between those objects (e.g., Jiang, Olson, & Chun, 2000). Thus, objects can be stored as parts of a larger spatial configuration. But does this mean that VWM stores all visual information as parts of a larger spatial configuration? There is growing evidence that VWM contains separate, specialized systems for retaining view-dependent 'snapshot' information and view-invariant 'object identity' information (Wood, 2009, in press; see also Hollingworth & Rasmussen, 2010). A snapshot consists of a relatively unprocessed sensory representation of the scene (Trullier, Wiener, Berthoz, & Mayer, 1997). Thus, in a snapshot, visual features will be stored as parts of a larger spatial configuration. In contrast, some cognitive abilities operate over representations of individual movable objects, and the VWM system that stores these representations may not bind object features to spatial positions (Hollingworth & Rasmussen, 2010). Accordingly, VWM might store visual features as parts of a larger spatial configuration in some contexts (when features are stored in the form of a snapshot) but not in other contexts (when features are stored as part of a representation of a movable, manipulable object).

The goal of the current study was to shed light on these issues by characterizing the conditions in which VWM and SWM interact. I focused on two related questions: (1) Can VWM and SWM function independently from one another or are resources from SWM necessary in order to encode and maintain information in VWM? (2) If VWM and SWM can operate independently, then under what conditions do they operate together?

To address these questions, I used a dual-task paradigm. In the first memory task, participants attempted to remember as many locations as possible in a location array. In the second memory task, participants attempted to remember as many objects as possible in an object array. After a brief retention interval, a test probe appeared that consisted of either a single location or a single object. Participants did not know whether the test item would be a location probe or an object probe, and therefore needed to remember simultaneously the locations from the location array and the objects from the object array.

If the location and object information can be stored in separate, independently operating SWM and VWM memory buffers, then performance on one task should not suffer when the other task is performed concurrently. Thus, the number of locations that can be remembered from the location array will be independent from the number of objects retained from the object array, and vice versa. However, if SWM is needed to retain object information in VWM, then performance on one or both of the tasks will suffer when the other task is performed concurrently. Thus, the number of locations that can be remembered from the location array will be lower when observers also need to remember objects from the object array.

To characterize the conditions in which VWM and SWM interact, I varied the types of objects that needed to be remembered from the object array. In different experiments, participants needed to remember colored objects, shapes, integrated color-shape objects, and colored objects that were tested at the same locations that they were encoded.

To preview the findings, the results show that VWM and SWM can operate independently from one another when observers remember colored objects that are tested at a neutral location. However, memory for all other object types (shapes, integrated color-shape objects, and colored objects that are tested at the same locations that they were encoded) requires resources from both VWM and SWM.

Experiment 1

Experiment 1 examined whether SWM is needed to retain representations of colored objects in VWM. In a location memory task, participants attempted to remember 0, 2, 4, or 6 locations from a location array. In an object memory task, participants attempted to remember 0, 2, 4, or 6 colored objects from an object array. The object test probe appeared at a neutral location at the center of the screen.

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[1] I use the terms feature value and feature dimension as they are used in the attention literature and in previous studies of VWM (Wheeler & Treisman, 2002). For example, *blue* is a feature value along the feature dimension of *color*. Color and orientation are commonly accepted feature dimensions (Treisman, 1986).

Method

Participants Ten individuals (male: 4; female: 6; mean age = 21.8 years, SD = 3.26) with normal or corrected-to-normal vision participated to receive credit toward a course requirement or for monetary payment. Informed consent was obtained.

Design A dual-task version of the sequential comparison procedure, which has been used previously to measure the storage capacity of working memory for objects, locations, and observed movements, was implemented (e.g., Jiang et al., 2000; Luck & Vogel, 1997; Wood, 2007). On each trial, participants viewed a location array consisting of varying numbers of locations in a spatial grid, an object array consisting of varying numbers of colored squares, and then a test display consisting of either a single location or a single object. Participants then indicated whether that location or object had been present in the location array or the object array.

For the location array, a visible empty 5 × 5 grid (17.5° width × 14.5° height) was presented for 400 ms on a black background. Then, 0, 2, 4, or 6 white dots (2° in diameter) were presented for 500 ms at randomly selected locations within that grid.

For the object array, 0, 2, 4 or 6 colored squares (red, orange, yellow, green, blue, grey, purple; see Fig. 3) were presented on a black background for 500 ms. The objects appeared in the same locations for all of the trials from each load condition (2, 4, 6 objects). For the 2-object arrays, the objects were presented on the horizontal midline, offset 3.5° from the center of the screen. For the 4-object arrays, the objects were presented equidistant from the middle of the screen in four quadrants, offset 3.5° from the vertical midline and 1.5° from the horizontal midline. For the 6-object arrays, 2 objects were presented on the horizontal midline, offset 3.5° from the middle of the screen, and the remaining 4 objects were offset 3° above and below those objects. No color was presented more than once in the object array.

During a 1,000-ms retention interval, the word “test” appeared, followed either by a single location appearing within the 5 × 5 grid (50% of trials) or a single object presented at the center of the screen (50% of trials). The test probe remained visible until observers made their response. The test item was different from all of the items in the location array and the object array on 50% of the trials. Participants received 24 trials for each unique set size combination of objects (0, 2, 4, 6 objects) and locations (0, 2, 4, 6 locations). The testing session was preceded by ten practice trials. In all experiments reported in this study, participants were instructed to prioritize accuracy as opposed to speed and accuracy.

On each trial, participants performed a concurrent articulatory suppression task that inhibits the use of verbal recoding of the stimulus in memory tasks (Besner, Davies, & Daniels, 1981).

Procedure Each trial began with a 1,000-ms presentation of two randomly selected letters, and participants were required to repeat those letters continuously and out loud until the end of the trial. The offset of these letters was followed by a 500-ms presentation of a screen displaying the word “ready” and then a 500-ms presentation of a blank screen, followed by the presentation of the location array and then the object array. The location array and the object array were separated by an 800-ms inter-array interval. The object array was followed, after a 500-ms delay interval, by a 500-ms presentation of the word “test,” followed by the presentation of the test probe, which consisted of a single location or a single object presented at the center of the screen. Participants were required to make a response to this test probe, indicating whether that item had been present in the trial. See Fig. 1 for a schematic illustration of a trial.

Results

Figure 1 depicts the results. See Table 1 for the proportions of hits, false alarms, correct responses, and the reaction times for all conditions.

The data were analyzed in terms of “percent correct,” defined as the percentage of time that participants correctly indicated whether or not the test probe had been present in the trial. In addition, the data were converted into storage capacity estimates by using the formula developed by Pashler (1988), modified by Cowan (2001). The logic of this approach is that if an observer can retain K items in memory from an array of S items, then the item that changed should be one of the items being held in memory on K/S trials, leading to correct performance on K/S of the trials on which an item changed. This measure takes into consideration the effects of guessing, by factoring in the false alarm rate [F = false alarms/(false alarms + correct rejections)] and the observed hit rate [H = hits/(hits + misses)]. The formula is defined as $K = S\,(H - F)$.

Memory for objects

An ANOVA with factors of set size (2, 4, 6 objects) and location memory load (0, 2, 4, 6 locations) revealed a main effect of set size, $F(2, 18) = 53.16$, $p < 0.001$; $h_p^2 = 0.86$. The main effect of location memory load and the interaction did not approach statistical significance (Fs < 1). Further-

