MAINTAINING CROSS-DOMAIN OBJECTS AND FEATURES IN WORKING MEMORY: IMPLICATIONS FOR STORAGE IN MODELS OF WORKING MEMORY

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by
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The undersigned, appointed by the Dean of the Graduate School, have examined the dissertation titled

MAINTAINING CROSS-DOMAIN OBJECTS AND FEATURES IN WORKING MEMORY: IMPLICATIONS FOR STORAGE IN MODELS OF WORKING MEMORY

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a candidate for the degree Doctor of Philosophy,
and hereby certify that, in their opinion, it is worthy of acceptance.

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ABSTRACT

A great deal of evidence, both from behavioral studies of cross-domain interference and from neuroimaging, suggests the need for a domain-general store in models of working memory. Baddeley included such a store in an updated version of the influential multiple-component model (2000), but it is still unknown how this new component interacts with better-known working memory components. Using cross-domain objects (letters in spatial locations) for memoranda, the following experiments aimed to learn whether domain-specific and domain-general stores can be used concurrently, and in doing so to better understand how components of a working memory system interact. A critical finding shows that concurrent articulatory suppression impairs memory for integrated cross-domain objects that include spatial location features, but does not affect spatial locations when they are represented as isolated features. This evidence is interpreted as support for a domain-general store capable of accommodating different representations for spatial materials and capable of interfacing with verbal rehearsal mechanisms, depending on memory demands.

Introduction

There is a scarcity of information explaining how verbal and spatial information is integrated and maintained in working memory. Several models of working memory posit a domain-general store capable of maintaining cross-domain associations (Baddeley, 2000; Cowan, 1995, 2001, 2005; Jones, Beaman, & Macken, 1994). However, because models of working memory (Baddeley, 1986, 2000; Baddeley & Logie, 1999) also posit domain-specific stores capable of holding isolated within-domain features, it is unclear how cross-domain associations are maintained: it is possible that they could be maintained as integrated object files (cf. Kahneman, Treisman, & Gibbs, 1992), as separate features with associated links, or as both objects and isolated features simultaneously. Whereas many studies have examined concurrent memory for auditory-verbal and visuo-spatial materials, only a few have measured memory for items with verbal and visuospatial components. None of these studies attempts to discern whether cross-domain objects and their component features can be simultaneously maintained in working memory or indeed, what kind of representation is contained in domain-general working memory. The goal of this work is to evaluate working memory for cross-domain materials, particularly to learn how a domain-general store may interact with other components of the working memory system if these components are not independent. In order to introduce the theoretical problems with current explanations of cross-domain memory, the prominent explanations of working memory and its components will be described and current debates regarding feature binding in working memory will be discussed.

Components and Function of Human Working Memory

The notion of a *working memory* system highlights the dynamic and integrated processes required to maintain and manipulate information in real time (Baddeley & Hitch, 1974; Miller, Galanter, & Pribram, 1960). Trying to remember a list of items to pick up from the grocery store benefits from more than a short-term store: memory for such a list also benefits from processes that protect the items from information loss due to interference or decay, processes that group the items into larger themes (e.g., chunks (Cowan, 2001; Miller, 1956)) that might aid in retrieval, and processes that interface with long-term learning (such as categories, Olsson & Poom, 2005). For instance, one might verbally rehearse such a list covertly or out loud or group the items into categories based on semantic relationships (e.g., group produce items together) or their locations in the supermarket. These component processes unite and contribute to the apparently seamless phenomenological experience perceived when interacting with the environment, though the processes may be dissociated in the laboratory.

The most influential model of working memory is the multiple-component model of Baddeley & Hitch (1974; see also Baddeley, 1986; Baddeley & Logie, 1999; Repovš & Baddeley, 2006). The classic version of the multiple-component model includes separate within-domain stores (the phonological loop for verbal materials and the visuo-spatial sketchpad for visual and spatial information) and the central executive, a domain-general processing mechanism thought to coordinate activities of the working memory system. It is possible that these components could be further reduced into more constituents; for instance, the phonological loop might be composed of an auditory-verbal

store and a rehearsal component (Baddeley, Lewis, & Vallar, 1984), and the visuo-spatial sketchpad might be similarly deconstructed (Baddeley & Lieberman, 1980; Logie & Marchetti, 1991). The central executive is also thought by some to have separable components (Morris & Jones, 1990), perhaps responsible for several distinguishable processes (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000).

Building on the classic multiple-component model of working memory (Baddeley, 1986), Baddeley (2000) posited a domain-general storage buffer termed the *episodic buffer* which, unlike the domain-specific phonological loop and visuo-spatial sketchpad, can accommodate materials from multiple modalities and codes. This domain-general store is the only store in the multiple-component model that could hold binding of visual-spatial and auditory-verbal features necessary to maintain a cross-domain object like a location on map and its name (Cowan, Saults, & Morey, 2006). However, it is currently unknown in what form these cross-domain bindings may be represented; a domain-general store might hold bound copies of features or rather, hold abstract links between features held in domain-specific stores. Access to the episodic buffer was thought to occur through the central executive, though in the visual domain, it has been shown that under some circumstances, maintaining bindings is no more attention-demanding than maintaining features only (Allen, Baddeley, & Hitch, 2006). Cowan's model of working memory (1995, 1999, 2001, 2005) proposes the focus of attention, a capacity-limited store that is integrated with attention operations, apparently similar to Baddeley's conception of the episodic buffer and central executive.

This primary deconstruction of working memory into separate, largely within-domain components has been supported by a wealth of dual-task research showing little

or no interference between two tasks of differing codes, contrasting with clear interference between two tasks of the same code (Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002; Duncan, Martens, & Ward, 1997; Farmer, Berman, & Fletcher, 1986; Fougnie & Marois, 2005; Logie, Zucco, & Baddeley, 1990). Characteristically, a series of studies by Logie, Zucco, and Baddeley (1990) showed a dual-task cost for performing cross-domain tasks at the same time compared with carrying out within-domain tasks at the same time. In cross-domain conditions, participants either 1) performed a verbal arithmetic task while remembering positions in a matrix or 2) performed a spatial task while remembering letters. In these cases, memory accuracy decreased 15-20% compared with a single task baseline. In within-domain conditions, participants either 1) performed a verbal arithmetic task while remembering letters or 2) performed a spatial task while remembering matrix locations. In these cases, memory accuracy decreased by 53-66%, a far more substantial decline than that observed for cross-domain dual-tasks.

Similarly, Farmer, Berman, and Fletcher (1986) observed clear effects of articulatory suppression on a verbal reasoning task but no effect of articulatory suppression on a spatial reasoning task. However, converse effects of spatial movement on the verbal and spatial reasoning tasks failed to emerge; rather, spatial suppression seemed to impair both spatial and verbal reasoning in some experimental conditions. Even so, their results were interpreted as support for domain-specific separation in the working memory system.

How domain-specific is working memory?

As suggested by Farmer et al's lop-sided results, there are also cases in which cross-domain tasks do interfere with each other (Arnell & Jolicœur, 1999; Jolicœur, 1999; Jones, Farrand, Stuart, & Morris, 1995; Morey & Cowan, 2004, 2005; Sanders & Schroots, 1969). Controlling for the effects of articulation alone, Morey and Cowan (2004) showed that maintaining a 7-digit verbal memory load impaired accuracy in a visual array comparison task; later they showed that the locus of the interference occurred during maintenance of the visual arrays, rather than during their encoding, and only occurred if the digit load was spoken aloud (2005). Baddeley's classic model of working memory (1986) accommodated moderate cross-domain interference by supposing that concurrent operations competed for the processing resources of the central executive. But because in Morey and Cowan's work, the interference occurred during maintenance of memoranda rather than during encoding, it is difficult to explain the observed cross-domain interference in terms of access to a central executive processor rather than a shared general store. There is also at least one case of a pure articulation task impairing a visuo-spatial memory task. Jones et al (1995) found clear negative effects of articulatory suppression and separately, irrelevant speech, on a sequential spatial location memory task. Rather than distinguish verbal stores from spatial stores, Jones suggested that memory for sequential stimuli is unitary regardless of its code or modality.

