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INTEGRATED CROSS-DOMAIN OBJECT STORAGE IN WORKING MEMORY: EVIDENCE FROM A VERBAL-SPATIAL MEMORY TASK

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Abstract

Working memory theories often include domain-specific verbal and visual stores (e.g., the phonological and visuo-spatial buffers of Baddeley, 1986), and some also posit more general stores thought to be capable of holding verbal or visuo-spatial materials (Baddeley, 2000; Cowan, 2005). However, it is currently unclear which type of store is primarily responsible for maintaining objects that include components from multiple domains. In these studies, a spatial array of letters was followed by a single probe identical to an item in the array or differing systematically in spatial location, letter identity, or their combination. Concurrent verbal rehearsal suppression impaired memory in each of these trial types in a task that required participants to remember verbal-spatial binding, but did not impair memory for spatial locations if the task did not require verbal-spatial binding for a correct response. Thus, spatial information might be stored differently when it must be bound to verbal information. This suggests that a cross-domain store such as the episodic buffer of Baddeley (2000) or the focus of attention of Cowan (2001) might be used for integrated object storage, rather than the maintenance of associations between features stored in separate domain-specific buffers.

Keywords: Working Memory, Focus of Attention, Episodic Buffer

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The working memory system is thought to include separate components for maintaining memoranda from various sensory sources. Until recently, the influential model of working memory proposed by Baddeley and colleagues (1986; Baddeley & Hitch, 1974; Baddeley & Logie, 1999) included no store capable of holding objects comprising verbal and spatial features. Rather, it included only separate, domain-specific stores for verbal and visual-spatial information. Many pointed out the necessity of incorporating a domain-general store into models of working memory to explain the moderate cross-domain interference sometimes observed (Arnell & Jolicoeur, 1999; Jolicoeur, 1999; Jones, Farrand, Stuart, & Morris, 1995; Morey & Cowan, 2004, 2005; Sanders & Schroots, 1969) and to accommodate the storage of cross-domain associations (Allen, Hitch, & Baddeley, in press; Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000). In everyday life, memoranda frequently contain features from multiple domains, such as the name of a location and its spatial position on a map. The association between a verbal feature (such as a word or letter) and a visual feature (such as a spatial location) could not easily be maintained in a domain-specific verbal or visual storage buffer, and inclusion of some more general store in a working memory system allows some explanation of how such associations are remembered.

However, little is actually known about how cross-domain associations are maintained. According to Baddeley (2000), the episodic buffer is ". . . a limited-capacity temporary storage system that is capable of integrating information from a variety of sources . . . ." (p. 421). Repovš and Baddeley (2006) added that the episodic buffer holds integrated features in a unitary representation, implying that all associated features, meaning components like letters or spatial locations, are stored within one structure, or object, in the episodic buffer. Similarly, Cowan's domain-general focus of attention (2001, 2005) measures storage capacity in chunks rather than features, which suggests an agreement with Baddeley's conception of object storage. However, storage of objects with cross-domain features is plausible at the feature level or at the object level within the structures of Baddeley's multiple component model. Cross-domain representations could be maintained as discrete objects in a general working memory store, as suggested by some previous research (Campo, Maestu, Ortiz, Capilla, Santiuste, Fernandez, & Amo, 2005; Cowan, Saults, & Morey, 2006; Prabhakaran et al., 2000). But it is equally plausible that the constituent features of a cross-domain association are separately maintained and their association is either separately maintained apart from those features or deduced from other factors, such as serial order (Cowan et al., 2006). Although the introduction of a domain-general store to the working memory system seemed to clarify how complex cross-domain relationships are represented, it actually created two possibilities with different implications for the boundary conditions of theories of working memory.

Research on feature binding in visual working memory provides potential explanations for how cross-domain associations might be maintained. In visual memory research, theories of discrete object storage (Vogel, Woodman, & Luck, 2001) and parallel feature storage (Wheeler & Treisman, 2002) attempt to explain how conjunctions are remembered. Although the strictest interpretation of the parallel feature storage hypothesis seems implausible (Allen, Baddeley, & Hitch, 2006), much research suggests that mechanisms for object and information storage might be used concurrently (Alvarez & Cavanaugh, 2004; Awh, Barton, & Vogel, 2007; Xu & Chun, 2006). Debate over separate or unified mental representations is even more salient for cross-domain binding, given that working memory is already widely assumed to include separate stores for visual and verbal features. It is therefore important to ascertain how cross-domain associations are maintained and to learn whether there is any flexibility in the working memory system for accommodating these representations.

A study by Prabhakaran et al. (2000) is widely cited as evidence that verbal-spatial representations are maintained as unified objects in working memory. Prabhakaran et al. presented displays of four letters and four spatial locations chosen from positions on an imaginary ellipse. Within these displays, letters were either situated within the spatial locations (*bound presentation*) or situated in the center of the imaginary ellipse, with locations indicated by empty parentheses (*separate presentation)*. Regardless of presentation format, Prabhakaran et al probed participants with a single letter appearing in one of the ellipse locations. They instructed participants to respond positively if *both* the letter and its location were represented in the memory array, regardless of whether they were bound together in one object (this distinction was only relevant in the bound presentation condition). They compared BOLD activation in the bound and separate presentation blocks and found a region in right anterior prefrontal cortex unique to the bound presentation condition, which was understood to be the neural substrate for a working memory store capable of holding cross-domain objects. Latency evidence also seemed to support this proposal. Because participants were not actually making judgments about binding, target probes in the bound presentation condition came in two varieties: target probes that were congruent with respect to the original binding (congruent targets) and target probes that included a letter and location from the presentation, but had been recombined using two features that were not bound together at study (incongruent targets). Comparing congruent with incongruent targets, Prabhakaran et al. observed faster responses for the congruent targets. Prabhakaran et al. therefore concluded that the letter-location associations were stored as discrete objects in a general working memory store.