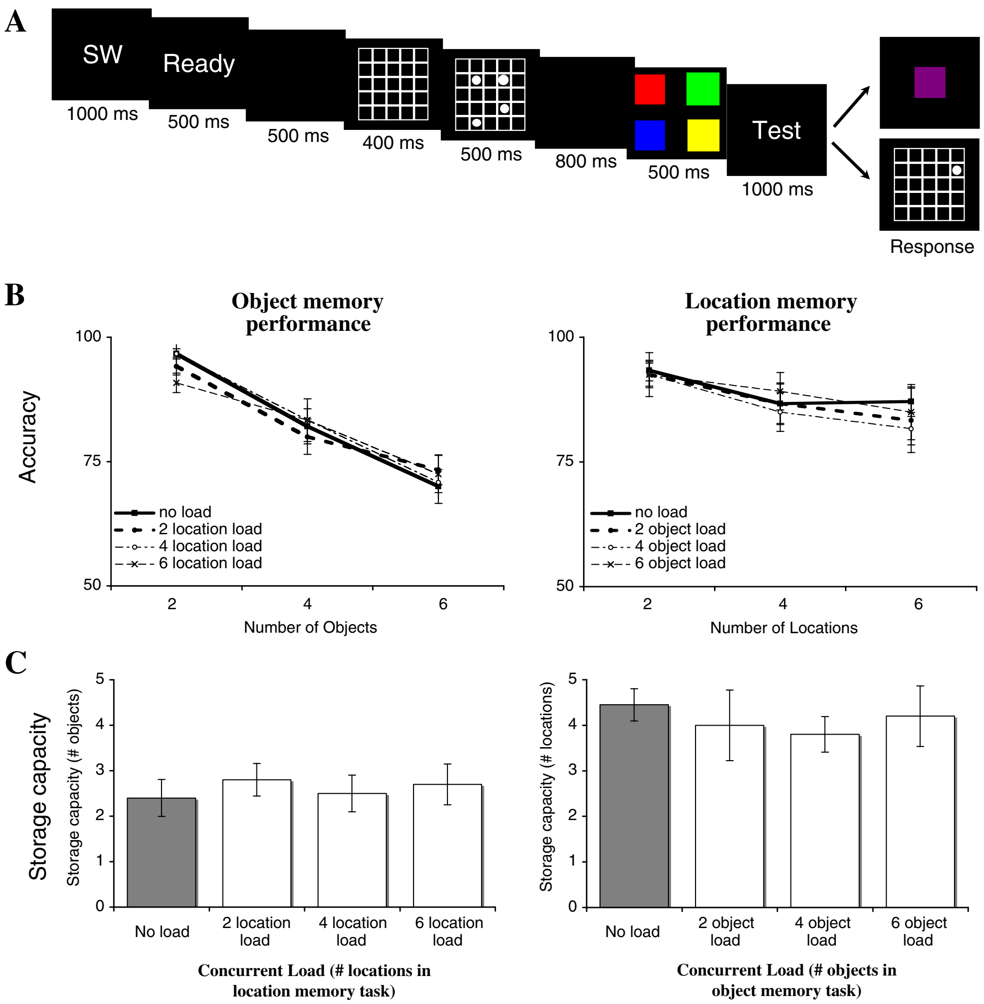

Fig. 1 (**a**) Schematic illustration of a trial from Experiment 1, presenting four locations and four objects. In this example, the test object and the test location are different from all of the objects and locations in the trial. (**b**) Accuracy (% correct) for the object memory test trials and the location memory test trials. (**c**) Storage capacity estimates for the object memory test trials and the location memory test trials. Error bars represent standard error

more, an ANOVA with factors of set size (2, 4, 6 objects) and presence of a location memory load (0 locations versus 2, 4, 6 locations) revealed a main effect of set size only, $F(2, 18) = 53.75$, $p < 0.001$; $h_p^2 = 0.86$. The main effects of location memory load ($F < 0.10$) and the interaction ($F < 1.60$) were not statistically significant. Thus, the location memory task had no significant effect on performance in the object memory task. This conclusion was supported by the storage capacity estimates, computed from the trials in which observers attempted to remember 6 objects. Observers remembered nearly identical numbers of objects irrespective of whether they were also retaining 0 locations (2.4 objects), 2 locations (2.8 objects), 4 locations (2.5 objects), or 6 locations (2.7 objects).

Memory for locations

An ANOVA with factors of set size (2, 4, 6 locations) and object memory load (0, 2, 4, 6 objects) revealed a main effect of set size, $F(2, 18) = 7.40$, $p = 0.005$; $h_p^2 = 0.45$. The main effect of object memory load and the interaction did not approach statistical significance (Fs < 0.60). Furthermore, an ANOVA with factors of set size (2, 4, 6 locations) and presence of an object memory load (0 objects versus 2, 4, 6 objects) revealed a main effect of set size only, $F(2, 18) = 5.14$, $p = 0.02$; $h_p^2 = 0.36$. The effects of object memory load and the interaction were not statistically significant ($F < 0.90$). Thus, the object memory task had no significant effect on performance in the location memory task. This conclusion was supported by the storage capacity estimates, computed from the trials in which observers attempted to remember 6 locations. Observers remembered nearly identical numbers of locations regardless of whether they were also retaining 0 objects (4.5 locations), 2 objects (4.0 locations), 4 objects (3.8 locations), or 6 objects (4.2 locations).

Discussion

Experiment 1 examined whether SWM is needed to retain colored objects in VWM. Results showed that participants retained the location information from the location array and the object information from the object array by using

Table 1 The proportion of hits (responding *different* on change trials), the proportion of false alarms (FA) (responding *different* on same trials), the proportion of correct responses, and the average reaction time (RT) for the conditions in Experiment 1

	0 objects				2 objects				4 objects				6 objects			
	Hits	FA	Correct	RT	Hits	FA	Correct	RT	Hits	FA	Correct	RT	Hits	FA	Correct	RT
0 locations																
locations	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
objects	N/A	N/A	N/A	N/A	0.94	0.01	0.97	1004	0.88	0.23	0.82	1151	0.78	0.38	0.70	1268
2 locations																
locations	0.97	0.10	0.93	1042	1.00	0.15	0.93	1067	0.97	0.12	0.93	1033	0.95	0.10	0.93	1000
objects	N/A	N/A	N/A	N/A	0.97	0.08	0.94	1029	0.88	0.28	0.80	1137	0.90	0.43	0.73	1323
4 locations																
locations	0.94	0.21	0.87	1194	1.00	0.27	0.87	1120	0.88	0.18	0.85	1101	0.93	0.15	0.89	1201
objects	N/A	N/A	N/A	N/A	0.98	0.05	0.97	1051	0.87	0.20	0.83	1252	0.85	0.43	0.71	1220
6 locations																
locations	0.88	0.13	0.87	1156	0.82	0.15	0.83	1096	0.92	0.28	0.82	1307	0.95	0.25	0.85	1143
objects	N/A	N/A	N/A	N/A	0.93	0.12	0.91	1140	0.88	0.22	0.83	1187	0.88	0.43	0.73	1293

separate working memory buffers, each of which was subject to its own storage limit. Participants remembered 2-3 objects irrespective of the number of locations also being retained in memory and 4-5 locations irrespective of the number of objects also being retained in memory. This 2-3-item storage capacity for colored objects converges with previous reports. For example, Vogel, Woodman, and Luck (2001) reported storage capacity estimates of 2-3 colored objects when the data were analyzed with Cowan's (2001) formula. Importantly, the absence of any dual-task interference between the location memory task and the object memory task provides strong evidence that SWM and VWM can function independently from one another.

But what, exactly, are the units of VWM independent of contributions from SWM? There are at least three possibilities. First, the units of VWM might be integrated object representations (e.g., "red square"). This hypothesis predicts that observers will be able to remember bound color-shape objects without using resources from SWM. Second, the units of VWM might be integrated representations of features from the same feature dimension (e.g., "square"). Thus, basic features from the same feature dimension, such as oriented lines, might be stored as an integrated representation, such as a shape. For example, two identically oriented lines make either an 'L-shape' or a 'T-shape,' depending on whether the horizontal line is located lower-right or upper-middle with respect to the vertical line. VWM might store integrated shapes (e.g., the 'L-shape') rather than the more basic features that compose the shapes (e.g., the 'two oriented lines'). This hypothesis predicts that observers will be able to remember basic shapes without using resources from SWM. Third, the units of VWM might be basic features. This hypothesis predicts that observers will be able to remember basic features, such as colored objects, without using resources from SWM. However, when observers need to remember combinations of features, such as shapes or integrated color-shape objects, VWM will require resources from SWM.

To distinguish between these possibilities, I used the dual-task methodology from Experiment 1 but varied the types of objects that needed to be remembered in the object memory task. Specifically, in the *color condition* observers needed to remember colored objects; in the *shape condition* observers needed to remember shapes; in the *binding condition* observers needed to remember integrated color-shape objects.

Experiment 2

If the units of VWM are integrated objects, then performance on the location memory task should be independent from performance on the object memory task in all three conditions because SWM would not be needed to retain information about colors, shapes, or integrated color-shape objects. If the units of VWM are integrated representations of features from the same feature dimension, then performance on the location memory task should be independent from performance on the object memory task in the *color condition* and *shape condition*. A color representation consists of a single feature value, and a shape representation consists of a combination of feature values from the same feature dimension. Thus, memory for colored objects and memory for shapes should not require resources from SWM. However, memory for integrated color-shape objects in the *binding condition* should require resources from SWM to maintain the links between the color and shape values stored in VWM. Finally, if the units of VWM are basic features, then performance on the location memory task should be independent from performance on the object memory task in the *color condition* because color values are basic features and could therefore be retained in VWM without recruiting resources from SWM. However, representations of shapes and representations of integrated color-shape objects consist of combinations of basic features. Thus, SWM should be needed in the *shape condition* (to remember how basic features were organized into shapes) and in the *binding condition* (to remember how colors and shapes were organized into objects).

Subjects

Fifteen different participants served in each condition:

> *Color condition*: male: 7; female: 8; mean age = 19.93 years, SD = 2.74.
> *Shape condition*: male: 6; female: 9; mean age = 19.87 years, SD = 2.45.
> *Binding condition*: male: 4; female: 11; mean age = 21.07 years, SD = 3.49.

The data from two additional participants were excluded from the final analyses because they responded at chance levels.

Methods

The methods were identical to those used in Experiment 1 except in the following ways. First, the location arrays consisted of 0, 3, or 9 locations. Second, the object array consisted of 0 or 4 objects. Third, the type of object that needed to be remembered from the object array varied across three conditions. In the *color condition*, each object had a unique color and participants were instructed to remember the colors of the objects. On different trials, the test object consisted of a color that had not been present in the object array. In the *shape condition*, each object had a unique shape and participants were instructed to remember the shapes of the objects. On different trials, the test object consisted of a shape that had not been present in the object array. In the *binding condition*, each object had a unique color and shape and participants were instructed to remember how the colors and shapes were organized into objects. On different trials, the test object consisted of a color from one study object and a shape from a different study object; thus, participants needed to retain integrated object representations, remembering which color was associated with which shape.