A parallel debate on the domain-specificity of working memory storage engages neuroimaging research in working memory. Early research seemed to support domain-specific separation of working memory storage (cf. Smith & Jonides, 1997) but this dissociation has been questioned. Chein, Ravizza, and Fiez (2003) examined the role of a

specific region of the parietal cortex in verbal working memory, which was thought by some to subserve the phonological store portion of the multiple-component model's (Baddeley & Logie, 1999) phonological loop system (Awh, Jonides, Smith, Schumacher, Koeppe, & Katz, 1996; Paulesu, Frith, & Frackowiak, 1993). Chein et al observed that throughout the literature, this region of parietal cortex was not activated *only* during studies of verbal memory but also showed increased activity during non-verbal memory tasks. Because this region seems to be recruited for non-verbal tasks, it cannot subserve the phonological store described by Baddeley (1986), and all prior arguments that relied on this region's activation as evidence for a dissociable phonological store and rehearsal mechanism are compromised.

Similarly, what appeared at first to be a domain-specific dissociation between neural correlates of spatial and non-spatial stores in the dorsal-lateral pre-frontal cortex could be explained at least as well by supposing a distinction based on processing style. In a meta-analysis of previous neuroimaging data, D'Esposito, Aguirre, Zarahn, Ballard, Shin, and Lease (1998) proposed a processing-based explanation for the dorsal-ventral dissociation between spatial and non-spatial tasks in the prefrontal cortex (PFC). Rather than supposing the apparent dissociation occurred because tasks required the storage of spatial versus non-spatial information, D'Esposito et al distinguished the tasks by whether they required only maintenance of memoranda or maintenance and also manipulation. With this definition, D'Esposito and colleagues appear to find a better fit with the apparent functional anatomy of the PFC. With fMRI methods, Nystrom, Braver, Sabb, Delgado, Noll, and Cohen (2000) confirmed this hypothesis, finding no basis for a

supposed hemispheric verbal/non-verbal or the dorsal-ventral spatial/non-spatial distinctions in the PFC.

Further behavioral support for a process-based explanation of interference in working memory was demonstrated by Cowan and Morey (in press). Cowan and Morey compared memory for within- and between-domain stimulus sets in a cued-probe paradigm. Only one of two presented stimulus sets was tested on each trial, and participants were sometimes given a post-stimulus cue that told them which set would be tested. This cue allowed participants to focus on maintaining only the relevant memoranda. In different conditions, post-stimulus cues gave no information about which stimulus set would be probed; in these cases participants were to try to remember all the presented stimuli. This design enabled the comparison of interference due to concurrent maintenance (when both stimulus sets were to-be-maintained) versus interference due to encoding a stimulus (when the one stimulus set was cued). Cowan and Morey demonstrated that encoding interference occurred only within a single domain: encoding of verbal and visuospatial materials produced little interference, whereas encoding two verbal or two visuospatial stimulus sets produced more substantial interference. However, *maintaining memoranda from separate domains impaired memory as much as maintaining within-domain memoranda*.

In summary, the evidence suggesting modality- or code-based distinctions in working memory storage is much weaker than is often supposed, but evidence does tend to point to multiple components. However, these components might not be modality-specific, and might not be working memory stores per se. In behavioral cognitive research, encoding, maintenance, and responding are frequently confounded such that it

is difficult to say which processes interfere with each other (Cowan & Morey, in press); it is possible that these interpretation confounds have led to an over-zealous tendency to declare new, independent components of the working memory system. The addition of a domain-general store to Baddeley's model (1986) at once makes the model stronger by adding a component that can account for more data, but it also poses further questions, including: Is any other store really necessary to explain working memory data if a domain-general store is included? How are bindings maintained in a domain-general store, as object files or as links between features stored only in domain-specific stores?

Disputes Regarding Components of Working Memory

The symmetry of Baddeley's classic model (1986; Baddeley & Hitch, 1974) seems inherently appealing, and has inspired a literature that is largely uncritical of the assumption of domain-specific separation of working memory storage. However, there have been critics of this model who found redundancy in its components. One such critic is Phillips (1983), who observed interference with visual short-term memory from a variety of sources, such as concurrently making simple arithmetic calculations and repeating a list of 5 or more digits (Phillips & Christie, 1977; see also Morey & Cowan, 2004, 2005). Phillips criticized the tendency to interpret double dissociations as evidence for three rather than two independent working memory components. Rather than supporting the distinctions advocated by Baddeley and Hitch, Phillips and colleagues questioned the inclusion of a visual store *and* a central executive in a working memory model. Because a variety of tasks attributed to the central executive of Baddeley and Hitch's model interfered with visual memory, Phillips suggested that these structures

were not dissociable; at the least, a dependent relationship existed between them. This critique is important, and has unfortunately received relatively little attention despite other findings of similarity between executive tasks and visual working memory tasks (cf. Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). Phillips and Christie's argument in favor of parsimony when proposing multiple working memory components is especially apt now that an additional component, the episodic buffer, has been added to the multiple-component model (Baddeley, 2000). These components are supposed to be relatively independent, but if they are not, their interactions would become increasingly complex as new model components are added.

Feature Binding in Working Memory

One of the functions a domain-general working memory store is to maintain binding between features of different modalities or codes, for instance the binding between the spatial location of a verbal feature and the verbal feature's identity. This information could not be held in the domain-specific stores posited by Baddeley and Hitch (1974); this is one observation that motivated the addition of the episodic buffer to the classic multiple-component model (Baddeley, 2000). Little is currently known about the maintenance of cross-domain binding, but binding between visual features has been extensively studied. Depending on whether this binding requires attention for successful maintenance, a point that is currently under debate, complex visual objects may also require the use of the episodic buffer as conceived by Baddeley (Allen, Baddeley, & Hitch, 2006). In the following section, I will review literature on visual feature binding as well as the few studies of cross-domain binding, to prepare for predictions about

maintenance of cross-domain bindings that will be made in the experiments presented here.

It is commonly supposed that attention is required to form bindings between features (also called conjunctions), maintain conjunctions, or both (Treisman & Gelade, 1980; Wheeler & Treisman, 2002). This notion was supported by the observation of slower search times in visual search studies for multi-feature objects than for single features and the formation of illusory conjunctions (spurious bindings between features that are not actually part of the same object) with impaired attention or when attention is withdrawn. Kahneman, Treisman, and Gibbs (1992) supposed that when attention was applied to conjunctions, an object file was formed to represent the features in the object. Depending on what information was attended, Kahneman et al supposed that objects could be formed at several levels of a stimulus (see Figure 1). Figure 1 depicts the representation that might be maintained when attention is focused globally compared to when it is focused more narrowly (cf. Navon, 1977). In the least focused option (orange circle) an object might be defined as the entire scene, in this case, two red clover-like shapes. An object could also be defined as one of these clover-like shapes (green circle), and more detail may be observed: in this case, three separate red circles are distinguished instead of the clover-like shape. In the most focused option (blue circle) an object is one of these circles, and still more detail is observed (the black outline around the red circle). By defining objects at more global or more local levels, different characteristics may be attached to the object and others perhaps lost.