A developmental study by Cowan et al. (2006) suggested that cross-domain object maintenance might be induced when feature maintenance is impaired. Participants viewed arrays of pentagons ("houses") scattered on a computer screen, with names appearing sequentially inside them. Given a name at the end of the trial, the participant was to place it in the "house" where it belonged. Cowan et al. compared two conditions: 1) in the one-to-one mapping condition, each location in a sequence was unique and 2) in the uneven mapping condition, locations could be repeated within a sequence (e.g., two names could be associated with one "house"). In the one-to-one mapping condition, it was plausible that verbal and spatial sequences were separately maintained, and the associations determined simply by matching the order of the items in each sequence (e.g., first verbal item with first spatial location, etc.). However in the uneven mapping condition this strategy would be prone to errors. For adults, lower accuracy was observed in the uneven mapping than in the one-to-one mapping condition, but this difference disappeared when participants engaged in concurrent articulatory suppression, which reduced their ability to rehearse sequences (Jones, Farrand, Stuart, & Morris, 1998). During articulatory suppression, the adults' accuracies were similar to those of nine-year-olds. Cowan et al. suggested that adults' default strategy was to separately maintain lists of names and locations, using order information to deduce which were linked together. In the uneven mapping condition or during articulatory suppression, this strategy was not optimal and might have been replaced by a more effortful strategy of maintaining cross-domain object representations.

Cowan et al.'s (2006) evidence offers two critical ideas regarding the nature of cross-domain binding in working memory. First, regardless of whether cross-domain associations *can* be mentally represented as unitary structures in a general working memory store, any within-domain resources that could be used to maintain separate features might also be engaged. Therefore, accuracy in the one-to-one mapping condition of Cowan et al.'s verbal-spatial memory task could not be considered a pure measure of a domain-general store because even if some cross-domain associations were maintained in a domain-general store, it appears that verbal and spatial serial lists might also have been maintained. Second, the introduction of a concurrent task such as articulatory suppression might change the way in which these features are mentally represented. Cowan et al.'s explanation depends on the supposition that different combinations of resources available to maintain verbal and spatial information might be engaged under different circumstances, perhaps depending on whether domain-specific interference is present in the environment.

Campo et al. (2005) compared MEG activation during a verbal-spatial binding task and simultaneous verbal and spatial memory tasks. Campo et al. noted the similarities observed between MEG data during the bound verbal-spatial and simultaneous separate tasks, which suggests that similar neural mechanisms are used to accomplish binding as to remember separate features. However, one aspect of their research pointed to a difference in how these features might be maintained during binding. During the verbal-spatial binding task, greater activation was observed in the inferior parietal lobe than during the concurrent verbal and spatial memory tasks. Because this region has been linked in previous studies to spatial memory (cf. Munk, Linden, Muckli, Lanfermann, Zanella, Singer, & Goebel, 2002), Campo et al suggested that in the binding version of the task, the verbal stimuli took on some of the properties of spatial stimuli. Even so, these results do not unequivocally favor an object hypothesis for cross-domain associations.

Two plausible explanations for cross-domain association maintenance in working memory suggest themselves. One explanation is the *discrete object hypothesis*, which suggests that cross-domain associations are maintained by storing the verbal and visuo-spatial features as a unified structure in a domain-general working memory store. The *discrete object hypothesis* is similar to Luck and Vogel's (1997) explanation of visual feature binding in that it supposes a capacity limit of about 3 or 4 objects (see also Cowan, 2001; 2005) regardless of how many features comprise each object. Baddeley's (2000) domain-general working memory store, the episodic buffer, is also supposed to store unified objects. Applied to the notion of a general working memory store, the *discrete object hypothesis* holds that 1) features are maintained in a unified representation, such as a chunk (Miller, 1956) or an object file (Kahneman, Treisman, & Gibbs, 1992), 2) a limited number of these objects can be held at once, and 3) maintaining these objects does not impose an additional cost on maintaining features, therefore objects including multiple features and individual representations of the same features might be simultaneously active in working memory.

Another possible explanation for cross-domain association maintenance may be termed the *parallel features hypothesis*, which derives from Wheeler and Treisman (2002). Wheeler and Treisman advocated an explanation of visual feature binding in which features are maintained in parallel separately, and binding information (i.e., which feature is associated with which other feature) is separately maintained by another mechanism. In this model, maintaining binding does not detract from maintenance of features, but binding is vulnerable to general sources of interference whereas features are only vulnerable to domain-specific interference. Allen et al. (2006; see also Allen et al., in press) discounted the strongest form of this hypothesis as an explanation of visual feature binding by showing that visual conjunctions were no more vulnerable to interference than their constituent features, but it does not necessarily follow that associations between verbal and visual-spatial features are not maintained in this manner. Indeed the *parallel features hypothesis* maps quite nicely onto Baddeley's (2000) updated multiple component model of working memory, supposing that 1) features are maintained in separate, independent stores, 2) binding information is maintained separately and independently from feature information in the episodic buffer, and 3) binding information is only vulnerable to general interference while the feature information is vulnerable only to domain-specific interference.

Either hypothesis is plausible under Baddeley's (2000; 2007; Repovš & Baddeley, 2006) multiple-component model of working memory, but support falsifying either hypothesis would suggest new boundary conditions for models of working memory, thereby limiting how components of a working memory system might interact. Figure 1 identifies the stores available for maintaining an array of letter-location objects, assuming the stores posited in the updated multiple-component model of working memory. Given the sample memory array, one might maintain a sub-list of the presented letters with the auditory-verbal store, some representation of the array's spatial configuration in the visuo-spatial store, and some representation of the letter-location associations (either as unified object structures or as a more abstract link between features stored elsewhere) in the domain-general store (i.e., the episodic buffer). These representations might be held simultaneously and may not interfere with one another, but each domain-specific store may be subject to interference from domain-specific sources.

(Figure 1 about here)

It is currently unknown whether unified objects or abstract links between features stored separately are represented in a domain-general store. Supposing unified objects are held in some domain-general buffer, it is also unknown whether features are simultaneously held in their respective domain-specific buffers. The purpose of the following studies is to test whether unified objects or abstract associations are maintained and also to ascertain whether unified objects and features might be stored simultaneously.

Methods

These experiments constitute an initial attempt to learn the form of information maintained during a cross-domain storage task. The cross-domain stimuli were inspired by those of Prabhakaran et al. (2000), who claimed that cross-domain associations were remembered by maintaining the features as unified objects. Despite their seemingly clear results, their methods might not actually permit strong inferences about cross-domain object storage. In the bound condition of their task, Prabhakaran et al presented to-be-remembered letters in to-be-remembered locations, but at test, participants' task was to indicate whether the probe letter and spatial location were both present at study, *regardless of whether they were presented together in one object*. Considering that the task instructions did not require binding, it is difficult to conclude that results were attributable to binding maintenance. Prabhakaran et al might actually have measured incidental binding in a feature memory task. By altering their paradigm, I aim instead to compare memory for features presented in bound format (Experiment 1) and the contribution of any incidental feature memory in a binding memory task (Experiment 2). Because the methods in Experiments 1 and 2 are similar and the results of each study are clearest when taken together, the methods and results for each are presented jointly.