For all conditions the test object was presented at a neutral location at the center of the screen. To equate the perceptual demands of the task across all of the trials, during the 0-object trials the outlines of four empty “filler” objects were presented, and during the 0-location trials the grid was presented but without any dots to designate locations within the grid. See Fig. 2 for a schematic illustration of a trial from each condition.

Results

Figure 2 depicts the results. See Table 2 for the proportions of hits, false alarms, correct responses, and the reaction times for all conditions.

Memory for objects

An ANOVA analyzing the effect of location memory load (0, 3, or 9 locations) on object memory performance was nearly significant for the *binding condition* ($F(2, 28) = 2.86$, $p = 0.07$, $h_p^2 = 0.17$) and significant for the *shape condition* ($F(2, 28) = 3.56$, $p = 0.04$, $h_p^2 = 0.20$), but was not significant for the *color condition* ($F(2, 28) = 1.73$, $p = 0.20$, $h_p^2 = 0.11$). Further, an ANOVA analyzing the effect of a concurrent location memory load (0 locations versus 3 and 9 locations) on object memory performance was significant for the *binding condition* ($F(1, 14) = 6.69$, $p = 0.02$, $h_p^2 = 0.32$) and significant for the *shape condition* ($F(1, 14) = 5.29$, $p = 0.04$, $h_p^2 = 0.27$), but was not significant for the *color condition* ($F(1, 14) = 1.43$ $p = 0.25$, $h_p^2 = 0.09$). Thus, the location memory task did not interfere with the color memory task but did interfere with the shape memory task and the binding memory task.

These conclusions were supported by the storage capacity estimates. In the *color condition*, participants remembered nearly identical numbers of objects irrespective of whether there was no location memory load (3.07 colors), a 3-location memory load (2.75 colors), or a 9-location memory load (2.96 colors). In contrast, in the *shape condition* and the *binding condition,* participants remembered fewer objects as the demands of the location

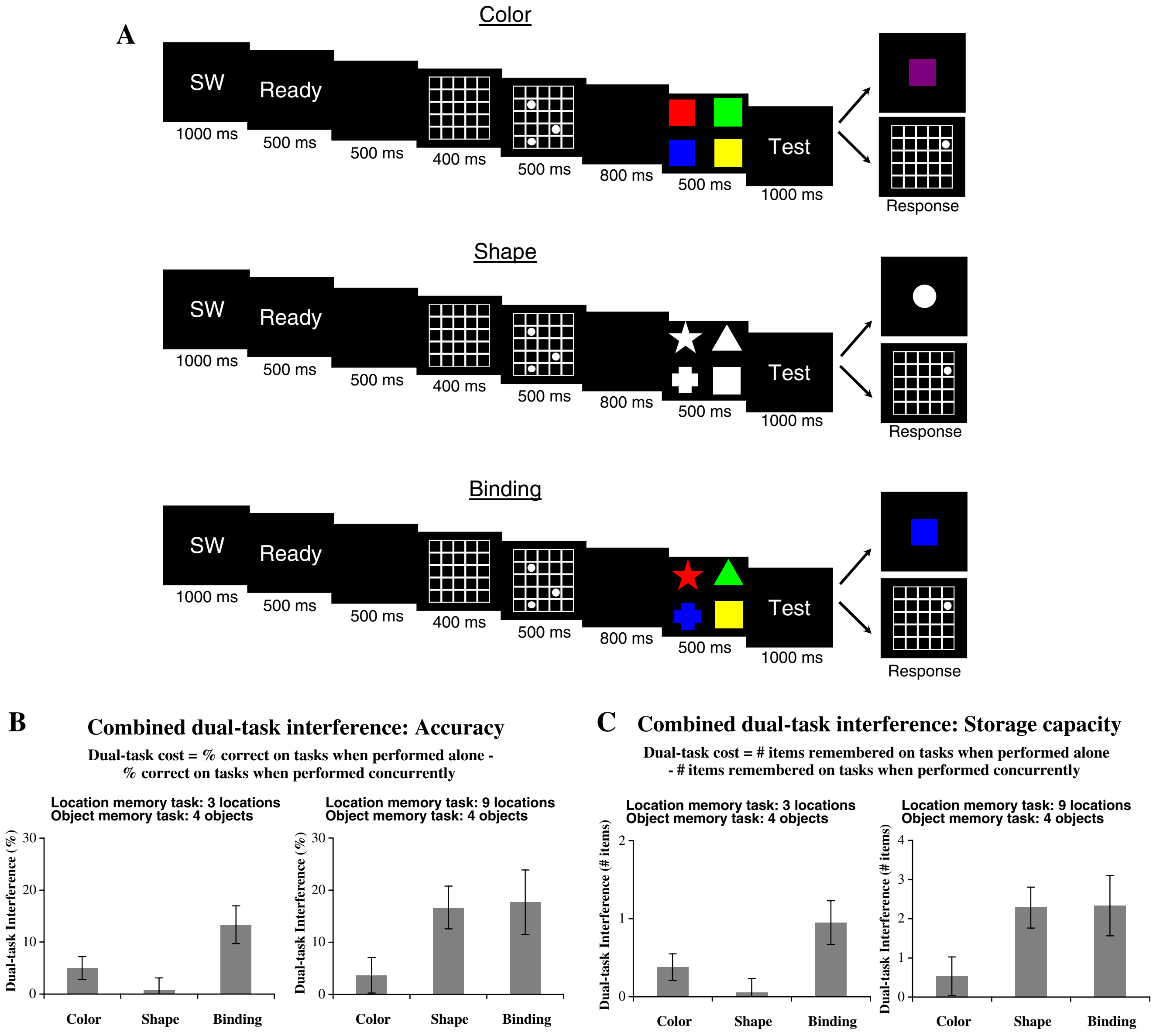

Fig. 2 (**a**) Schematic illustration of a trial from the color condition, the shape condition, and the binding condition in Experiment 2. For each example, the test object and the test location are different from all of the objects and locations in the trial. (**b**) The combined dual-task interference (accuracy) for the color condition, the shape condition, and the binding condition. (**c**) The combined dual-task interference (storage capacity) for the color condition, the shape condition, and the binding condition. Error bars represent standard error

memory task increased (*shape condition*: no location memory load = 2.79 shapes, 3-location memory load = 2.72 shapes, 9-location memory load = 2.21 shapes; (*binding condition:* no location memory load = 2.20 objects, 3-location memory load = 1.60 objects, 9-location memory load = 1.52 objects).

Memory for locations

An ANOVA analyzing location memory performance with factors of set size (3, 9 locations) and load (0 versus 4 objects) revealed a significant main effect of set size for the *binding condition* ($F(1, 14) = 184.11$, $p < 0.001$; $h_p^2 = 0.93$), the *shape condition* ($F(1, 14) = 148.55$, $p < 0.001$; $h_p^2 = 0.91$), and the *color condition* ($F(1, 14) = 81.61$, $p < 0.001$; $h_p^2 = 0.85$). The main effect of load was significant for the *binding condition* ($F(1, 14) = 19.47$, $p = 0.001$, $h_p^2 = 0.58$) and the *shape condition* ($F(1, 14) = 8.67$, $p = 0.01$; $h_p^2 = 0.38$), but was not significant for the *color condition* ($F(1, 14) = 0.98$, $p = 0.34$; $h_p^2 = 0.07$). The interaction was not significant for the *binding condition* ($F(1, 14) = 0.71$, $p = 0.42$, $h_p^2 = 0.05$) or the *color condition* ($F(1, 14) = 0.16$, $p = 0.69$; $h_p^2 = 0.01$), but was significant for the *shape condition* ($F(1, 14) = 12.67$, $p = 0.003$; $h_p^2 = 0.48$).

Table 2 The proportion of hits (responding *different* on change trials), the proportion of false alarms (FA) (responding *different* on same trials), the proportion of correct responses, and the average reaction time (RT) for the conditions in Experiment 2

	0 objects				4 objects			
	Hits	FA	Correct	RT	Hits	FA	Correct	RT
Color Condition								
0 locations								
locations	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
objects	N/A	N/A	N/A	N/A	0.95	0.18	0.88	1285
3 locations								
locations	0.98	0.06	0.96	1168	0.97	0.07	0.95	1207
objects	N/A	N/A	N/A	N/A	0.93	0.24	0.84	1290
9 locations								
locations	0.79	0.25	0.77	1395	0.77	0.27	0.75	1450
objects	N/A	N/A	N/A	N/A	0.94	0.20	0.87	1358
Shape condition								
0 locations								
locations	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
objects	N/A	N/A	N/A	N/A	0.84	0.14	0.85	1333
3 locations								
locations	0.97	0.10	0.94	1072	0.96	0.09	0.94	1134
objects	N/A	N/A	N/A	N/A	0.84	0.16	0.84	1299
9 locations								
locations	0.86	0.27	0.80	1265	0.79	0.39	0.70	1281
objects	N/A	N/A	N/A	N/A	0.75	0.19	0.78	1281
Binding condition								
0 locations								
locations	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
objects	N/A	N/A	N/A	N/A	0.82	0.27	0.78	1391
3 locations								
locations	0.98	0.06	0.96	1007	0.91	0.11	0.90	1179
objects	N/A	N/A	N/A	N/A	0.77	0.37	0.70	1331
9 locations								
locations	0.87	0.27	0.80	1232	0.80	0.39	0.71	1324
objects	N/A	N/A	N/A	N/A	0.71	0.33	0.69	1340

Thus, the color memory task did not interfere with the location memory task, but the shape memory task and the binding memory task did interfere with the location memory task.