Luck and Vogel (1997) presented data that seemed to disconfirm the notion that attention is required for the maintenance of feature conjunctions. With a visual

comparison task in which participants made same/different judgments about two displays of randomly-located colored squares, Luck and Vogel (1997) found a capacity limit of about four objects, regardless of whether those objects included only one feature (e.g. color) or multiple features (e.g., color and shape, two colors). They concluded that a visual working memory store must therefore be limited by objects, not by features, hypothesizing that features might be associated by simultaneous neural firing patterns. Luck and Vogel emphasized that no disadvantage whatsoever was observed for memory of complex visual objects with many features compared to simple objects with only one feature.

Wheeler and Treisman (2002) challenged Luck and Vogel's assertion that as many as four bound features could be maintained without any additional cost to memory performance. In close extensions of Luck and Vogel's (1997) experimental design, Wheeler and Treisman utterly failed to replicate the critical finding that equal numbers of single-feature and bi-feature objects could be maintained accurately in visual working memory. They also found that binding was only impaired with respect to feature memory when a whole-report probe, rather than a partial-report probe, was used, indicating that binding errors occurred because of interference from re-interpreting the feature bindings in the test display. This argument further implies that whatever working memory component is storing the associations is also needed to interpret the stimuli, or alternatively, that two components needed for these tasks cannot be used simultaneously.

If attention is required for remembering bindings between features but not necessarily features themselves, then one would expect that a concurrent, attention-demanding task would impair memory for binding more than memory for features alone.

This does not appear to be the case. Allen, Baddeley, and Hitch (2006) compared memory for color, shape, and colored shapes with and without various concurrent tasks such as backward counting by threes and digit list memory, and found no additional decreased impairment during memory for colored shapes than during memory for only shapes or colors. The one exception proved to be for sequential memory of colored shapes. When colored shapes were presented in sequences rather than all at once in an array, memory for the binding was significantly worse than memory for colors or shapes alone. This is consistent with Wheeler and Treisman's (2002) finding that maintaining binding between visual features was impaired by the processing of subsequent visual stimuli, though the conclusions differ from Wheeler and Treisman's predictions. Allen, Baddeley, and Hitch suggested that at least some features can be bound at no cost, and offer speculation as to whether these objects are held in the visuospatial working memory buffer or the domain-general episodic buffer, a point currently unclear in the literature because of the disagreement over the involvement of attention in the formation and maintenance of integrated multi-feature objects.

Other research suggests a compromise position in which both the number of objects and their complexity determine visual working memory capacity. Alvarez and Cavanaugh (2004) compared change detection and visual search rates for visual stimuli that varied in complexity from single-color squares to line drawings and shaded cubes. The most complex objects yielded slower search rates and lower estimates of total memory capacity, but regardless of complexity, a limit of 4-5 objects (comparable to Luck & Vogel's, 1997) seemed to be a constant ceiling on visual working memory capacity. Recent neuroimaging research similarly suggests an accommodation for

theories that say visual working memory is limited by objects versus those that say it is limited by total complexity of to-be-remembered features. Xu and Chun (2005) showed that different neural regions were sensitive to increases in the total number of to-be-remembered features versus the number of to-be-remembered multi-feature objects, implying that mechanisms for both feature and object memory co-exist.

Overall, the research on feature binding in visual memory suggests some flexibility in the storage capacity for visual objects. At best, binding between visual features is fragile, although it may not require any more attention than maintaining a similar number of visual features.

Relatively little research has tested memory for cross-domain binding, such as memory for the spatial locations of verbal items. One problem in measuring memory for cross-domain objects directly is that it is not absolutely clear which information is maintained in a domain-general store; it is plausible that some associations might be held in domain-general storage whereas some domain-specific features are separately maintained, or that all features are separately maintained and the bindings between them deduced from serial order or some other cue. Thus, the overall measure of memory accuracy for cross-domain materials may reflect more than the capabilities of a domain-general store, particularly if the cross-domain associations can be reconstructed from some aspect of feature memories. For example, Cowan, Saults, and Morey (2006) compared memory for sequences of name-location associations when 1) each location in a sequence was unique (one-to-one mapping) versus when 2) locations could be repeated within a sequence (uneven mapping, e.g., two names could be associated with one location). In the one-to-one mapping condition, it is plausible that a verbal sequence and

a spatial sequence could be separately maintained, and the associations correctly determined simply by matching the order of the items in each sequence (e.g., first verbal item goes with first spatial location, second verbal item goes with second spatial location, etc.). However in the uneven mapping condition, a completely separate maintenance strategy might be more prone to error. Indeed for adult participants, lower accuracy rates were observed in the uneven-mapping than in the one-to-one mapping condition. This difference disappeared when adult participants engaged in concurrent articulatory suppression, which reduced their ability to rehearse sequences in the one-to-one condition (Jones et al, 1995), presumably forcing the more effortful strategy of cross-domain association storage. In the one-to-one mapping condition without concurrent rehearsal suppression, the measure of cross-domain associations could not be considered a pure measure of a domain-general store because of the apparent contribution of verbal rehearsal to memory accuracy.

Another study of memory for verbal-spatial associations was carried out by Prabhakaran, Narayanan, Zhao, and Gabrieli (2000). In some conditions of their study, participants were shown four bound letter-location items to remember, but were instructed to respond positively to a probe letter-location if *both* the letter and the spatial location were represented in the memory array, *regardless of whether they were bound together in one object*. Comparing positive-probe trials in which the probe was an original letter-location item (congruent positive trial) with those in which the probe was a recombination of a letter and a spatial location from the memory array (incongruent positive trial), Prabhakaran et al observed faster, somewhat more accurate responses for the congruent positive trials. This evidence led them to conclude that participants were

maintaining the letter-location stimuli as objects in a domain-general working memory store. This conclusion was enhanced by their finding of unique right anterior pre-frontal cortex activation using fMRI for the bound letter-location trials compared to activation in conditions with unintegrated verbal and spatial stimulus presentations.

It is unclear whether within-domain visual binding is held in a visual working memory buffer or a domain-general store (Allen, Baddeley, & Hitch, 2006). In Baddeley's conception (2000), the domain-general store was thought to be accessible only through the central executive, and as reviewed above, much evidence suggests that visual features require attention for maintenance of their binding (Wheeler & Treisman, 2002). There is currently enough disagreement about within-domain binding in visual working memory that generalizations cannot be made between within-domain and cross-domain binding. As it is now, cross-domain binding itself has hardly been studied. In fact, most of what is known about domain-general storage in working memory is surmised from dual-task interference studies rather than studies of cross-domain binding, and these studies furnish little additional information about a domain-general store than that it must exist.

Cross-domain Binding: A Means for Studying a Domain-general Store

There must be a domain-general store accessible to the working memory system because some research shows interference between visuospatial and verbal memory maintenance (Cowan & Morey, in press). However, dual-task interference studies are not ideal for discerning characteristics of a domain-general store. These studies cannot quantify the capacity of a domain-general store or learn its interaction with other

components of working memory, because it is difficult to know when a domain-general store is being used, especially if domain-specific stores are also assumed. The assumption (cf. Morey & Cowan, 2004) that a domain-general store was in use typically depended on presenting so many stimuli in a dual-memory task experiment that any within-domain stores must be considered loaded, and surplus memoranda must have spilled over into a domain-general store where they competed for its resources. Identifying which information or how much was held in the domain-general store was entirely speculative.