Experiments 1 and 2

Method

Participants

Experiment 1. Thirty psychology students participated in exchange for course credit. One participants' data was excluded from analyses because of a 0% hit rate in one cell of the design and one was excluded because of an empty cell after response time trimming, leaving N=28 (11 male, 17 female).

Experiment 2. Thirty-one psychology students participated. Two participants failed to finish the study due to computer malfunctions or scheduling conflicts. Three participants' data were excluded due to below-chance accuracy in silent conditions, leaving N=26 (9 male, 17 female).

Apparatus and Stimuli

Tasks were completed in private booths at computers with 17-inch monitors. Stimulus presentation and response collection were controlled with E-Prime software (Schneider, Eschman, & Zuccolotto, 2002).

Letter-location stimuli. On each trial, 2-6 letters were drawn randomly without replacement from {B, F, G, H, J, M, Q, R, T, Y}. Consonants were included in this set for minimal phonological and visual confusability and because capital and lower-case graphemes looked different in Arial font. Vowels were excluded to eliminate the possibility that English words could be formed. Spatial locations were chosen randomly from 12 positions centered on the squares of an invisible 4x3 grid occupying the center-most 270 x 201 pixel (7.14 x 5.32 cm) area of the monitor; the closest possible locations were separated by 2 degrees of visual angle. Letters were drawn in bold, upper-case 18-point Arial font, encircled in black. To encourage verbal encoding of the letters, probe letters always appeared in lower-case so that study and probe letters differed visually.

Articulatory suppression. For half of the experiment, participants repeated the word "the" approximately twice per second during the memory task. Participants were instructed to begin speaking when the fixation appeared and to continue until the probe item appeared. The experimenter enforced these instructions during practice sessions and monitored the participant's speech throughout the study to ensure compliance. No participants needed to be reminded to speak or to adjust their tempo more than once after the end of the practice session. Order of the silent and suppression blocks was counterbalanced across participants.

(Figure 2 about here)

Procedure

Experiment 1. The session lasted 60-90 minutes. After completing eight supervised practice trials, the participant completed one block of 240 trials independently. This procedure was repeated for the second block of trials.

Figure 2 depicts the trial events for both experiments. Each trial began with a 1000-ms fixation, followed by the sample memory array, which remained onscreen for 125 ms per item. A blank grey screen appeared for 3000 ms, followed by the test stimulus, which remained onscreen until the participant responded. (Refer to Figure 2.) Yes/no responses were registered on a keyboard using the "y" and "n" keys. On half of the trials, the probe feature was present in the memory array (target); in these cases, participants were to respond "yes". On half of the trials, the probe was not present in the memory array (lure), ideally eliciting a "no" response.

Experiment 2. Experiment 2 differed from Experiment 1 only in that participants were tested on each trial with a letter-location object probe rather than a single feature probe, and were to indicate whether the letter-location object, had been present in the studied memory array. Only intact letter-location objects from the studied array were considered targets. Half of the trials were probed with targets; on the remaining half, the lure differed from the studied objects systematically. Three types of lures occurred with equal likelihood: (1) In a *new letter* trial, the probe's letter was not present in the memory array, but the probe's location was occupied; (2) In a *new location* trial, the probe's letter was present in the memory array, but the probe's location was unoccupied; (3) In a *recombination* trial, the probe's letter and location were both present in the memory array but not in the same object. This condition was the same as the positive incongruent condition of Prabhakaran et al (2000), but here, these probes were to be rejected. These trial types were randomly intermixed.

Predictions

In Experiment 1, either letter or location but not their binding was probed on each trial, so there was no incentive for maintaining bound representations. However, because they did not know whether letters or spatial locations would be tested, participants needed to try to maintain both types of feature, just as in Prabhakaran et al.'s (2000) task. In Experiment 2, stimulus presentation was identical to that in Experiment 1, but at test participants encountered a letter-location object and were asked whether that object (i.e., both features and their binding) had been present at study, rather than whether both the verbal and spatial features had been present. This modification to Prabhakaran et al.'s procedure was intended to further encourage maintenance of a unified object representation, if this type of representation truly occurs.

Comparing accuracy by trial type in Experiment 2 should reveal something of which features and objects were maintained during this task. The contents of the domain-specific stores may assist in making a judgment about new letter or new location lures; indeed in these cases, complete domain-specific feature memory would be sufficient for correct rejection. Referring to Figure 1, when confronted with a new letter probe, the contents of the domain-general store and the auditory-verbal store may be compared with the probe and used to decide whether that object was present, and in the case that all letter features are stored, the contents of the domain-specific verbal store alone might suffice for making a correct rejection. A parallel situation arises for the new location lures, with the contents of the domain-general store and the visuo-spatial store contributing to a decision. In both of these conditions, a correct rejection might be made regardless of whether any binding information is stored. However, the contents of the domain-general store are necessary for successful rejection of a recombination lure. If each type of store is engaged during the cross-domain memory task, then participants should be able to reject the new letter and new locations lures more accurately than the recombination lures because more information is available to inform these decisions. New letter and new location detection can also be compared between experiments to learn whether accuracy on feature judgments differs when binding is necessary for correct responding (as for most trials in Experiment 2) versus when binding is not required (Experiment 1).

Another method for determining what kind of memories aid decisions in this task is to examine task accuracy during articulatory suppression, which should selectively impair memory for verbal information (Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002; Farmer, Berman, & Fletcher, 1986). If verbal and spatial features are only maintained separately in a cross-domain binding task, then concurrent articulation should only impair memory for letters and leave memory for locations intact because articulation alone does not impair simultaneously-presented visuo-spatial representations (Morey & Cowan, 2004). This would result in decreased rejection of new letter lures during concurrent articulation, but intact rejection of new location lures during articulation blocks compared with silent blocks. Manipulating set size ensured that for some subset of the trials, complete domain-specific feature storage would occur.

Results

The standard criterion of $p<0.05$ was a prerequisite for declaring significant effects in all analyses. *P*-values are therefore reported only for non-significant results.

Mean proportions correct, trimmed mean latencies, and standard deviations for Experiments 1 and 2 are given in Tables 1 and 2, respectively. Accuracy was the primary focus of the task instructions and predictions, and is therefore the primary focus of the analyses. Inferential analyses conducted with A', a nonparametric measure of discriminability, are reported. Analyses were also performed with proportions correct; these allowed the same inferences to be drawn. Analyses of latency of correct responses only are reported for each study to show that unintended speed-accuracy trade-offs were not observed. For each latency analysis, responses under 300 ms and over 4700 ms (4700 ms was >5 *SD*s from the mean) were excluded from analyses based on the assumption that very fast and slow outliers were not likely to reflect task processes. Less than 3% of correct trials were excluded using these criteria.