Analysis of combined dual-task interference

To compare the extent of interference across conditions, the combined dual-task interference from the location and object memory tasks was computed using the following procedure:

> Combined dual-task interference = [(% correct on object memory task when performed alone) – (% correct on object memory task when performed concurrently with location memory task)] + [(% correct on location memory task when performed alone) – (% correct on location memory task when performed concurrently with object memory task)]

An ANOVA on the combined dual-task interference with the within-subjects factor of location load (3 and 9 locations) and the between-subjects factor of object type (color, shape, binding) revealed a significant main effect of location load ($F(1, 42) = 5.57$, $p = 0.02$, $h_p^2 = 0.12$) and a significant interaction ($F(2, 42) = 3.59$, $p = 0.04$, $h_p^2 = 0.15$). Post hoc analyses revealed the pattern of dual-task interference depicted in Fig. 2. For the easier location memory load (3 locations), the combined dual-task interference was nearly identical in the *shape condition* and the *color condition* ($t(28) = 1.27$, $p = 0.22$). However, there were significant or nearly significant differences in the combined dual-task interference between the *binding condition* and the *shape condition* ($t(28) = 2.84$, $p = 0.009$) and between the *binding condition* and the *color condition* ($t(28) = 1.94$, $p = 0.06$). For the harder location memory load (9 locations), there were significant or nearly significant differences in the combined dual-task interference between the *binding condition* and the *color condition* ($t(28) = 1.98$, $p = 0.06$) and between the *shape condition* and the *color condition* ($t(28) = 2.45$, $p = 0.02$). The combined dual-task interference was nearly identical in the *binding condition* and the *shape condition* ($t(28) = 0.12$, $p = 0.90$).

Discussion

When participants performed a location memory task and an object memory task for colored objects, there was little to no interference between the two memory tasks. Thus, VWM can retain color information without using resources from SWM. This replicates the main finding from Experiment 1 with a new group of participants and with a more demanding memory load of 9 locations. In contrast, when participants performed a location memory task and an object memory task for either shapes or integrated color-shape objects, there was significant interference between the memory tasks. This suggests that retaining shapes and integrated color-shape objects in VWM requires resources from SWM.

As shown in Fig. 2, there was interference between the binding memory task and the location memory task for both the easier (3 locations) and harder (9 locations) loads, whereas there was interference between the shape memory task and the location memory task for the harder load (9 locations) only. This suggests that retaining a bound color-shape object in VWM requires greater resources from SWM than retaining a shape alone.

In sum, these results suggest that VWM can retain colors without using resources from SWM; however, retaining shapes and integrated color-shape objects requires resources from both VWM and SWM. Thus, the only units of information that could be retained in VWM without using resources from SWM were basic color features.

There are, however, three alternative explanations for this pattern of data. First, the binding memory task was more difficult than the color and shape memory tasks. Thus, the binding task might have placed greater demands on the visual system in general, thereby leading to greater dual-task interference. This alternative explanation was tested in Experiment 3.

Second, the interference between the location memory task and the binding and shape memory tasks may have occurred from processes other than working memory storage, such as those used to perceive or identify the objects. This alternative explanation was tested in Experiment 4.

Third, despite performing an articulatory suppression task on each trial, participants might nonetheless have retained a significant portion of information in verbal working memory. This alternative explanation was tested in Experiment 5.

The lack of interference between the location memory task and the color memory task in Experiments 1 and 2 also appears to be inconsistent with previous reports showing that VWM retains information about colored objects as part of a larger spatial configuration (Jiang et al., 2000). Presumably, these spatial configurations require resources from SWM, which should therefore have caused interference between the location memory task and the color memory task. Experiment 6 reconciles these ostensibly conflicting findings by showing that resources from SWM are needed to retain colored objects in VWM in some, but not all, contexts. Specifically, resources from SWM are needed when colored objects are tested at the same locations that they were encoded.

Experiment 3

In Experiment 2, the overall performance on the object memory task was lower in the *binding condition* compared to in the *color condition* and the *shape condition*. The greater difficulty of this task might have placed greater loads on the visual system in general, which raises the possibility that the dual-task interference observed in the *binding condition* was not due to interference between VWM and SWM more specifically. This alternative account predicts that any manipulation that increases the difficulty of the object memory task will increase demands on the visual system, thereby leading to interference between the two tasks.

To test this prediction, the color memory task from Experiment 2 was replaced with a more difficult color memory task. Specifically, the seven color values that needed to be remembered were selected from a smaller portion of the color spectrum. Thus, the color values were more similar to one another, which made the colors more difficult to discriminate from one another. Critically, this made the object memory task more difficult without changing the nature of the memory task (i.e., the task still required memory for colored objects).

Methods

Thirteen new participants (male: 4; female: 9; mean age = 19.77 years, SD = 1.01) served. Two additional participants were excluded due to chance performance. The methods were identical to the *color condition* in Experiment 2 except that the color values were selected from a smaller portion of the color spectrum. See Fig. 3 for a visual comparison of the color values used in Experiments 2 and 3.

Results

See Table 3 for the proportions of hits, false alarms, correct responses, and the reaction times for all conditions.

Memory for objects

On the trials in which there was no location memory load, performance was significantly lower in Experiment 3 compared to Experiment 2 for the *color condition* ($F(1, 26) = 17.11$, $p < 0.001$) and the *shape condition* ($F(1, 26) = 15.45$, $p = 0.001$), but not for the *binding condition* ($F(1, 26) = 0.75$, $p = 0.40$). Thus, the color memory task used in Experiment 3 was more difficult than the color memory task used in Experiment 2.

An ANOVA analyzing the effect of location memory load (0, 3, or 9 locations) on object memory performance was nearly significant ($F(2, 24) = 3.04$, $p = 0.07$; $h_p^2 = 0.20$). However, an ANOVA analyzing the effect of a concurrent location memory load (0 locations versus 3 and 9 locations) on object memory performance did not approach significance ($F < 0.1$). Thus, the location memory task had little to no effect on the color memory task. This conclusion was supported by the storage capacity estimates. Participants remembered nearly identical numbers of objects regardless of whether there was no location memory load (1.95 colors), a 3-location memory load (1.63 colors), or a 9-location memory load (2.28 colors).

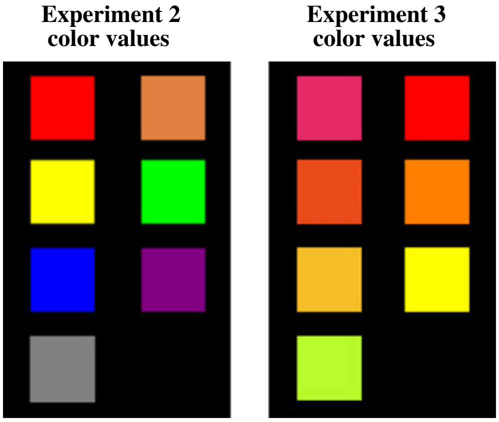

Fig. 3 The color values used in Experiments 2 and 3. The color values used in Experiment 3 were selected from a smaller portion of the color spectrum than the color values used in Experiment 2

Memory for locations

An ANOVA analyzing location memory performance with factors of set size (3, 9 locations) and load (0 versus 4 objects) revealed significant main effects of set size ($F(1, 12) = 66.39$, $p < 0.001$; $h_p^2 = 0.85$) and load ($F(1, 12) = 19.29$, $p = 0.001$; $h_p^2 = 0.62$). The interaction was also significant ($F(1, 12) = 6.91$, $p = 0.02$; $h_p^2 = 0.37$). The color memory task interfered with the location memory task when there was a 9-location memory load, but not when there was a 3-location memory load. This pattern of interference contrasts with the pattern observed in the *binding condition* in Experiment 2, where the object memory task interfered with the location memory task both when there was a 9-location memory load and a 3-location memory load (see Fig. 2). Post hoc analyses confirmed this observation, revealing a significant difference in the total amount of dual-task interference between this experiment and the *binding condition* from Experiment 2 ($t(26) = 1.72$, $p = 0.05$; 1-tailed), but not between this experiment and the *color condition* ($t(26) = 0.70$, $p = 0.49$) or the *shape condition* ($t(26) = 0.44$, $p = 0.66$) from Experiment 2.