Letter-location stimuli present a much clearer logic for experimental interpretation. Letter-location objects presented in a simultaneous array, like those used in the integrated stimulus presentation conditions of Prabhakaran et al (2000), must be maintained in a domain-general store because such a store is the only working memory component capable of preserving that type of information. This is not to say that features of these objects might not also be stored simultaneously, but if an association is remembered, it can be assumed to have been maintained in a domain-general store. These stimuli are therefore ideal for acquiring a better understanding of domain-general storage. Little information about the nature of domain-general storage can be gleaned from Prabhakaran et al's study itself because their goal was to contrast bound versus separate stimulus presentations to identify neural correlates of a domain-general store if it existed. Their task might be altered so that 1) instructions better emphasize maintaining the cross-domain stimuli as objects and 2) contributions to working memory from domain-specific stores can also be measured and distinguished somewhat from contributions of a domain-general store.

The task instructions of Prabhakaran et al (2000) encouraged separate maintenance of the letter and location information, making it especially difficult to determine whether all remembered items were maintained in a domain-general store or rather as some combination of domain-general objects (or links between within-domain features) and isolated within-domain features. Indeed, their strongest evidence to support the claim that cross-domain objects were being maintained was selective fMRI activation in the right anterior PFC during the integrated stimulus conditions. Their task can be altered so as to emphasize memory for the stimuli as objects, and therefore increase the validity of the assumptions guiding the interpretation of behavioral data. In the versions of the Prabhakaran et al task used here, participants were instructed to reject probes that were not letter-location objects from the memory array; that is, the incongruent positive trials of Prabhakaran et al were negative trials in this study, termed *recombination* trials (See Figure 2). This change in instructions should serve to encourage cross-domain object maintenance in working memory.

It is also possible to test more explicitly whether cross-domain objects and single-domain features are simultaneously maintained, while avoiding any need to present separate memory stimulus sets. In the following studies, this is done by comparing *new letter* and *new location* trials with recombination trials. (Refer to Figure 2.) If only the integrated letter-location objects are held in working memory, then estimates of total working memory capacity should be the same regardless of whether two features from the memory array are recombined or whether a new feature (e.g. a "new" letter or location) is introduced in the test stimulus. However, if features are maintained as cross-domain representations in a domain-general store and also as isolated features in domain-

specific stores, as depicted in Figure 3, then new letter and new location trials should produce higher estimates of total working memory capacity than recombination trials, because in those trials more information is stored that can contribute to a correct response.

Predictions

By comparing accuracy rates and estimates of total working memory capacity during new letter, new location, and recombination trials, I hope to ascertain whether letters, locations, and letter-location objects or associations can be simultaneously maintained in working memory. According to Baddeley's updated model of working memory (2000), these stores are separate and independent. If these stores are truly separate and independent, then even when a task calls for binding maintenance, at least as many isolated features as links between them should be maintained. By this model then, new letter and new location trials should produce higher estimates of total working memory capacity than recombination trials, because in these cases, the extra stored features increase the likelihood that enough information is maintained for a correct response on those trials. This model of working memory storage for these stimuli is depicted in Figure 3. Suppose a limited number of verbal-spatial bindings can be retained. In the three-store model, at least as many letter or spatial features should be retained, since some isolated features of each type may also be stored. If these stores are independent, then recombination trials, which can benefit only from information held in the domain-general store, should produce lower estimates of total working memory capacity than new letter or new location trials. If the stores are not independent, or if the addition of a domain-general store makes one or both of the domain-specific stores

redundant, then estimates of working memory capacity on new letter or new location trials might not exceed those of recombination trials.

Extending Phillips and Christie's (1977) argument that the visuospatial sketchpad and the central executive might be redundant, it could be that a domain-general store actually makes a domain-specific visuospatial store redundant, given the close relationship observed in other research between visual working memory and a variety of attention-demanding tasks. If this is the case, then only new letter trials will produce higher capacity estimates than recombination trials; new location trials might offer no additional advantage.

Common Methods

In each of the following experiments, participants completed a letter-location memory task modeled after the one used by Prabhakaran et al (2000). This variant of this task is well-suited for studying a cross-domain storage mechanism like Baddeley's episodic buffer (2000) because on many trials, accuracy depends on remembering the correct associations between letters and their spatial locations. Below, the parameters of this task are delineated; these descriptions of this task are suitable for each of the experiments in this project.

Participants

All participants in these studies were students from introductory psychology courses at the University of Missouri, Columbia, who completed experiments in partial fulfillment of their course requirements; some participants were financially compensated. One hundred sixty eight college students (age 17-30 years old) took part in the studies reported in this manuscript (the sample was 48% female, 82% Caucasian, 8% black, 6%

Asian, 3% Hispanic, 1% other/unreported). Each participant's informed consent was acquired in writing. In addition to reading the consent documents, all participants were informed verbally of their right to withdraw from studies for any reason, and were assured of confidentiality.

Apparatus and Stimuli

Tasks were completed in quiet, private booths at personal computers equipped with 17-inch monitors. All stimuli were presented with E-Prime software (Schneider, Eschman, & Zuccolotto, 2002).

For the letter-location memory task, letters were drawn randomly without replacement on each trial from the set {B, F, G, H, J, M, Q, R, T, Y}; consonants were selected for inclusion in this set based on 1) minimal phonological confusability; 2) minimal visual similarity; 3) capital and lower-case graphemes that look different from each other in Arial font. Vowels were excluded from this set to eliminate the possibility that a valid English word could be formed from the letter stimuli chosen on a trial. Spatial locations were chosen randomly without replacement from 12 equally-spaced points centered on the squares of an imaginary 3x4 grid occupying the center-most 270 x 201 pixel (7.14 x 5.32 cm) area of the monitor. Assuming a viewing distance of 50 cm, the closest spatial locations were separated by 2° of visual angle. These location parameters have similar limits to those of similar visual working memory studies (cf. Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). As shown in Figure 2, the effect of this presentation was that the letters were scattered within an area well within the 24-30° generally considered the central visual field. Participants were not restricted from making eye movements. Letters were drawn in bold, upper-case 18-point Arial type. The single

probe letter appeared after a 3000-ms delay, and always appeared in lower-case form, not upper-case as during stimulus presentation, in order to encourage verbal rather than visual encoding of the letters. A 3000-ms delay was chosen to accommodate the concurrent judgment tasks, while keeping within a timeframe that is plausibly limited to working memory.

Yes/no responses were registered on the keyboard with the "y" and "n" keys. On half of the trials, the probed letter-location object was identical to one of the to-be-remembered objects in the sample memory array. In these cases, participants were to press "y", to indicate that yes, the item was presented in the memory array. On half of the trials, the probed letter-location was not an object from the memory array, and participants should respond "n", for no, the item was not present in the memory array. For "no" trials, the test stimulus could have changed from the objects in the sample in three equally-likely ways, described in Figure 2: (1) In a *new letter* trial, the probe letter was not present in the sample array but the probe's location was occupied by another letter in the sample array; (2) In a *new location* trial, the probe letter was present in the sample array, but the probe's location was previously unoccupied; (3) In a *recombination* trial, the probe's letter and location were both present in the sample array but were not part of the same object. (Refer to Figure 2.) Recombination trials were equivalent to the incongruent positive probe trials of Prabhakaran et al (2000), except that in Prabhakaran et al, these trials merited a "yes" response because both the letter and location were presented in the memory array, though not bound together.

In the new letter trials, participants could respond correctly even if they did not remember the locations of the letters; similarly in the new location trials, participants

could respond correctly even if they did not remember the identities of the letters. However in the recombination trials, participants must remember the correct letter-location bindings to correctly reject the probe as a target. These change trial types, along with trials in which the probe object was present in the sample array (50% of all trials), were randomly intermixed at run time.