Experiment 1: Single-Feature Probes

A' values were entered into a 3-way repeated-measures ANOVA with articulation instructions (silent or suppression), probe type (letter or location), and set size (2, 3, 4, 5, or 6 items) as factors. A significant effect of articulation ($F_{(1,27)}$=27.29, *MSE*=.02, η_p^2=.52) was observed, with recognition impaired during suppression (*M*=.77, *SEM*=.02) compared to silence (*M*=.84, *SEM*=.01). A significant effect of set size ($F_{(4,108)}$=52.65, *MSE*=.01, η_p^2=.66) was observed. There was no effect of probe type (*p*=.27, η_p^2=.04).

(Table 1 about here)

As one might expect, a significant interaction between articulation condition and probe type was observed ($F_{(1,27)}$=34.60, *MSE*=.01, η_p^2=.56). Post-hoc Neuman-Keuls tests confirmed that articulatory suppression impaired memory for letters (Silent *M*=.87, *SEM*=.02, Suppression *M*=.75, *SEM*=.02) but had no effect on memory for locations

(p=.12). A significant interaction between probe type and set size ($F_{(4,108)}$=8.51, MSE=.01, η_p^2=.24) was also observed. The three-way interaction was also significant ($F_{(4,108)}$=2.96, MSE=.01, η_p^2=.10) .The interaction between articulation condition and set size (p=.69, η_p^2=.02) did not reach statistical significance.

An analysis of latencies was conducted for the important variables revealed by the *A'* analysis: probe type factor (letter target, letter lure, location target and location lure (target and lure recognition both contributed to *A'* values)) and articulation condition. The 2-way ANOVA yielded significant effects of articulation condition ($F_{(1, 27)}$=4.58, MSE=113507.34, η_p^2=.15) and probe type ($F_{(3,81)}$=10.82, MSE=22964.91, η_p^2=.29). The interaction was non-significant (p=.24). Responses tended to be slower during articulatory suppression (M=1431, SEM=54) than during the silent condition (M=1334, SEM=45), consistent with discrimination accuracy. The effect of probe type reflects differences between target and lure trials for letter and location detection. Responses to letter lures (M=1449, SEM=50) were slower than responses to location lures (M=1319, SEM=48), but responses to letter targets (M=1332, SEM=44) were faster than responses to location targets (M=1431, SEM=48). However, because there were no significant differences in discrimination accuracy between these probe types in *A'* or raw proportions correct (same four levels as in latency analysis, p=.43), there is no evidence of a speed-accuracy trade-off.

Experiment 2: Bound Object Probes

Another 3-way repeated-measures ANOVA with the factors articulation condition (silent, suppression), probe type (new letter, new location, or recombination), and set size (2, 3, 4, 5, or 6 items) was conducted. Significant effects were observed for each factor:

articulation condition ($F_{(1,25)}$=21.49 , *MSE* =0.04, η_p^2=.46); probe type ($F_{(2,50)}$=18.76, *MSE*=0.02, η_p^2=.43); and set size ($F_{(4,100)}$=49.75, *MSE*=0.01, η_p^2=.67). Recognition decreased in the suppression condition (*M*=.80, *SEM*=.02) compared to the silent condition (*M*=.86, *SEM*=.01), and tended to decrease as set size increased. Neuman-Keuls post-hoc tests of the probe type factor revealed that new letter lures (*M*=.87, *SEM*=.01) were recognized more accurately than new location lures (*M*=.81, *SEM*=.02) or recombination lures (*M*=.80, *SEM*=.01), which did not significantly differ (*p*=.46).

(Table 2 about here)

The advantage of new letter over new location trials is interesting, especially given that significant differences between letter and location discrimination were not observed in Experiment 1. However, this advantage itself should not be over-emphasized. This might have occurred if the locations were less discriminable than well-known letters, although the locations were intentionally spaced and limited to a small set in order to ensure easy discriminability. More theoretically interesting is the absence of any difference between new location and recombination trials. This finding can be interpreted in at least two ways: 1) no bound object information is stored at all, and spatial location is the rate-limiting factor determining whether an association can be reconstructed from separately-stored letters and locations or 2) bound object information is stored, but domain-specific spatial location features are not maintained independently from it in a domain-specific store.

The articulatory suppression manipulation can be used to judge between these two interpretations. It has been shown that articulatory suppression alone does not impair memory for visuo-spatial stimuli (Morey & Cowan, 2004); this prediction was confirmed with the current paradigm in Experiment 1. If we assume, consistently with the parallel features hypothesis, that no unified objects are maintained, then letters and locations must be maintained separately from each other as they seemed to be in Experiment 1 (in which the stimulus presentation was exactly the same), with linking information maintained elsewhere, perhaps in a general working memory store. If this were the case, then articulatory suppression would not impair memory for the spatial representations, and thus would not impair rejection of new location lures, which could be carried out on the basis of visuo-spatial memory alone. This does not appear to be the case. The interaction between articulation condition and probe type was non-significant (p=.40, η_p^2=.04). Critically, post-hoc Neuman-Keuls tests showed that new location lure recognition was impaired in the articulatory suppression condition (M=.79, SEM=.02) compared to the silent condition (M=.84, SEM=.02). That the two-way interactions between articulation condition and set size ($F_{(4,100)}$=2.53, MSE =0.01, η_p^2=.09) and probe type and set size ($F_{(8,200)}$=2.21, MSE=0.01, η_p^2=.08) reached the threshold for statistical significance suggests that this analysis had sufficient power to detect existing interactions. The three-way interaction was non-significant (p=.19, η_p^2=.05).