Discussion

This experiment examined whether the dual-task interference in the *binding condition* from Experiment 2 occurred because the binding memory task was simply more difficult than the color or shape memory tasks. To test this, an examination was made of whether a more difficult color memory task would interfere with a location memory task. Results revealed moderate interference between the color memory task and the location memory task when participants needed to retain information about 9 locations, but little to no interference when participants needed to retain information about 3 locations. Thus, the extent of dual-task interference was less pronounced than in the *binding condition* from Experiment 2, despite being a more difficult object memory task. The difficulty of the binding memory task therefore cannot be the sole explanation for the dual-task interference observed in the *binding condition* in Experiment 2.

Experiment 4

A second alternative explanation for the dual-task interference in the *shape condition* and the *binding condition* is that the interference was due to competition between processes other than working memory storage, such as those used to perceive and/or identify the objects. During immediate perception, spatial attention binds basic features

Table 3 The proportion of hits (responding *different* on change trials), the proportion of false alarms (FA) (responding *different* on same trials), the proportion of correct responses, and the average reaction time (RT) for the conditions in Experiment 3

	0 objects				4 objects			
	Hits	FA	Correct	RT	Hits	FA	Correct	RT
0 locations								
locations	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
objects	N/A	N/A	N/A	N/A	0.66	0.17	0.74	1245
3 locations								
locations	0.97	0.05	0.96	943	0.95	0.05	0.95	1123
objects	N/A	N/A	N/A	N/A	0.65	0.24	0.70	1226
9 locations								
locations	0.87	0.19	0.84	1181	0.78	0.35	0.72	1205
objects	N/A	N/A	N/A	N/A	0.79	0.22	0.78	1189

into integrated percepts (Treisman & Gelade, 1980), and there is evidence that spatial attention and SWM draw upon a common capacity-limited resource (e.g., Woodman & Luck, 2004). Thus, the spatial attention needed to perceive the shapes and integrated color-shape objects may have drawn resources from SWM, thereby leading to interference between the two tasks.

To test this possibility, I conducted an additional experiment in which participants needed to identify, but not remember, the objects in the object array. In particular, participants performed a visual search task, searching for a particular target object, while concurrently performing the SWM task. Accurate performance in the visual search task requires that the observer identify the objects in the search array so that they can determine whether the target object is present, but it does not require that they remember the features of the objects.

If the dual-task interference observed in the *shape condition* and the *binding condition* was due to competition between SWM and spatial attention, then the visual search task should interfere with the SWM task. However, if the dual-task interference was due to competition between SWM and VWM, then the visual search task should not interfere with the SWM task.

Methods

Nine new participants served (male: 3; female: 6; mean age = 21.0 years, SD = 4.95). The data from two additional participants were excluded from the final analyses because they responded at chance levels. Each trial began with a 1,000-ms presentation of two randomly selected letters, and participants were required to repeat those letters continuously and out loud until the end of the trial. The offset of these letters was followed by the 300-ms presentation of the spatial grid, followed by the 500-ms presentation of either three dots or nine dots appearing within randomly selected positions within the grid. After the presentation of the dots, the spatial grid remained visible for 300 ms, followed by the presentation of a 500-ms black screen and then the search array. The search array consisted of four objects and remained visible for 1,500 ms, during which participants were required to make an unspeeded button-press response to indicate whether the target object was present or absent in the search array. The target object was present on 50% of the trials. The offset of the search array was followed by the 300-ms presentation of the spatial grid, followed by the appearance of a single dot within the grid. Participants were required to make an unspeeded response to indicate whether the location had been present in the location array.

Participants completed four conditions, which were counterbalanced across participants. In the *color search condition*, the target object was a red square. The non-target objects in the display consisted of squares of other colors. In the *shape search condition*, the target object was a white circle. The non-target objects in the display consisted of white objects of other shapes. In the *binding search condition*, the target object was a red circle. The non-target objects in the display consisted of objects of other shapes and colors. On target-absent trials, one of the objects was red and a different object was a circle. In the *no search condition*, the search array consisted of four empty “filler” objects (i.e., four box outlines). Participants were instructed to push the target-present button when the filler objects appeared.

Participants were asked to search for the same target object within each condition to minimize demands on VWM (i.e., if participants had been asked to search for a different target object on each trial, then they would have needed to store a representation of the target object in VWM). See Fig. 4 for a schematic illustration of a trial from each condition. Participants received 48 trials in each condition. Each condition was preceded by six practice trials.

Results

Figure 4 depicts the results. See Table 4 for the proportions of hits, false alarms, correct responses, and the reaction times for all conditions.

Visual search performance

An ANOVA analyzing visual search performance with factors of location memory load (3 or 9 locations) and visual search condition (color search, shape search, binding search) did not reveal any significant main effects or interactions (Fs < 1.30). Search performance was 93% correct or higher when the condition required a search for a color target, a shape target, or an integrated color-shape target. Further, an ANOVA analyzing visual search performance on the target-absent trials with factors of location memory load (3 or 9 locations) and visual search condition (color search, shape search, binding search) did not reveal any significant main effects or interactions (Fs < 0.60). Search performance on the target-absent trials was 94% correct or higher when the condition required a search for a color target, a shape target, or an integrated color-shape target.

An ANOVA on the reaction time data with factors of location memory load (3 or 9 locations) and visual search condition (color search, shape search, binding search) did not reveal any significant main effects or interactions (Fs < 1.7).

Memory for locations

An ANOVA analyzing location memory performance with factors of set size (3, 9 locations) and search condition (color search, shape search, binding search, no search) revealed a main effect of set size ($F(1, 8) = 45.98$, $p < 0.001$; $h_p^2 = 0.85$). The main effects of search condition ($F < 0.60$) and the interaction were not significant ($F < 1.40$). Further, a nearly identical pattern was observed when the analysis was restricted to target-absent trials: an ANOVA with factors of set size (3, 9 locations) and search condition (color search, shape search, binding search) revealed a main effect of set size ($F(1, 8) = 22.78$, $p = 0.001$; $h_p^2 = 0.74$). The main effect of search condition and the interaction were not significant (Fs < 0.60).

Discussion

This experiment shows that observers can perform a simple visual search task for colors, shapes, and integrated color-shape objects without using significant resources from SWM. Specifically, performance on the SWM task was nearly identical whether observers did, or did not, perform a visual search task. Further, performance on the SWM task was nearly identical whether the visual search task required searching for a color target, a shape target, or an integrated color-shape target. Thus, little to no resources from SWM were needed in order to perceive and identify the object stimuli used in Experiment 2.

To be clear, these results do not show that SWM and spatial attention operate independently from one another in all contexts. Indeed, there is evidence that SWM and spatial attention draw upon a common capacity-limited resource in some contexts (e.g., Woodman & Luck, 2004). Rather, the present results suggest that in order to observe significant competition between a SWM task and a visual search task, it may be necessary to use a more demanding search task, such as the one used by Woodman and Luck (2004). Importantly for the present investigation, the objects used in Experiment 2 could be perceived and identified without requiring significant resources from SWM. The dual-task interference between the location memory task and the shape and binding memory tasks in Experiment 2 therefore did not result from interference between SWM and spatial attention. Rather, the dual-task interference presumably resulted from competition between SWM and VWM.

Experiment 5

To what extent does verbal working memory contribute to performance in this task? Although participants performed an articulatory suppression task throughout each trial, they may nonetheless have sustained some object information using verbal working memory (e.g., by remembering the word “red” to remember a red object). To test this, the extent to which participants use verbal working memory to retain information in this object memory task was measured.

Participants performed two concurrent memory tasks. In the first memory task, they attempted to remember as many letters as possible. In the second memory task, they attempted to remember as many colored objects as possible.

In the *verbal only condition*, participants performed the letter memory task alone. This condition provided a baseline measure of the number of letters that can be retained in verbal working memory at one time. In the *verbal and object (neutral location) condition*, participants performed the letter and object memory tasks concurrently, with the test object appearing at a neutral location at the center of the screen, as in Experiments 1-3. This condition provided a measure of the number of letters and the number of colored objects that can be retained in working memory concurrently. In the *verbal and object (same location) condition*, participants performed the letter and object