Procedure

After participants signed the informed consent document, they completed a demographic information sheet that included questions about race, sex, language, medicine use, vision, and hearing. Participants could complete the session regardless of their responses to these queries, but participants reporting relevant medicine use or subnormal vision or hearing were excluded from data analysis. Each individual study includes justification of exclusion of participants' data from analysis. In each experiment, data were examined for chance or near-chance performance. Participants with overall accuracy rates of 50% or lower (in silent conditions only, when articulatory suppression instruction was a within-subjects variable) were excluded from all analyses. Participants with overall accuracy rates lower than 65% were examined more closely for evidence of task-misunderstanding or random responding. For instance, below-chance accuracy in only one type of change trial was taken as evidence that a participant did not understand what merited a "no" response. These few participants were also excluded from analyses.

Each participant was situated in front of a computer in a quiet, private booth. The experimenter read the instructions aloud and invited the participant to ask questions, and supervised a short practice session, which always included accuracy feedback. After the practice trials were complete and the participant understood the procedure, the

experimenter left the participant to complete the study at his or her own pace. The experimental trials never included accuracy feedback. Halfway through each experiment, the program forced the participants to take a break lasting at least one minute. In cases in which a new block of trials with new instructions began after this break, the experimenter returned to explain the new instructions and supervise another short practice session before allowing the participant to complete the remainder of the study independently.

For all experiments in this paper, the standard criterion of $p < 0.05$ was a pre-requisite for declaring significant effects. P-values are therefore reported only for non-significant results. Data are expressed throughout this manuscript in mean proportion correct and also as mean capacity units (cf Cowan, Elliott, Saults, Morey, Mattox, & Hismatjullina, 2005). Cowan's capacity formula estimates the average number of objects maintained in each condition, given hit rate (responding "yes" to a correct target), false alarm rate (responding "yes" to a new probe), and number of to-be-remembered objects (e.g., 4 * (p(hits)-p(fa)) when 4 items were to-be-remembered). Across probe trial types, this measure accounts for common rates of accuracy reflected in "yes" trials, in which the probed item was present in the memory array, because differentiated false alarm rates are subtracted from this common hit rate. Inferential analyses are all reported on capacity units, but it was rarely the case that a critical inference differed between proportions correct and the capacity measure; when it did, the inferential analysis was repeated with proportions correct. Cowan's capacity estimate formula has been used frequently to describe data from visual change detection tasks (see Morey & Cowan, 2004, 2005; Todd & Marois, 2005; Xu & Chun, 2005), but is logically consistent for describing cross-domain object memory as well. It should be noted that although the measure yields an

estimated number of objects contained in memory, it is not meant to assume that only objects and not features are stored: the proper interpretation of the capacity unit is therefore an *object's worth* of information. Throughout the analyses, it is assumed that this is a measure of total working memory capacity and not a measure of one specific store; implications regarding which stores contribute to working memory capacity are taken from the change trial manipulation.

Project Overview

Four experiments are reported below. Each includes some version of the letter-location memory task described above.

- In Experiment 1, participants completed the letter-location memory task while making a simple or choice stimulus judgment in between the offset of the sample memory array and the onset of the test stimulus. Experiment 1 showed few differences between effects of different types of judgment stimuli, but a robust effect of change trial type in which estimates of total working memory capacity in the new letter condition exceeded those of the location and recombination conditions, which did not significantly differ.
- In Experiment 2a, participants completed the letter-location memory task at varying levels of load (2-6 letter-location objects), with and without articulatory suppression; Experiment 2b replicated Experiment 2a with circles around the letter stimuli to further encourage separate maintenance of spatial locations in a visuospatial store. In both cases, the superior estimates of working memory capacity in the new letter trial conditions persisted. Concurrent articulatory suppression impaired memory in all change trial conditions.

- Experiment 3 tested letter-location memory with sequential, rather than simultaneous stimulus presentation. No differences in serial position effects were observed in the different change trial conditions, but estimates of working memory capacity in the new letter trials remained higher than those in the location and recombination trials. Concurrent articulatory suppression impaired memory in all change trial conditions.
- Experiment 4 examined memory for only one feature of the letter-location stimuli (e.g., only the letter or the spatial location), with and without articulatory suppression. Estimates of capacity for letters and spatial locations did not significantly differ, and concurrent articulatory suppression impaired memory for letters but did not impair memory for spatial locations.

Experiment 1: Effects of brief sensory judgments on cross-domain object memory

Methods

Participants

Twenty-eight college students (19 male, 9 female) took part in this two-session study in partial fulfillment of requirements of their general psychology course. Some participants who no longer needed course credit after their first session finished their second session for $10. Each session lasted between 60 and 90 minutes, and sessions were typically scheduled for the same times on different days during the same week. Two participants failed to complete the study, one due to a computer error and one to cancellation of the second experimental session. One participant's data were excluded from analyses because of near-chance accuracy on the letter-location memory task, and two were excluded on suspicion of randomly responding in at least one condition of the judgment task, leaving a sample of 23 (17 male, 6 female).

Stimuli and Tasks

Refer to Figure 4 for examples of stimuli and Experiment 1 procedure. Participants completed the letter-location memory task described above, with 4 simultaneously-presented objects in each trial. In the 3000-ms interval between the offset of the sample letter-location array and the onset of the letter-location test stimulus, participants made a judgment about a brief sensory stimulus.

Four types of stimulus judgment task were presented in simple and choice judgment conditions. For each block of trials, participants made judgments about tone frequency, letter identity, color shade, or spatial location. After a warning fixation

appeared for 1000 ms, participants saw or heard a 1000-ms stimulus and then made a judgment about it as quickly as possible. Responses were recorded within 2000 ms from the onset of the judgment stimulus. For each type of stimulus judgment task, three stimuli were chosen based on easy discriminability and as comparable in distinctiveness as possible between codes and modalities. Low, medium, and high tone stimuli were 972, 529, and 87 Hz, respectively. Letter stimuli include the spoken vowels A, E, and O, in a female voice. Both tones and letters were presented via headphones at about 74 dB. Light (255, 149, 43), medium (234, 177, 0), and dark (170, 85, 0) shades of orange were chosen from spectrums with hue=20 and saturation=240. Color stimuli appeared as a rectangle encompassing 25% of screen height and width, centered. For location judgment, an "*" appeared in bold 18-point Arial font either in the center of the screen or 131 pixels above or below it, eliciting a judgment of high, middle, or low. All stimuli occurred against a neutral light grey background.

For choice judgment tasks, participants were instructed to indicate with a key press which of the three stimuli of a type (i.e. the lowest, medium, or highest tone; the lightest, medium, or darkest color, etc.) occurred during that trial. Keys in the number keypad were labeled for responses. For simple judgment tasks, participants were to press a key if any stimulus occurred (50% of trials) during the trial and do nothing if they observed no stimulus. Choice judgment blocks also included control trials (25% of trials) in which no stimulus occurred.

Each type of judgment task was presented alone to obtain a baseline measure of judgment performance, and also embedded in the letter-location memory task in a dual-task block of trials. In the dual-task trials, a judgment stimulus could occur 1000 ms after

the offset of the sample memory array, and the response to the judgment stimulus had to be received within 2000 ms, before the letter-location probe appeared. These parameters were maintained for the control blocks of the judgment trials.