Mean latencies (trimmed with the same criteria described above) underwent a similar analysis to test for speed-accuracy trade-offs in the key variables: articulation condition and probe type, which had four levels in this analysis (letter, location, and recombination lures, and targets). A significant main effect of probe type ($F_{(3,75)}$=11.02, MSE=14538.34, η_p^2=.31) was observed, as well as an interaction between articulation condition and probe type ($F_{(3,75)}$=3.79, MSE=5674, η_p^2=.13). The effect of articulation condition was non-significant (p=.16). In the silent condition, recombination lures

(*M*=1473, *SEM*=51) and targets (*M*=1421, *SEM*=43) elicited the slowest response times, then location lures (*M*=1401, *SEM*=43), and letter lures (*M*=1307, *SEM*=41), corresponding with accuracy analyses. Post-hoc Neuman-Keuls comparisons indicated that response times to letter lures were faster than the others and recombination lures were slower than location lures, but not slower than targets (p=.11); location lures and targets also did not differ (p=.34). During articulatory suppression, letter lure recognition (*M*=1436, *SEM*=60) lost its edge over location lure (*M*=1454, *SEM*=65, p=.40) and target recognition (*M*=1457, *SEM*=53, p=.59), while recombination lures were slower than the rest (*M*=1541, *SEM*=62). This pattern is consistent with observed discrimination accuracy, ruling out an unintended speed-accuracy trade-off.

Between-Experiments Comparison

In Experiment 1, participants were only tested with single features and therefore never needed to retain information about binding, whereas in Experiment 2, participants were always tested with a bound letter-location object, though in some trial types, stored feature information was sufficient for making a correct response. Critically, the outcome of Experiment 1 is consistent with previous research in working memory, which suggests that verbal and visual features may be separately stored and subject only to domain-specific interference. Yet in Experiment 2, concurrent articulatory suppression impaired recognition on trials in which stored information about spatial locations alone might have been sufficient for making a correct response. This finding supports the position that features from different sensory modalities might be maintained as a unified object in a domain-general working memory store when maintaining binding information is necessary for a task. For this interpretation to be correct, a three-way interaction between experiment, articulation condition and probe type must be observed; this interaction would confirm that the effects of articulation on detecting letter and location changes differ based on a need to maintain binding information.

A 4-way ANOVA was carried out, with experiment (1 or 2) as a between-subjects factor and articulation condition (silent or suppression), probe type (estimates of letter and location discrimination; no estimate of binding was possible in Experiment 1), and set size (2, 3, 4, 5, or 6 items) as within-subjects factors. In this analysis, the critical 3-way interaction between experiment, articulation condition, and probe type was significant ($F_{(1,52)}$=11.06, *MSE*=0.01, η_p^2=.18). Post-hoc Neuman-Keuls analyses indicate that in the binding experiment, correct recognition of a new location was impaired by articulatory suppression, whereas in the feature experiment, it was not (*p*=0.26). This pattern of results is depicted in the upper panel of Figure 3.

(Figure 3 about here)

Likewise, mean latencies were entered into a 4-way ANOVA with experiment as a between-subjects factor and with articulation condition, probe type (only letter and location change trials from Experiments 1 and 2 could be meaningfully compared in this manner), and set size as within-subjects factors. A significant interaction between the experiment and probe type factors ($F_{(1,52)}$=25.34, *MSE*=97586, η_p^2=.33) was observed. This result is depicted in the lower panel of Figure 3. In Experiment 1, location changes (*M*=1327, *SEM*=47) were detected significantly faster than letter changes (*M*=1465, *SEM*=47), but in Experiment 2, when binding was required, there was no difference (*p*=.05); if anything, letter change detection (*M*=1375, *SEM*=49) was faster than location change detection (*M*=1428, *SEM*=49) in the binding memory context. Possibly, in the binding context locations had to be extracted from an object representation in order to make a judgment; this explanation for the response time data seems most consistent with the recognition data. If the recognition advantage of new letter trials over new location and recombination trials in Experiment 2 is taken as evidence that some letter but no location features were maintained separately from letter-location objects, then one might predict that in the binding context new letter judgments would be made at least as quickly as new location judgments. This finding agrees with the discrimination measure in suggesting that features are maintained differently when binding is encouraged than when binding is unnecessary.

Interestingly, discrimination was significantly better in Experiment 2 (*M*=.84, *SEM*=.01) than in Experiment 1(*M*=.80, *SEM*=.01). This is consistent with the idea, supported by evidence from recognition and latencies given above, that in the cross-domain binding task, some letter-location objects and some separate letter features were simultaneously maintained. A post-hoc Neuman-Keuls test of this comparison shows that in Experiment 2, letter discrimination during suppression (*M*=.83, *SEM*=.02) was better than in Experiment 1 (*M*=.75, *SEM*=.02).

Discussion

When memoranda contain both verbal and visual features, are domain-specific or domain-general working memory resources used to maintain them? The results of these experiments suggest that both are used, and that the resources engaged depend on exactly what information is necessary to complete the task. These experiments demonstrate that spatial locations may be encoded and maintained differently during a cross-domain binding memory task than in a task that emphasizes the separate maintenance of the features of cross-domain memoranda. Experiment 1 tested memory for the features of verbal-spatial objects; in this context, articulatory suppression impaired recognition of letters but did not affect recognition of spatial locations. In Experiment 2, participants viewed the same cross-domain objects, but were explicitly tested on their memory for the cross-domain associations. In this case, concurrent articulatory suppression impaired recognition of every probe type, even new location lures, for which memory of spatial locations alone would have been sufficient for a correct response.

These results cast doubt on the strictest interpretation of the parallel features hypothesis, which states that binding occurs between features that are separately maintained. Instead, these results support the inclusion of a component in models of working memory that can hold discrete objects comprised of features from different sensory modalities. However, these data do not suggest that cross-domain stimuli are always maintained in a bound format and also suggests that features and cross-domain objects may be simultaneously maintained.

If a general working memory store is presumed in addition to specific ones, these data may be accounted for by supposing that when objects are maintained, their locations are stored as part of the objects' structures and are not separately maintained elsewhere. Zimmer, Speiser, and Seidler (2003) formed a similar conclusion when they observed that visual and spatial secondary tasks, shown to interfere with Corsi location memory, had no effect on memory for the locations of visual objects. Taken together, these data suggest that in memory tasks that encourage the maintenance of an item with its location, any domain-specific spatial working memory contribution to storage is minimal.

Domain-specific spatial and verbal stores may differ in their contributions to the maintenance of cross-domain associations. In the binding experiment, correct recognition of the new letter probes was higher than the other probe types; indeed, it was at least equivalent with other probe types during articulatory suppression. This could be taken as evidence that some letters were stored apart from the letter-location objects, thereby increasing the total amount of letter information maintained. This possibility is further supported by a between-experiments comparison which showed that letter discrimination during concurrent articulatory suppression was better in Experiment 2, where maintenance of objects was encouraged, then in Experiment 1, where accurate responses could be given regardless of whether objects were stored. This suggests that during binding more information is preserved from domain-specific interference, presumably by the domain-general working memory store. Possibly, concurrent articulatory suppression posed some general distraction that somewhat impaired a general working memory store (resulting in the impairment of new location and recombination lure detection during suppression compared with silence) but also specifically interfered with verbal feature storage, as expected from previous research (Cocchini et al., 2002; Farmer et al., 1986).