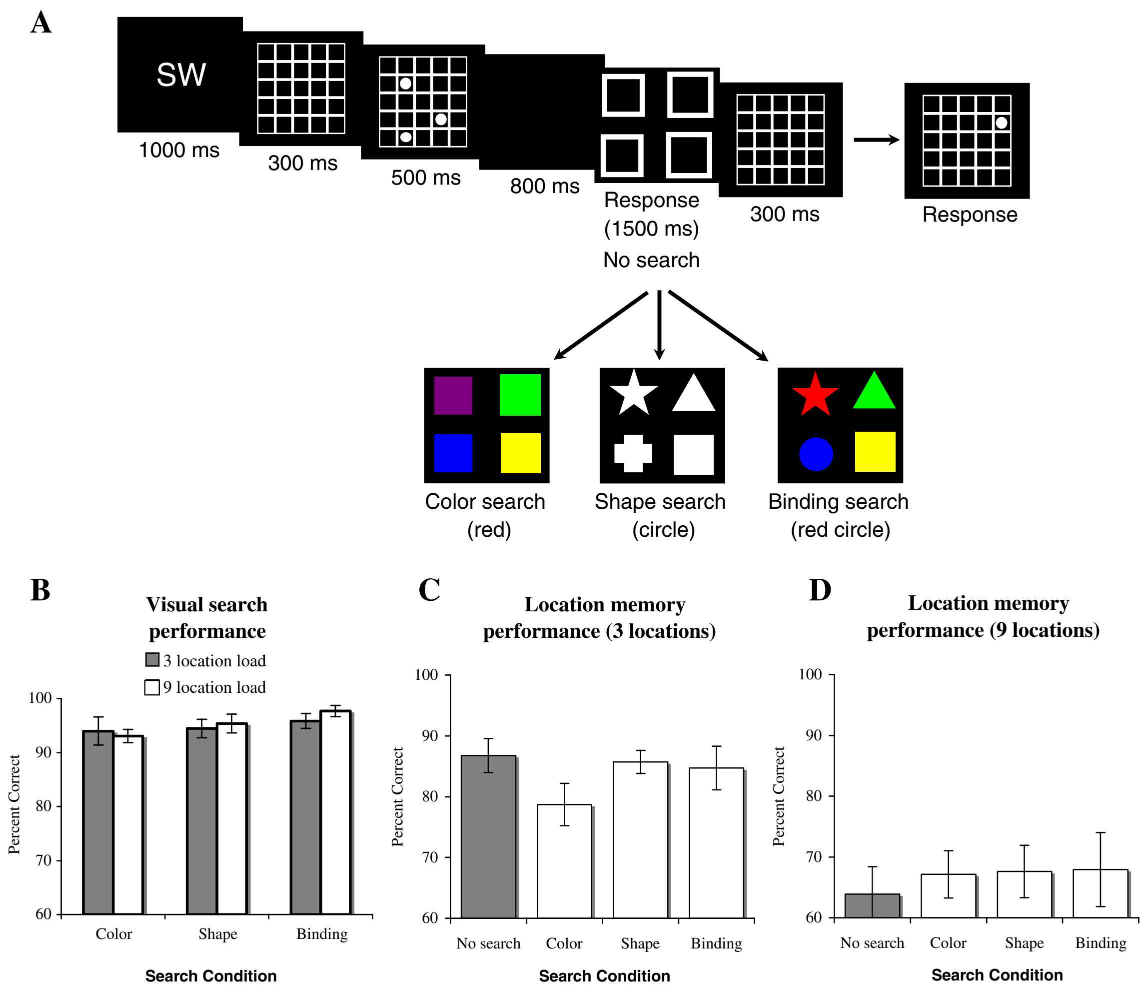

Fig. 4 (**a**) Schematic illustration of a trial from Experiment 4, presenting three locations in the location memory task and an example of a display from each of the search conditions: no search, color search, shape search, and binding search. For each example, the test location is different from all of the locations in the trial, and the visual search displays depict target-absent trials. (**b**) Performance on the visual search task. (**c**) Performance on the location memory test trials for three locations. (**d**) Performance on the location memory test trials for nine locations. Error bars represent standard error

memory tasks concurrently, with the test object appearing at the same location in the study and test arrays. This condition provided a measure of the number of letters and the number of colored objects at specific locations that can be retained in working memory concurrently.

Methods

Nine new participants served (male: 2; female: 8; mean age = 21.9 years, SD = 4.43). Each trial began with the 500-ms presentation of a fixation cross, followed by the presentation of the letter sequence. Each letter appeared for 200 ms, followed by an 800-ms inter-stimulus interval. Seven letters appeared in the sequence, selected at random without replacement from the following set: (F, G, K, N, P, Q, R, S, T, X, Y, Z). After the presentation of the letter sequence, the object array appeared, which consisted of four colored squares. In the *verbal only condition*, the outlines of four empty filler objects were presented in the object array. In the *verbal and object (neutral location) condition*, participants performed the letter and object memory tasks concurrently, with the test object appearing at a neutral location at the center of the screen, as in Experiments 1-3. In the *verbal and object (same location) condition*, participants performed the letter and object memory tasks concurrently, with the test object appearing at the same location in the study and test arrays.

During a 1,000-ms retention interval, the word “test” appeared, followed either by a single test object (50% of trials) or a single letter (50% of trials). The test item was different from all of the items in the letter sequence and the object array on 50% of the trials. To encourage the use of verbal working memory rather than VWM, the letters in the study sequence were presented in uppercase and the test letter was presented in lowercase (Vogel et al., 2001). This encouraged participants to remember abstract identities rather than the low-level visual features of the letters. See Fig. 5 for a schematic illustration of a trial from each condition.

Participants received 40 trials in each of the three conditions, which were counterbalanced across subjects. Each condition was preceded by six practice trials.

Results and discussion

Figure 5 depict the results. See Table 5 for the proportions of hits, false alarms, correct responses, and the reaction times for all conditions.

Object memory performance did not differ significantly when the objects appeared at a neutral location in the test array versus at the same location ($F < 0.30$). An ANOVA analyzing the effect of a concurrent object memory task (0 objects, 4 objects-same location, 4 objects-neutral location) on verbal memory performance did not approach statistical significance ($F < 0.80$). Participants could remember 4-5 letters irrespective of the number of colored objects also being retained in memory.[2] Thus, this result shows that the articulatory suppression task used in these experiments successfully inhibits the verbal recoding of stimuli, which rules out the possibility that verbal working memory sustained a significant portion of information in the object memory tasks.

Experiments 1–5 provide evidence that VWM requires resources from SWM to retain shapes and integrated color-shape objects. Do VWM and SWM also interact in other contexts? One well-known characteristic of VWM is that objects can be stored as parts of a larger spatial configuration. Specifically, when observers retain objects in VWM and the objects appear at the same locations in the study and test arrays, they also retain information about the spatial relations between those objects (Jiang et al., 2000). This raises the possibility that when objects are encoded and tested at the same locations, VWM retains features as parts of a larger spatial configuration by using resources from SWM. Experiment 6 tested this possibility by examining whether resources from SWM are needed to remember colored objects that appear at the same locations in the study and test arrays.

Table 4 The proportion of hits (responding *different* on change trials), the proportion of false alarms (FA) (responding *different* on same trials), the proportion of correct responses, and the average reaction time (RT) for the conditions in Experiment 4

	Color search				Shape search				Binding search				No search			
	Hits	FA	Correct	RT	Hits	FA	Correct	RT	Hits	FA	Correct	RT	Hits	FA	Correct	RT
3 locations																
locations	0.83	0.28	0.79	855	0.88	0.16	0.86	909	0.85	0.15	0.85	875	0.89	0.15	0.87	770
search	N/A	N/A	0.94	848	N/A	N/A	0.94	779	N/A	N/A	0.96	780	N/A	N/A	N/A	N/A
9 locations																
locations	0.67	0.32	0.67	988	0.68	0.33	0.67	888	0.63	0.27	0.68	885	0.67	0.39	0.64	832
search	N/A	N/A	0.93	849	N/A	N/A	0.95	785	N/A	N/A	0.98	806	N/A	N/A	N/A	N/A

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[2] Results revealed minimal dual-task interference between the verbal working memory task and the object memory task. The magnitude of the small dual-task cost, 0.63 letter's worth of information, was no greater than the 0.60–0.80-item cost observed in previous dual-task experiments that placed high loads on verbal working memory and VWM concurrently (Morey & Cowan, 2004), and thus, presumably reflects demands on a more central, amodal component of working memory.