Procedure

The experimenter supervised a short practice session which included six letter-location memory trials, a demonstration of the twelve judgment stimuli (three stimuli for each of four stimulus categories), and 24 practice judgment trials (six trials each for four stimulus categories). Each session consisted of 4 blocks of single-task trials including 15 trials each of the letter-location memory task and the following four stimulus judgment tasks: tone, letter, color, and location for a total of 60 single-task control trials per session. Order of the single tasks was randomly determined in each single-task block. Alternating with these single-task blocks were four dual-task blocks of 60 trials each in which the letter-location memory task was carried out with a judgment embedded in the retention interval. The type of judgment stimulus (tone, letter, color, or location) was determined randomly with replacement, so that in one session one dual-task block of each stimulus type was presented. Choice and simple judgment instructions were counterbalanced by session. Feedback was only given during the experimental session when participants responded incorrectly on a judgment task, in order to prevent participants from responding randomly.

Results

The 23 participants included in the following analyses showed acceptable levels of performance in each of the tasks; participants with mean latency of 0 in any condition or below-chance accuracy in judgment tasks were excluded from all analyses. Descriptive

statistics on choice and simple judgment tasks can be found in Table 1. Despite efforts to equate judgment task difficulty, accuracy on the choice tone judgments was somewhat worse than accuracy on the other judgment tasks (F=8.18, MSE=.004, η_p^2=.27); post-hoc Neuman-Keuls analyses confirm that only the tone condition differed from the others (ps>0.40).

The most striking effect observed in these data was an effect of change trial type. A 3-way repeated-measures ANOVA with judgment instruction type (choice vs. simple), judgment stimulus type (no-judgment control, color, location, tone, or letter) and change trial type (new letter, new location, or recombination) was carried out on the letter-location memory task capacity estimates. Table 2 shows descriptive statistics for proportion correct measures; descriptive statistics for the capacity estimates in this analysis can be found in Table 3. Significant main effects of judgment stimulus type (F=5.13, MSE=.71, η_p^2=.19) and memory trial type (F=59.47, MSE=.70, η_p^2=.73) were observed. Surprisingly, no main effect of judgment instruction type was discernible (p=.14). No interaction reached the p<0.05 threshold necessary for statistical significance (all ps> 0.22; all η_p^2s < 0.06).

Post-hoc Fisher Least Significant Difference tests of the judgment stimulus type factor indicate that capacity estimates were significantly higher in the single-task control trials than in the dual-task trials, but revealed no differences in capacity estimates based on the type of judgment stimulus presented (all other ps > .12). This pattern of results, combined with the non-significant effect of judgment task instruction type, implies that maintenance of cross-domain objects is sensitive to interference from multiple domains and codes, regardless of whether a more attention-demanding decision is required.

The letter-location memory task was designed to compare situations in which memory for the cross-domain bindings was crucial (recombination trials) and situations in which memory for either type of feature could influence responses. If participants adopted a strategy of maintaining the letters and spatial locations separately, it would be reasonable to expect to observe a greater decrease in capacity for trials in which the judgment stimulus was most similar to the crucial features (e.g., lower capacity estimates for new location trials during the spatial judgment task, etc.). However, the non-significant interaction between judgment stimulus type and memory trial type provides no evidence for this scenario; indeed the interaction remains non-significant even if power is increased by collapsing across the non-significant factor judgment task instructions and the modality of judgment stimuli (e.g., grouping tone with letter trials and color with location trials; $p=.53$, $\eta_p^2=.03$). These results are shown in Figure 5.

The most remarkable aspect of these data was the effect of change trial type. In addition to the apparent lack of interaction between judgment stimulus type and change trial type, the direction of the effect of change trial type proved surprising. This manipulation was designed with Baddeley's updated model of working memory (2000) in mind, and it was therefore assumed that three separate stores (one for verbal codes, one for spatial codes, and one flexible store) were available to maintain information in working memory. Given this model, it was expected that new letter and new location trials would have an advantage over recombination trials, because in the new letter and new location trials, knowing either the identity or positions of the letters would be enough to choose the correct response. Post-hoc Neuman-Keuls tests showed that this was so in the new letter condition, which produced significantly higher capacity estimates

than the new location and recombination conditions, which did not significantly differ (p=.57). These differences are apparent in Figure 5.

Discussion

Experiment 1 provided some basic, previously unknown information about the maintenance of cross-domain objects. First, maintenance of cross-domain objects appears to be sensitive to a variety of sources of interference. Cross-domain object memory was tested with concurrent stimuli that varied in similarity to the to-be-remembered stimuli; judgment stimuli were of the same features as the to-be-remembered stimuli (e.g., letters, locations) or differing features of varying modality (e.g., tones, colors). However, these varying dimensions had no consistent effect on memory for cross-domain objects, indicating that maintenance of these objects can be disrupted by stimuli from either auditory-verbal or visuospatial sources. Furthermore, simple discrimination tasks disrupted cross-domain memory as much as choice discrimination tasks, suggesting that complex mental manipulations are not necessary to impair the functioning of a cross-domain memory system. However, because four items were to-be-maintained on each trial, the lack of effect of judgment task instructions could be due to floor effects and should be interpreted cautiously. It should be noted though that if four objects were ceiling level for most participants, no difference would have been observed between single and dual-task conditions at all, and this is clearly not the case.

The most pronounced finding in Experiment 1 was the effect of change trial type. Regardless of the secondary task condition, no advantage was observed for new location trials, those in which the probe item appeared in a previously unoccupied spatial location. The possible spatial locations used were distant enough to be easily discriminable, and

comparable numbers of letters and spatial locations comprised the sets from which the stimuli were constructed on each trial. In another visual change detection study comparable to this one but using within-domain visual stimuli, detection of spatial location changes was very good (Wheeler & Treisman, 2002, Experiment 3). Capacity estimates in the new location condition were expected to be comparable to those in the new letter condition, because of the assumption that the working memory system includes separate stores for verbal and spatial information in addition to the domain-general store that can accommodate cross-domain associations. Instead, the new location trials did not significantly differ from the recombination trials. This effect could mean that memory for binding is limited only by memory for one feature type, in this case spatial location, but that rather than interacting, exactly the same number of bindings and locations can be maintained. The effect of change trial type was explored more systematically in Experiments 2a and 2b. Articulatory suppression instructions were added as a within-subjects variable in order to assess the independent maintenance of spatial location features from letter features.

Experiments 2a and 2b: Interference between cross-domain object memory, feature memory and speech

Methods

The following two experiments examined letter-location change trial type, the most robust manipulation from Experiment 1. Experiment 2a was designed to replicate the unexpected pattern of change trial type observed in Experiment 1, whereas Experiment 2b was carried out to replicate Experiment 2a after incorporating a small change to the stimulus presentation; in Experiment 2b, each letter stimulus was surrounded by a thin circle. The circles were added to the stimulus presentation to test the notion that perhaps a separate spatial representation could not be maintained without a separate feature for it to be associated with. In both experiments, the new letter trial advantage found in Experiment 1 persisted.

Blocks of trials with concurrent articulatory suppression were included in Experiments 2a and 2b. If the capacity estimates of new letter trials were higher than those of new location and recombination trials because the phonological loop could hold a few letters from the presentation separately, then articulatory suppression should bring the capacity estimates of the new letter trials down to the levels of the location and recombination trials.

Participants

Thirty introductory psychology students participated in Experiment 2a (20 male, 10 female). Two participants' data were excluded from all analyses due to very low accuracy in silent conditions, leaving N=28 (18 male, 10 female).

Thirty-one introductory psychology students participated in Experiment 2b (9 male, 22 female). Two participants failed to complete the study, one due to a computer malfunction and one due to a scheduling conflict. Three participants' data were excluded from all analyses due to very low accuracy in silent conditions, leaving N=26 (9 male, 17 female).