In tasks in which the stimuli were always presented in bound format, why not always maintain bound objects in working memory? Presumably if a bound object is maintained, its features can be recovered. Because there appear to be differences between maintenance for the same stimuli when binding is necessary versus when it is not, it seems reasonable to conclude that there is some advantage to separately maintaining verbal and spatial features. Cowan et al (2006) suggested that maintaining bound objects might be more effortful than maintaining stimuli separately, but in that study, subjects might have matched serially-presented names and locations based on temporal order. Here, no temporal order cue was available. Supposing that more effort was needed to maintain unified objects, it seems that this effort may have resulted in better maintenance. Participants showed better discrimination overall in comparable conditions of the binding experiment than the feature experiment.

According to current conceptions of domain-general working memory stores (Cowan, 2005; Repovš & Baddeley, 2006) it is unclear why concurrent articulation impaired memory for cross-domain objects at all. If any letter features were stored separately, then articulation would certainly affect them, but why would it affect binding? In these studies, manipulation of precise timing of speech was not carried out. Participants spoke aloud throughout the whole of each trial in both experiments. It is therefore not possible to conclude that articulatory suppression selectively impaired the maintenance of verbal-spatial representations. Instead, perhaps suppression limited participants' ability to encode the objects well or to retrieve an object by its verbal identity. If no separate locations were stored and objects were referenced by letter, then concurrent articulation might be expected to produce a large effect. However the observed effect of articulation on location memory is difficult to reconcile with a conception in which letters and locations are stored or evaluated separately during an object memory task.

These data reveal a novel pattern of interference between verbal rehearsal suppression and memory for cross-domain objects, one that supports including a domain-general store like Baddeley's episodic buffer (2000) or Cowan's focus of attention (2001, 2005) in a comprehensive theory of working memory. These data support the idea that a domain-general working memory store should be capable of holding unified object representations including features from many sensory domains. These data also suggest that some domain-specific features might be maintained during a cross-domain binding task, sometimes in addition to unified objects. These results suggest a great deal of flexibility in working memory; even when the same stimuli are to-be-remembered, different combinations of working memory resources or different maintenance strategies might be employed, resulting in different effects of interference. Because some information imparted in an object memory task might be stored in multiple forms, researchers should exercise caution in interpreting cross-domain measures that seem to engage a general working memory store because other components may also influence performance. Possibly, incorporating a domain-general store into interpretations of dual-task working memory studies will reconcile conflicting reports of cross-domain interference. Ultimately, the inclusion of a general storage resource may yield a theory of working memory that gracefully accommodates more extant data.

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Table 1

Proportions correct by articulation condition, probe condition, and set size, Experiment 1

	Set Size				
	2	3	4	5	6
Silent					
New Letter					
Accuracy	.96(.06)	.96(.09)	.89(.17)	.86(.16)	.75(.20)
RT	1224(271)	1309(343)	1417(322)	1536(397)	1682(338)
Old Letter					
Accuracy	.97(.05)	.99(.03)	.94(.10)	.87(.12)	.82(.16)
RT	1182(277)	1193(281)	1309(293)	1305(244)	1323(277)
New Location					
Accuracy	.92(.10)	.86(.17)	.84(.17)	.78(.17)	.81(.14)
RT	1172(309)	1216(324)	1252(280)	1316(361)	1460(405)
Old Location					
Accuracy	.86(.12)	.84(.18)	.84(.18)	.76(.20)	.82(.12)
RT	1302(298)	1370(345)	1413(380)	1430(246)	1441(302)
Articulatory Suppression					
New Letter					
Accuracy	.92(.12)	.88(.16)	.78(.15)	.65(.22)	.64(.21)
RT	1323(305)	1459(443)	1525(389)	1503(373)	1673(576)
Old Letter					
Accuracy	.89(.11)	.84(.13)	.84(.17)	.71(.20)	.70(.21)
RT	1376(323)	1341(328)	1411(326)	1426(372)	1485(315)
New Location					
Accuracy	.88(.12)	.85(.16)	.86(.11)	.79(.17)	.75(.21)
RT	1254(349)	1341(287)	1445(370)	1381(341)	1428(378)
Old Location					
Accuracy	.80(.21)	.86(.17)	.80(.22)	.78(.20)	.79(.22)
RT	1432(437)	1405(398)	1547(438)	1471(358)	1489(388)

Note. Mean proportions correct and trimmed mean RTs in milliseconds (with standard deviations). Responses faster than 300 ms or slower than 4700 ms and incorrect responses were excluded from RT analysis (on average, 5 standard deviations from the mean); about 2.5% of correct trials were excluded using these criteria. N=28.

Table 2

Proportions correct and reaction times by articulation condition, probe condition, and set size, Experiment 2

	Set Size				
	2	3	4	5	6
Silent					
New Letter					
Accuracy	.99(.03)	.98(.06)	.97(.06)	.92(.09)	.89(.12)
RT	1204(250)	1247(251)	1294(251)	1361(232)	1445(297)
New Location					
Accuracy	.92(.12)	.87(.15)	.88(.15)	.85(.12)	.87(.12)
RT	1283(280)	1324(243)	1441(294)	1459(275)	1500(274)
Recombination					
Accuracy	.93(.11)	.86(.14)	.91(.11)	.86(.10)	.84(.13)
RT	1315(290)	1424(293)	1580(392)	1527(318)	1544(317)
Old Item					
Accuracy	.93(.07)	.92(.07)	.88(.11)	.81(.14)	.74(.16)
RT	1291(213)	1324(229)	1436(273)	1525(245)	1583(291)
Articulatory Suppression					
New Letter					
Accuracy	.94(.10)	.93(.10)	.94(.10)	.84(.14)	.82(.17)
RT	1322(301)	1440(376)	1496(335)	1454(335)	1489(399)
New Location					
Accuracy	.86(.12)	.86(.15)	.85(.14)	.83(.17)	.82(.17)
RT	1375(340)	1487(345)	1450(386)	1450(387)	1514(396)
Recombination					
Accuracy	.92(.11)	.86(.17)	.80(.19)	.76(.17)	.73(.17)
RT	1469(387)	1507(334)	1541(391)	1575(353)	1626(451)
Old Item					
Accuracy	.90(.09)	.85(.10)	.78(.12)	.68(.17)	.58(.19)
RT	1338(255)	1453(319)	1463(295)	1530(281)	1570(366)

Note. Mean proportions correct and trimmed mean RTs in milliseconds (with standard deviations). Responses faster than 300 ms or slower than 4700 ms and inaccurate responses were excluded from RT analysis; about 3% of correct trials were excluded using these criteria. N=26.