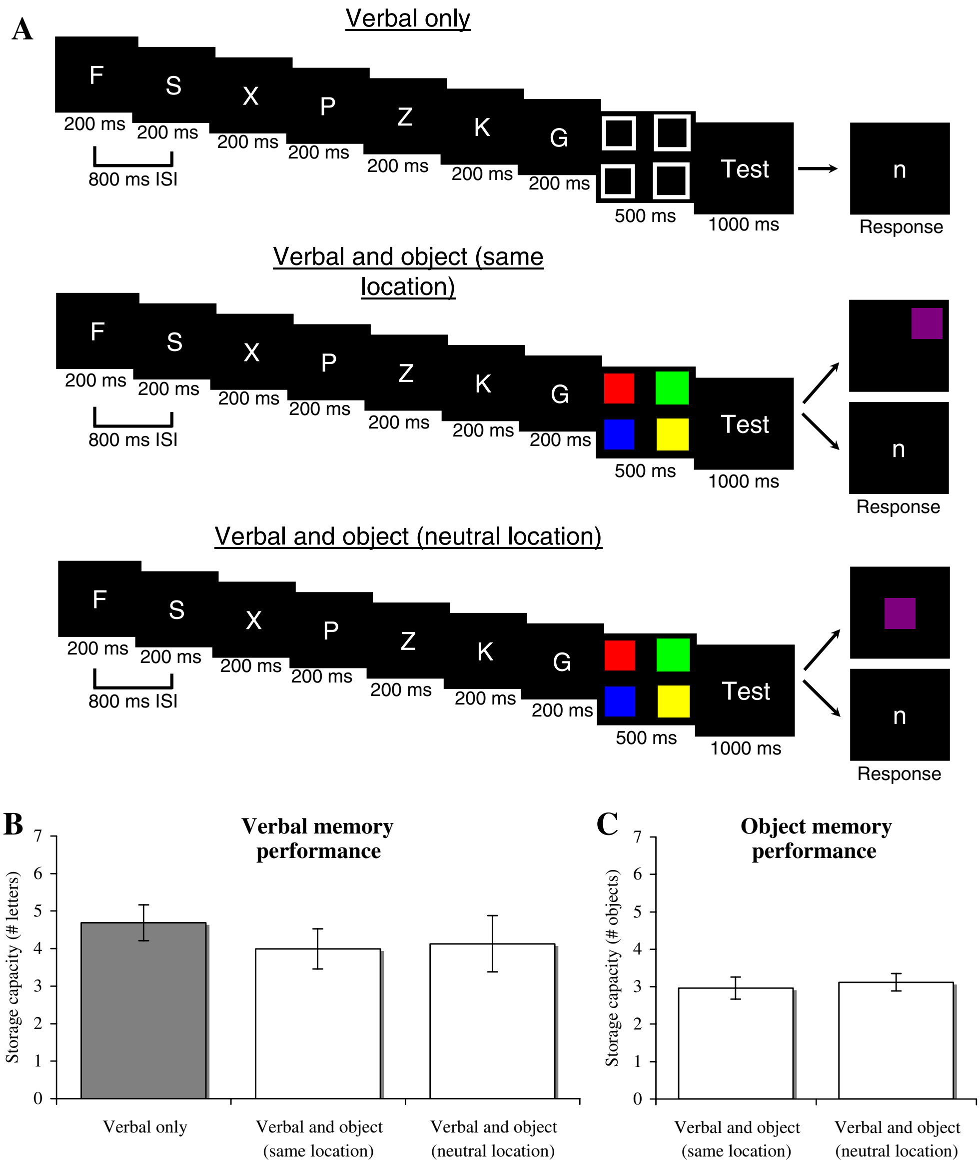

Fig. 5 (**a**) Schematic illustration of a trial from the three conditions in Experiment 5. For each example, the test object and the test letter are different from all of the objects and letters in the trial. (**b**) Performance on the letter memory test trials. (**c**) Performance on the object memory test trials. Error bars represent standard error

Experiment 6

Methods

Ten new participants served (male: 4; female: 6; mean age = 21.1 years, SD = 2.69). The methods were identical to those used in the *color condition* from Experiment 2 except in the following ways. On 50% of the object test trials, the object test array contained a single object presented in the same location as one of the four objects in the object array (*single item test condition*), and on the other 50% of the object test trials the object test array contained four objects presented in the same locations as the four objects in the object array (*full array test condition*). Object memory was tested in these two

Table 5 The proportion of hits (responding *different* on change trials), the proportion of false alarms (FA) (responding *different* on same trials), the proportion of correct responses, and the average reaction time (RT) for the conditions in Experiment 5

	Verbal only				Verbal & object (same loc.)				Verbal & object (neutral loc.)			
	Hits	FA	Correct	RT	Hits	FA	Correct	RT	Hits	FA	Correct	RT
Verbal	0.91	0.24	0.84	1870	0.80	0.23	0.79	2202	0.89	0.30	0.80	1993
Objects	N/A	N/A	N/A	N/A	0.97	0.23	0.87	1561	0.95	0.17	0.89	1513

ways to explore the possibility that needing to retrieve object information from more than one location might affect performance in some way. In the *single item test condition*, on 50% of the trials the test object changed to a new color that was different from the colors of all of the objects in the object array; on the other 50% of the trials the test object was identical to the object that appeared at that same location in the object array. In the *full array test condition*, on 50% of the trials one of the four test objects changed to a new color that was different from the colors of all of the objects from the object array; on the other 50% of the trials the four test objects were identical in color and location to the four objects that appeared in the object array. See Fig. 6 for a schematic illustration of a trial from each condition.

Results

Figure 6 depicts the results. See Table 6 for the proportions of hits, false alarms, correct responses, and the reaction times for all conditions.

Memory for objects

In the *single item test condition*, an ANOVA analyzing the effect of the number of locations (0, 3, 9 locations) on object memory performance did not approach statistical significance ($F < 0.40$). Furthermore, object memory performance did not vary as a function of the presence or absence of a location memory load (0 locations versus 3, 9 locations, $F < 0.80$). In the *full array item test condition*, there was a marginal but non-significant difference in object memory as a function of the number of locations (0, 3, 9 locations) that were also being retained in memory ($F(2, 18) = 3.12$, $p = 0.07$, $h_p^2 = 0.26$). Accuracy was similar when participants were also retaining 0 locations (84%) and 3 locations (87%), but slightly lower when they were also retaining 9 locations (80%). However, object memory performance did not vary as a function of the presence or absence of a location memory load (0 locations versus 3, 9 locations, $F < 0.05$). Thus, in general, the location memory task had little to no influence on the object memory task. This conclusion was supported by the storage capacity estimates. Across both the

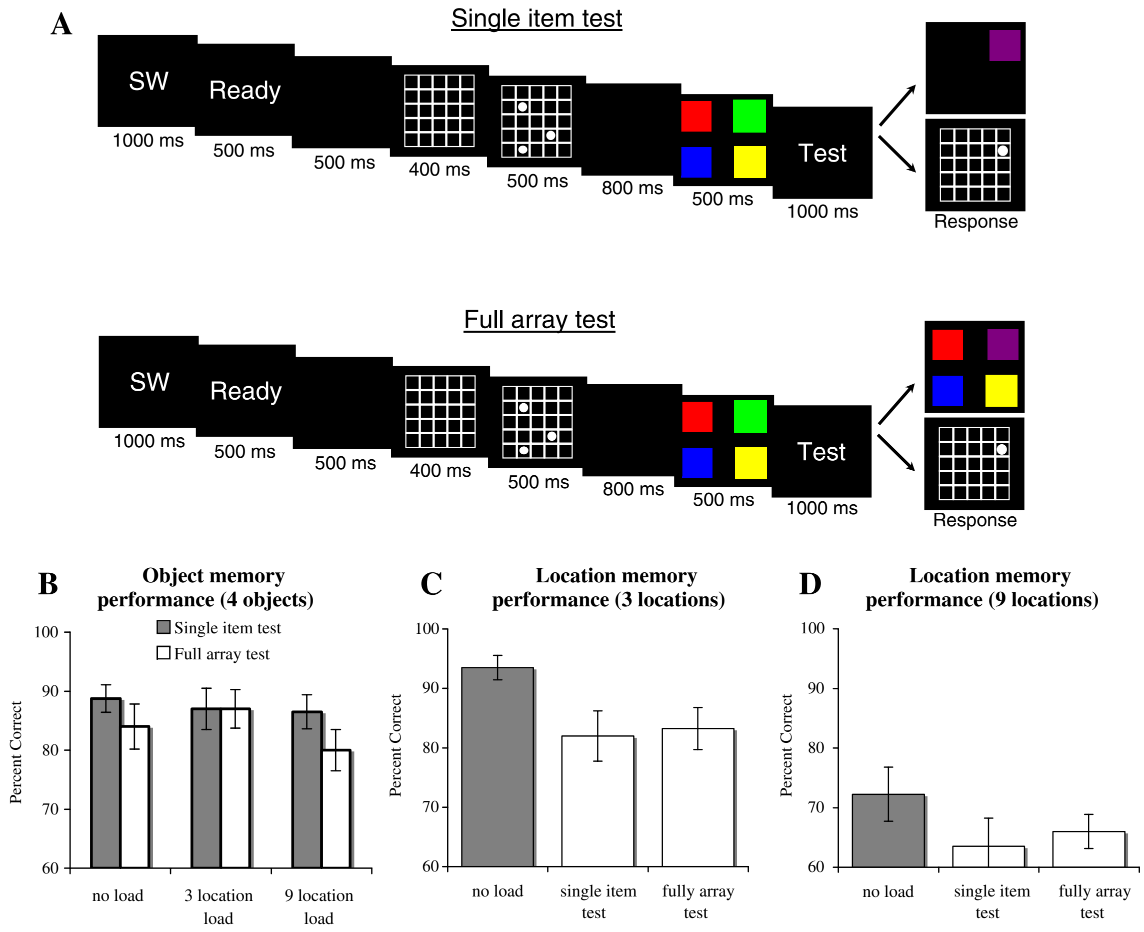

Fig. 6 (**a**) Schematic illustration of a trial from the two conditions in Experiment 6. (**b**) Performance on the object memory test trials. (**c**) Performance on the location memory test trials for three locations. (**d**) Performance on the location memory test trials for nine locations. Error bars represent standard error

Table 6 The proportion of hits (responding *different* on change trials), the proportion of false alarms (FA) (responding *different* on same trials), the proportion of correct responses, and the average reaction time (RT) for the conditions in Experiment 6

	0 objects				Single item test				Full array test			
	Hits	FA	Correct	RT	Hits	FA	Correct	RT	Hits	FA	Correct	RT
0 locations												
locations	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
objects	N/A	N/A	N/A	N/A	0.96	0.19	0.89	1325	0.71	0.03	0.84	1309
3 locations												
locations	0.97	0.10	0.94	1246	0.82	0.18	0.82	1348	0.91	0.22	0.85	1211
objects	N/A	N/A	N/A	N/A	0.95	0.21	0.87	1523	0.81	0.07	0.87	1354
9 locations												
locations	0.75	0.30	0.72	1405	0.70	0.43	0.64	1416	0.64	0.32	0.66	1444
objects	N/A	N/A	N/A	N/A	0.94	0.21	0.87	1314	0.61	0.01	0.80	1316

single item test condition and the *full array test condition*, participants remembered nearly identical numbers of objects irrespective of whether they were also retaining 0 locations (2.91 objects), 3 locations (2.96 objects), or 9 locations (2.66 objects).