Stimuli

Letter-location stimuli. The letter-location stimuli were similar to those described in the methods of Experiment 1, except that sample arrays could contain 2, 3, 4, 5, or 6 items. The sample array remained onscreen for 125 ms per item (i.e., 250 ms at set size 2, 375 ms at set size 3, etc.). Trials with arrays of each size were intermixed randomly at run time. In Experiment 2b, each letter in the memory array was surrounded by a thin black circle, and the probe letter was also surrounded by a circle.

Articulatory suppression. For half of the experimental trials, participants repeated the word "the" approximately twice per second while completing the letter-location memory task. Participants were instructed to begin repeating "the" as soon as the fixation "+" appeared onscreen after the initiation of a trial, and continue speaking until the probe item appeared and a response could be registered. During the practice trials, the experimenter ensured that the participant followed these articulation instructions. An experimenter stationed outside the participant's booth monitored speech throughout the session to ensure that participants remained silent during the silent block of trials and spoke, maintaining the rehearsed tempo, during the articulation block. No participant needed to be reminded to speak or to change their tempo more than once after the end of

the practice session. Order of silent and articulation blocks was counterbalanced across participants.

Procedure

Participants completed the study in one session lasting 60-90 minutes. After eight practice trials were completed and the participant seemed to understand the procedure, the experimenter left the participant to complete the first block of 240 trials at his or her own pace. The participant was advised to fetch the experimenter after the first of two blocks of trials was complete; the end of the first block was marked by a forced one-minute break. After this break, the experimenter explained the instructions for the second block of trials, supervised another short practice session, and allowed the participant to complete the second block of 240 trials independently.

Trial events were ordered as in Experiment 1 and are depicted in Figure 6. Each trial began with a 1000-ms fixation "+", followed by the sample memory array. The sample memory array remained onscreen for 125 ms per item. A blank grey screen then appeared for 3000 ms, followed by the test stimulus, which remained onscreen until the participant responded by key press.

Results

For each experiment, 3-way repeated measures ANOVAs were carried out with articulation condition (silent or "the, the,"), probe trial type (new letter, new location, or recombination), and set size (2, 3, 4, 5, or 6 items) as within-subjects factors. Descriptive statistics for proportion correct measures for both experiments can be found in Table 4 and capacity estimates corresponding to the variables in the full ANOVAs can be found in Table 5.

The effect of change trial type observed in Experiment 1, in which new letter trials yielded higher capacity estimates than new location and recombination trials, was replicated in Experiments 2a and 2b. The outcomes of Experiment 2a and 2b were extremely similar (see Figure 7), indicating that the presence of the circles had no effect on memory for the letter-location objects or any separate features. For Experiment 2a (no circles), significant main effects of articulation condition (F=71.20, MSE=1.48, η_p^2=.73), probe trial type (F=12.97, MSE=.44, η_p^2=.32), and set size (F=37.10, MSE=1.39, η_p^2=.58) were observed, as well as significant interactions between articulation condition and set size (F=13.68, MSE=.60, η_p^2=.34) and probe trial type and set size (F=3.80, MSE=.24, η_p^2=.12). The 2-way interaction between articulation condition and probe trial type (p=.42) and the 3-way interaction between all factors (p=.06) were non-significant.

The data for the same analysis in Experiment 2b (with circles) are depicted in Figure 7. Significant main effects were again observed for each factor: articulation condition (F=36.62, MSE=2.44, η_p^2=.59); probe trial type (F=16.87, MSE=.38, η_p^2=.40); and set size (F=37.92, MSE=1.21, η_p^2=.60). The same 2-way interactions reached significance: articulation condition and set size (F=16.30, MSE=.66, η_p^2=.39); and probe trial type and set size (F=2.37, MSE=.23, η_p^2=.09), whereas the two-way interaction between articulation condition and probe trial type (p=.13) and the 3-way interaction (p=.40) were non-significant.

Post-hoc Neuman-Keuls analyses of both experiments show the pattern of probe trial type observed in Experiment 1 remains: new letter trials produced an increase in capacity estimates relative to new location and recombination trials, which did not differ (2a, p=.42; 2b, p=.09.). The significant interactions involving set size are fairly trivial, as

they seem to be driven mainly by equality across conditions (e.g., probe trial types) at set size 2 (2a, ps range from .07-.41; 2b, .27-.48). There may also be a gradual increase in new location trial estimates as set size increases; at set size 6, new location trials produce higher estimates than recombination trials, and are equal to new letter trial estimates (2a, p=.57; 2b, p=.54). Across most set sizes however, the pattern of new letter trial estimates exceeding those of new location and recombination trials seems to hold.

The significant articulation condition by set size interactions show that under articulatory suppression, capacity estimates seem to plateau at about 4 items (ps for comparisons between set sizes 4, 5, and 6 range from .12-.75) whereas in the silent conditions, the estimates continue to increase at least until set size 5 (ps for comparisons between set sizes 5 and 6 and 4 and 6 range from .08-.21).

Regarding the insignificant interaction between articulation condition and probe trial type, in Experiment 2b, post-hoc analyses reveal a subtle difference in the overall probe trial type pattern and this pattern during articulatory suppression. In the articulatory suppression condition, new location trials produce significantly higher capacity estimates than recombination trials, but significantly lower than those of new letter trials. This shows that recombination estimates do not necessarily increase with new location estimates, and therefore the low estimates for recombination trials do not merely reflect a limitation due to poorer memory for spatial locations than letters. In other words, it is not clear that spatial location is merely the limiting factor on cross-domain object memory in this study.

In order to generate more power to detect potential small effects, the same analysis of variance was repeated on a data set including capacity estimates for all valid

participants in Experiments 2a and 2b. The same pattern of results was observed: critically, the mean for new letter trials was significantly greater than those for new location and recombination trials, which did not significantly differ (p=.06), and the interaction between articulation condition and probe trial condition did not reach significance (p=.10).

Discussion

In two studies, a clear pattern persisted in which new letter trials produced significantly higher estimates of storage capacity than new location or recombination trials. This pattern persisted even when circles were added to the display, which might have further encouraged a separate representation of the visuospatial features. This pattern questions the assumption that spatial feature information can be separately maintained during a cross-domain memory task. Concurrent articulatory suppression reduced estimates of capacity during new letter trials, bringing them beneath those of new location and recombination trials in the silent condition. However, concurrent articulatory suppression further reduced capacity estimates for new location and recombination trials, indicating a possible role for verbal rehearsal mechanisms in memory for cross-domain objects.

That articulatory suppression further reduced capacity estimates in the new location condition supports the presumption that spatial locations were not separately maintained as features in a domain-specific visuospatial store in addition to being maintained as components of cross-domain objects. If spatial locations had been separately maintained, evidence from many other studies (cf Cocchini et al, 2002) suggests that they would not have been harmed by concurrent speech. This finding also

casts doubt on the account of cross-domain maintenance in which features and their links are separately maintained in working memory. In this account, the similarity in capacity estimates for new location and recombination conditions could be seen as evidence that memory for location features are common, rating-limiting step for both of these probe trial types. If this were the case though, recombination trials should be limited by memory for letter features during articulatory suppression, and this does not seem to be the case. These data instead suggest that some letter-location objects are maintained as bound representations, perhaps along with some independent letter features.

Experiment 3: Memory for sequentially-presented cross-domain objects

Experiments 2a and 2b replicated the pattern of results observed in Experiment 1: probing participants with a new letter produced a much higher rate of correct change detection than when the probe combined an old letter with a new location or recombined used letters and locations. This pattern of results implies that some letters can be maintained concurrently with cross-domain objects, supporting a model of working memory that includes at least a phonological store and a cross-domain store.