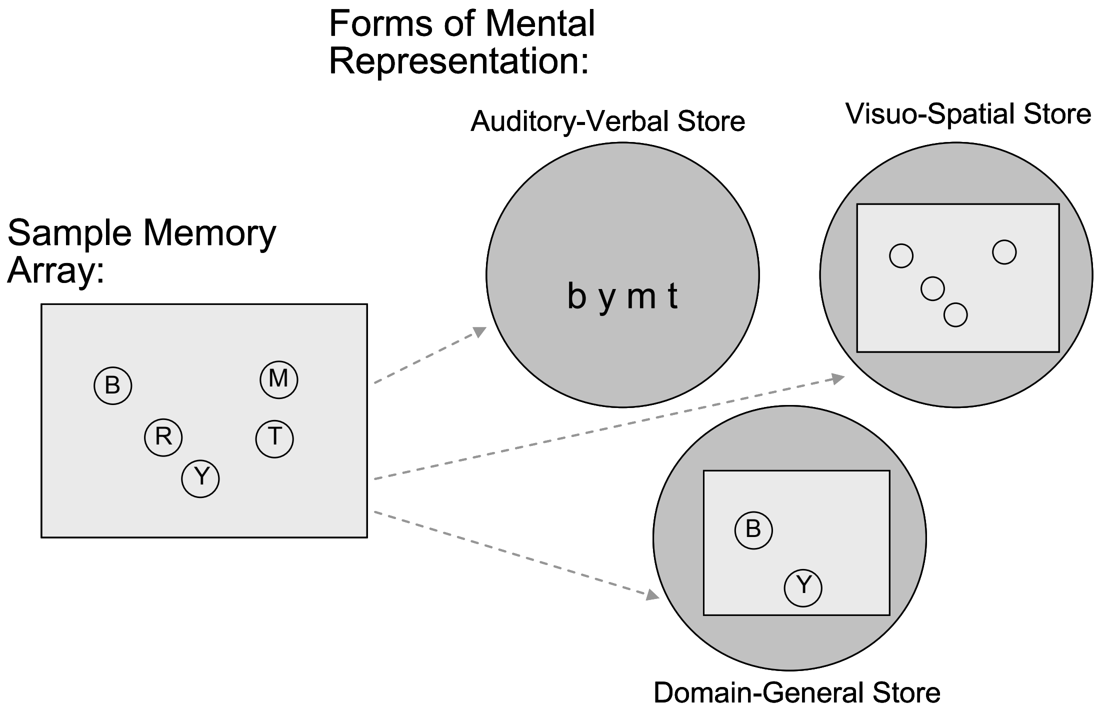
Figure Captions

Figure 1. Representation of working memory stores that might contribute to the memory of cross-domain associations. The domain-general working memory store might include unified objects as shown in Figure 1 (*discrete object hypothesis*) or alternatively might hold some abstract representation of which features in the domain-specific stores are associated with each other (*parallel features hypothesis*). Regardless of whether the domain-general store holds unified objects or associations, the domain-specific stores may also maintain representations of the features, though perhaps only a subset of them if there are many to be remembered.

Figure 2. Trial events and possible probe types, Experiment 1 (left) and Experiment 2 (right). A recombination probe in Experiment 2 was the same as an incongruent positive probe in Prabhakaran et al (2000).

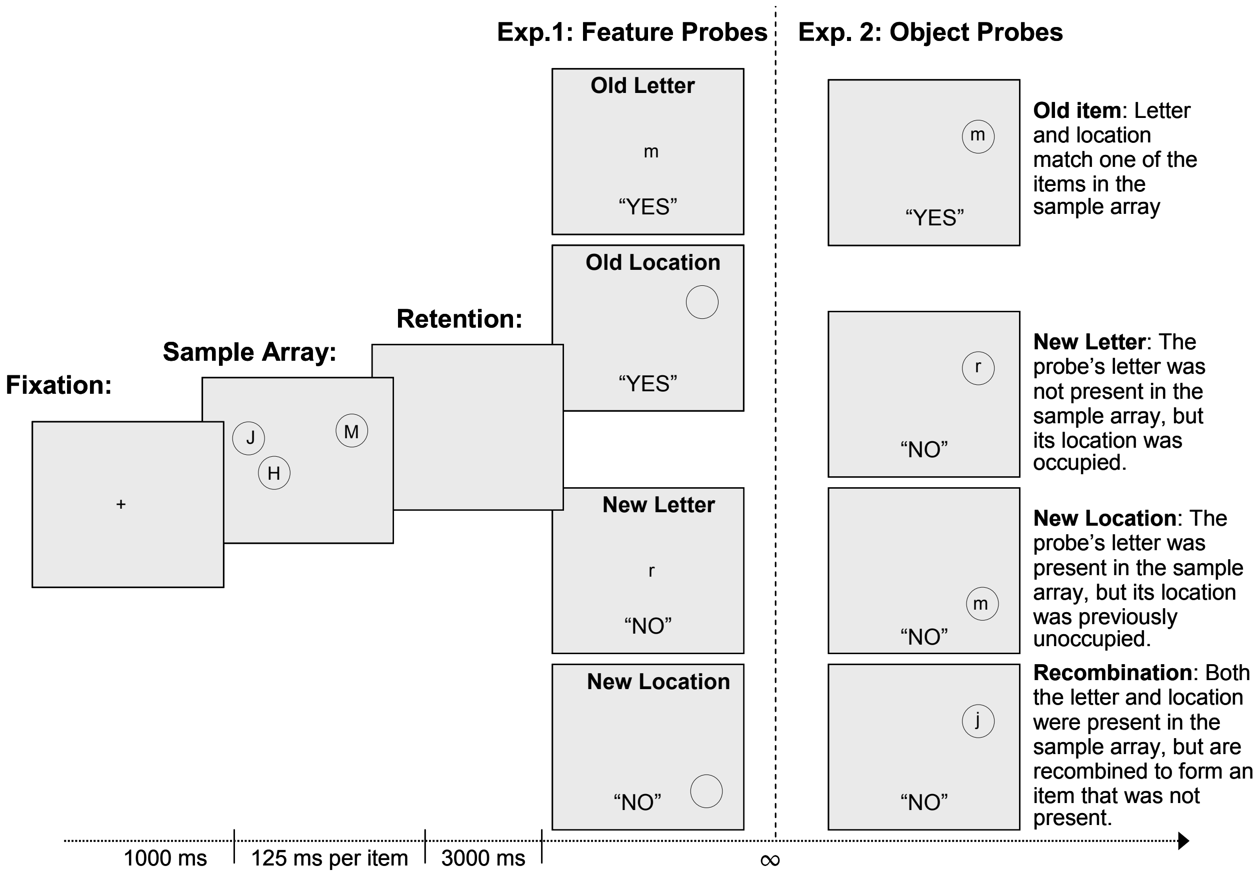
Figure 3. Between-experiments comparisons of corrected recognition (upper panel) and trimmed mean latency (lower panel). Corrected recognition rates for the new letter and new location probes in Experiment 2 were compared with letter and location recognition in Experiment 1. For analysis of latency, only letter and location change trials were compared. Error bars are standard errors of the mean.