Memory for locations

Location memory performance was nearly identical in the *single test item* and *full array test conditions* when participants needed to retain both 3 and 9 locations; thus, performance was collapsed across these conditions for the subsequent analyses. An ANOVA with factors of set size (3, 9 locations) and load (0 objects versus 4 objects) revealed highly significant main effects of set size ($F(1, 9) = 81.48$, $p < 0.001$; $h_p^2 = 0.90$) and load ($F(1, 9) = 25.72$, $p = 0.001$; $h_p^2 = 0.74$). The interaction was not significant ($F < 0.4$). Thus, the presence of the object memory task had a significant effect on performance in the location memory task. This conclusion was supported by the storage capacity estimates. Participants could remember 4.01 locations when they performed the location memory task alone, but only 2.66 locations (*single test item condition*: 2.43 locations; *full array test condition*: 2.88 locations) when they performed the location and object memory tasks concurrently.

Discussion

Experiment 6 provides evidence that VWM requires resources from SWM to retain information about colored objects at specific locations. Contrary to the color memory conditions in Experiments 1–3, there was significant interference between the object memory task and the location memory task when the location memory task required memory for 3 locations. Thus, although VWM and SWM can operate independently in some contexts, they operate together when objects are encoded and tested at the same locations.

It is worth noting that strictly speaking, it was not necessary for participants to remember the locations of the objects to succeed in this experiment because when an object changed from the study array to the test array its color was replaced with a new color that was not the same as any of the colors in the object array. Thus, participants could have succeeded in this task by detecting the presence of a new color that had not been present in the object array, irrespective of the location of that object. Nevertheless, resources from SWM were used when the objects appeared at the same locations in the study and test arrays.

General discussion

How do visual working memory (VWM) and spatial working memory (SWM) interact with one another to retain visual information about the environment? The goal of this study was to characterize the contexts in which VWM and SWM interact by focusing on two related questions: (1) Can VWM and SWM function independently from one another or is SWM always needed to retain information in VWM? (2) If VWM and SWM can operate independently from one another in some contexts, then under what contexts do they interact?

Experiment 1 examined whether VWM and SWM can operate independently from one another. In a dual-task paradigm, participants attempted to remember as many locations as possible in a location memory task and as many colored objects as possible in an object memory task. Participants could remember 4-5 locations irrespective of the number of colored objects also being retained in memory, and 2-3 colored objects irrespective of the number of locations also being retained in memory. Thus, performance on one task did not suffer when the other task was performed concurrently. These dual-task results provide evidence that VWM and SWM can operate independently from one another.

Experiment 2 investigated the contexts in which VWM and SWM interact by varying the types of objects that needed to be remembered in the object memory task. The results replicated the main finding from Experiment 1, showing that VWM operates independently from SWM when observers retain colored objects (and memory for those objects is tested at a neutral location). The results also showed that VWM requires resources from SWM when observers retain shapes[3] and integrated color-shape objects.

Control experiments ruled out three alternative explanations for this pattern of dual-task interference. Experiment 3 showed that the dual-task interference between the location memory task and the binding memory task was not solely due to the greater difficulty of the binding memory task compared to the color memory task and the shape memory task. Experiment 4 showed that the interference between the location memory task and the object memory tasks was not due to interference between SWM and spatial attention. And Experiment 5 showed that verbal working memory sustains little to no object information during this object memory task. Finally, Experiment 6 revealed another context in which VWM and SWM interact by showing that VWM requires resources from SWM to retain representations of colored objects at specific locations.

These results provide two main contributions to our understanding of how working memory represents the visual world. First, these results bear on the classic debate regarding the nature of the units of VWM. 'Object-based' models propose that VWM stores information in the form of integrated object representations (e.g., Luck & Vogel, 1997). Thus, for object-based models, SWM does not play a necessary role in retaining information about how individual features were organized as objects in VWM. In contrast, 'feature-based' models propose that VWM stores feature values from different feature dimensions in separate feature-specific memory stores, and requires SWM and attention to keep those features organized as integrated object representations in memory (e.g., Wheeler & Treisman, 2002). Thus, for feature-based models, SWM plays a necessary role in retaining information about how individual features were organized as objects in VWM. The present study provides evidence in support of feature-based models because resources from SWM were needed to retain information about how individual features were organized as objects in VWM. More specifically, these results support the VWM architecture proposed by Wheeler and Treisman (2002), in which feature values from different dimensions are each stored in parallel in their own dimension-specific store. Within each dimension-specific store, feature values compete for limited capacity representation, but between stores there is little to no competition. Feature values from different dimension-specific stores can be bound together; however, this binding depends on other limited resources such as SWM and attention.

This study provides evidence from a dual-task methodology that color-shape binding in VWM requires resources from SWM. Further support for this conclusion comes from studies using other methodologies. For example, in Treisman and Zhang (2006), participants observed a study display of objects and then a test display. On some trials the objects retained their original locations, while on other trials the objects switched locations. When the objects switched locations in the test display, individual features could be remembered with little decrement. However, memory for integrated objects (i.e., binding) was impaired by the location switch. This suggests that spatial information is used to keep features organized as objects in VWM because changing the locations of the items in the test display disrupted memory for feature organization but did not disrupt memory for individual features. Different methodologies therefore provide converging evidence that spatial processes maintain information about how features were organized as objects in VWM.

Second, these results reveal a set of conditions in which VWM and SWM can be isolated from one another. This is important because in order to infer the architecture of a cognitive mechanism from behavioral performance, it is critical to ensure that limits on performance reflect the mechanism under investigation as opposed to limits stemming from other mechanisms that are also engaged during the task. The method used in Experiment 6, in which the objects appeared at the same locations in the study and test arrays, has been widely used to study VWM on both behavioral and neural levels (e.g., Luck & Vogel, 1997). This method, however, may not be suitable for isolating VWM because it requires significant resources from both VWM and SWM. In order to obtain a more pure measure of VWM capacity and its underlying cognitive and neural mechanisms, it may be necessary to use testing conditions that isolate VWM, such as the conditions used in Experiment 1.

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[3] These results suggest that resources from SWM are needed to retain shapes in VWM because there was interference between the shape memory task and the 9-location memory task in Experiment 2. However, there is an alternative explanation for this interference. Participants may have used a shape representation to remember the 9 locations, using a "connect the dots" strategy. If so, then the interference between the shape memory task and the location memory task would have been due to concurrent demands on working memory for shapes as opposed to an interaction between VWM and SWM.

The architecture of visual working memory

In this paper, the data have been interpreted in terms of the most widely accepted architecture of working memory, an architecture with separate subsystems for retaining spatial information and object information. Elsewhere, however, working memory has been suggested to contain more specialized subsystems for retaining spatiotemporal information, object identity information, and view-dependent 'snapshot' information (Wood, in press). These subsystems parallel innate, evolutionarily ancient core knowledge systems that support object tracking, object recognition, and place recognition, respectively (Wood, in press). The present results are consistent with both architectures because the pattern of dual-task interference could have been produced from competition between spatial and object memory systems or from competition between more specialized memory systems for spatiotemporal information, object identity information, and snapshot information.

How might one distinguish between the spatial-object architecture and this core knowledge architecture? The dual-task paradigm used here might prove especially useful. The core knowledge architecture predicts that spatiotemporal information, object identity information, and snapshot information are stored in separate, specialized memory buffers. Thus, all three types of information should be subject to independent working memory storage limits (Wood, in press). In contrast, according to the spatial-object architecture, spatial information and object information are stored in separate memory buffers. This predicts that any two memory tasks that require retaining spatial information or require retaining object information will compete with one another for the limited storage resources of the spatial memory system or the object memory system, respectively.

The present results also have implications for the visual working memory architecture proposed by Xu and Chun (2009), which consists of two main components, object individuation and object identification. During object individuation, a fixed number of visual objects are selected via their spatial location, and during object identification, a subset of those selected objects are processed with their detailed feature information. The present results are consistent with this architecture because observers might have remembered the items from the location memory task using the object individuation component and the items from the object memory task using the object identification component. Accordingly, these results shed light on how these components interact, by revealing a set of conditions in which these components can operate independently from one another and a set of conditions in which resources from both components are needed.

Acknowledgments This work was supported by the University of Southern California, Harvard University, and a National Institute of Health (NIH) National Research Service Award (NRSA, grant F31MH075298). Its contents are solely the responsibility of the author and do not necessarily reflect the official views of NIH. I thank Samantha Waters, Susan Courtney, Bradley Gibson, and two anonymous reviewers for helpful comments on an early version of the manuscript.

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