Figure 1



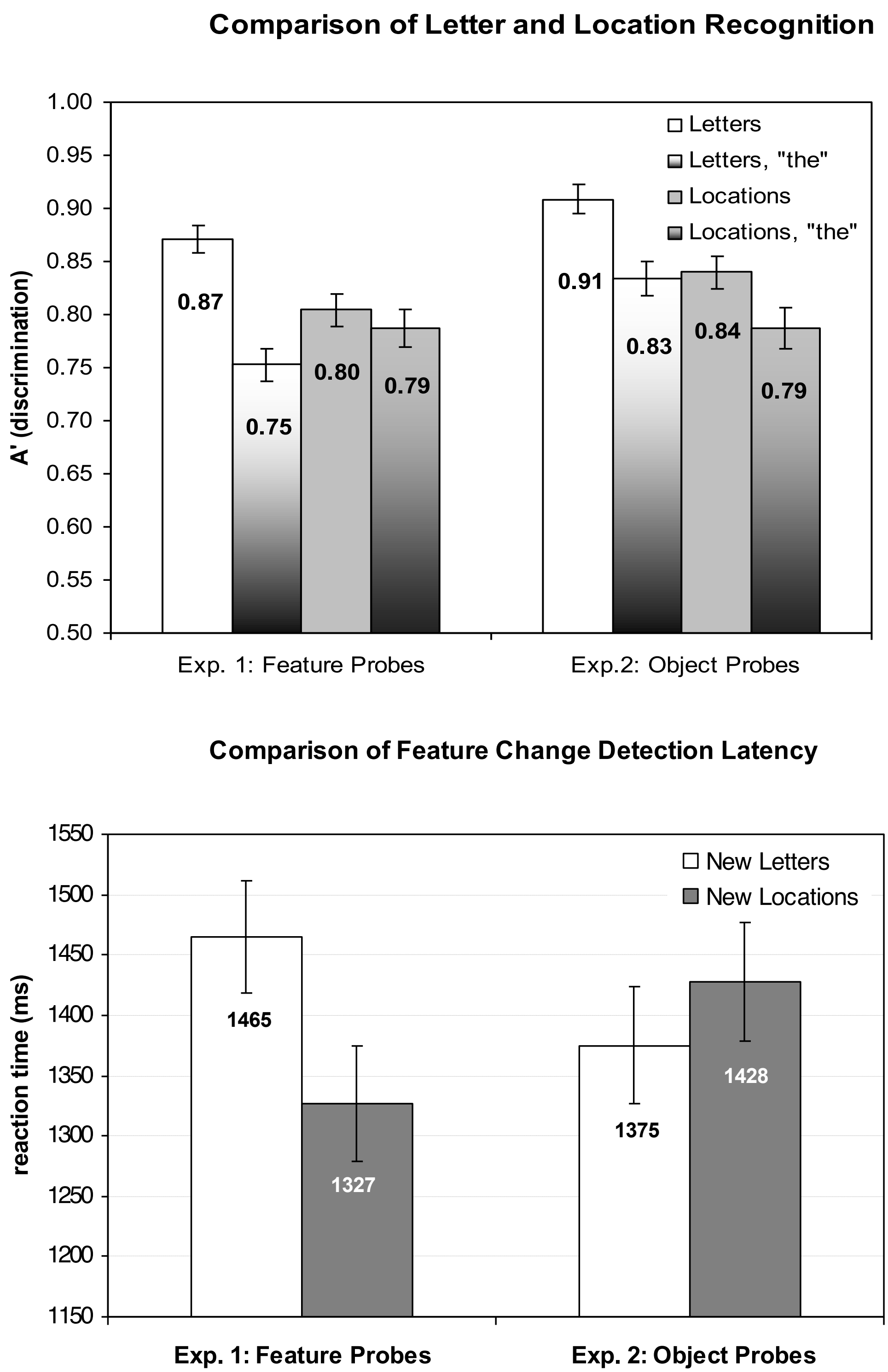
Forms of Mental Representation:
Auditory-Verbal Store
Visuo-Spatial Store
Sample Memory Array:
B
M
R
T
Y
b y m t
B
Y
Domain-General Store

Figure 2



Exp.1: Feature Probes
Exp. 2: Object Probes
Fixation:
Sample Array:
Retention:
+
J
M
H
Old Letter
m
"YES"
Old Location
"YES"
New Letter
r
"NO"
New Location
"NO"
m
"YES"
Old item: Letter and location match one of the items in the sample array
r
"NO"
New Letter: The probe's letter was not present in the sample array, but its location was occupied.
m
"NO"
New Location: The probe's letter was present in the sample array, but its location was previously unoccupied.
j
"NO"
Recombination: Both the letter and location were present in the sample array, but are recombined to form an item that was not present.
1000 ms
125 ms per item
3000 ms
∞

Figure 3


Comparison of Letter and Location Recognition
A' (discrimination)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
Letters
Letters, "the"
Locations
Locations, "the"
0.87
0.75
0.80
0.79
0.91
0.83
0.84
0.79
Exp. 1: Feature Probes
Exp.2: Object Probes
Comparison of Feature Change Detection Latency
reaction time (ms)
1550
1500
1450
1400
1350
1300
1250
1200
1150
New Letters
New Locations
1465
1327
1375
1428
Exp. 1: Feature Probes
Exp. 2: Object Probes