In Experiment 3, memory for sequentially-presented cross-domain objects was tested. Allen, Baddeley, and Hitch (2006) observed impaired memory for color-shape binding only for sequentially-presented color-shape stimuli. A similar super-impairment for recombination trials has not been observed so far, except in the articulation conditions of Experiment 2b, although all of the trials in these studies emphasize memory for cross-domain binding. Domain-general and domain-specific working memory stores might be further distinguished by distinct shapes of their serial position functions. As it happened, with this design no differences in serial position were detected, however the new letter trial advantage persisted.

Methods

Participants

Forty-eight introductory psychology students (21 female, 27 male) took part in an approximately 60-minute session in exchange for partial course credit. Four participants' data were excluded from all analyses because of below-chance performance in at least

one condition, leaving N=44 (19 female, 25 male). These four participants were all in the articulatory suppression between-subjects group.

Apparatus and Stimuli

Letter and location stimuli were restricted and selected as in Experiments 1 and 2, except that instead of being presented all at once, they were presented sequentially for 250 ms each with a 100-ms delay between their offsets and onsets. Each sequence contained four circled consonants. Trial types (new letter, new location, recombination, no change) were manipulated within-subjects and accounted for the same proportions of total trials as in previous experiments. In order to keep session length under 90 minutes and avoid requiring two sessions per participant, articulatory suppression conditions were manipulated between-subjects.

Procedure

The experimenter read the instructions to the participant and then supervised a 10-trial practice session, ensuring that participants followed their articulation instructions. After the practice session, the experimenter left the participant to complete the study unsupervised. Participants completed two blocks of 144 trials each, separated by a break of at least one minute. The entire session lasted 60-90 minutes.

Results

Figure 8 shows that, just as for simultaneous cross-domain stimuli, memory for sequential cross-domain stimuli exhibits the same patterns: new letter trials have a distinct advantage over new location and recombination trials, and all trial types are impaired by articulatory suppression. Proportions correct and their corresponding capacity estimates can be found in Table 6. A 3-way ANOVA with articulation

instructions (silent or "the, the, . . . "), probe trial type (new letter, new location, or recombination), and serial position of probed letter revealed significant main effects of articulation condition (F=6.24, MSE=6.11, η_p^2=.13), probe trial type (F=37.57, MSE=.40, η_p^2=.47), and serial position of probe item (F=12.96, MSE=.41, η_p^2=.24). All of the interactions were non-significant (ps range from .15-.83). Because the proportions correct (see Table 6), seem to differ mainly in the no change trials, this ANOVA was repeated with the same factors with the proportions correct as dependent variables. The effect of articulation instructions did not reach significance (p=.053); all other inferences were the same as in the analyses of capacity estimates.

Articulatory suppression tended to impair accuracy, although this effect did not reach significance when proportions correct were analyzed. The effect of probe trial type held the pattern observed in Experiments 1, 2a and 2b, with new letter trials (M=2.81) producing significantly higher estimates than new location (M=2.37) and recombination trials (M=2.25), according to a post-hoc Neuman-Keuls analysis. This analysis revealed no significant difference between new location and recombination trials (p=.08). Post-hoc Neuman-Keuls analyses of serial position showed advantages for probes from the fourth serial position (M=2.72) and the first serial position (M=2.54, significantly lower than serial position 4), which were both significantly higher than probes from the interior serial positions (serial position 2: M=2.27; serial position 3: M=2.36), which did not differ from each other (p=.24).

Discussion

Though it was a weak attempt to discover unique serial position functions between probe trial types (a strong attempt would use recall of sequences instead of a

probed response, include longer list lengths, and manipulate binding requirements), Experiment 3 replicated the new letter trial advantage observed in Experiments 1 and 2. Once again, new letter trials held an advantage over new location and recombination trials. Though new location and recombination trials did not significantly differ at the $p < .05$ criteria, Experiment 3 showed a slight advantage for new location trials over recombination trials. This marginal effect is not remotely as large as one would expect if independent visuo-spatial and domain-general stores are assumed to exist independently of each other, and work in conjunction to separately maintain verbal and spatial features.

Compared with memory for single features (e.g., shape, color), Allen, Baddeley, and Hitch (2006) only found evidence of a binding deficit when their visual stimuli were sequentially, rather than simultaneously, presented. Similarly, by informal across-experiment comparison, sequential presentation seems to result in somewhat reduced estimates of capacity for cross-domain objects compared with simultaneous presentation. (Compare Figures 8 and 9.) The presence of a slight recency advantage is consistent with Allen et al's finding that memory for bindings is fragile and quite prone to interference from intervening stimuli, and also consistent with the findings of Experiment 1 described above.

Experiment 4: Integrated letter-location presentation with a single dimension probe

Experiments 2a, 2b, and 3 all show clear impairment in this cross-domain memory task during concurrent articulatory suppression. This impairment is present even in conditions which could be successfully carried out by only maintaining the spatial locations (i.e., disregarding the verbal and association information). Lack of spatial memory impairment with concurrent articulation has been documented in many studies (Farmer et al, 1986; Cocchini et al, 2002), indicating that when spatial information is encoded separately, concurrent speech indeed has no effect on its maintenance (although see Jones et al, 1995).

Experiment 4 was carried out to confirm that concurrent articulation does not negatively affect working memory for spatial locations and to test whether stimuli integrated at presentation could even be maintained as separate features if participants were instructed to disregard their bindings. The stimulus presentation was exactly the same as in Experiment 2b, however at test only one feature, either a letter or a spatial location, was presented as a probe. Therefore in this task, the cross-domain binding information was irrelevant and could be ignored.

Methods

Participants

Thirty undergraduate psychology students (12 male, 18 female) took part in Experiment 4 in exchange for introductory psychology course credit. All of these participants' data was eligible for data analysis.

Apparatus, stimuli, and procedure

Letter and location stimuli were restricted and selected by the same rules as in the studies described above. The only difference between the stimuli in Experiment 4 and those in Experiment 2b was in the probe stimuli. Instead of a letter-in-location probe item, only a lone circle or a single letter was presented at the test screen. A circle probe could appear either at one of the locations occupied in the sample memory array (target) or at one of the allowable but previously unoccupied locations (lure). A letter probe appeared in the center of the screen (not an allowable location stimulus) and could be selected from the letters used in the sample array (target) or those unused (lure).

The participant's task was the similar to that in the previous studies. Given the probe, participants pressed "y" (for yes) if they believed that item had been present in the sample memory array and pressed "n" (for no) if they believed it was not present. Instead of judging a letter-location object, the decision was reduced to only one feature, either a letter or a spatial location, with information about the untested feature dimension excluded from the probe stimulus. Proportions of letter and location probes were equal, and so were proportions of change and no-change trials. The session and trial procedures were identical to those of Experiments 2a and 2b. Articulatory suppression instructions were manipulated within-subjects with order of silent and spoken blocks counterbalanced across participants.

Results

Unlike in Experiments 2a, 2b, and 3, in which concurrent articulatory suppression impaired memory for cross-domain associations and their features, the data from Experiment 4 show that if the features are to be separately maintained, articulatory

suppression only impairs memory for the letters and does not affect memory for the spatial locations. Descriptive statistics corresponding to the following 3-way ANOVA can be found in Table 7 and a graphical representation can be seen in Figure 9. Estimates of verbal and spatial capacity were subjected to a 3-way ANOVA with articulation instructions (silent or "the, the,"), probe modality (verbal or spatial), and set size (2, 3, 4, 5, or 6 letter-location objects). Significant main effects of articulation instructions (F=54.25, MSE=.94, η_p^2=.65) and set size (F=30.38, MSE=1.12, η_p^2=.51) were observed; there was no main effect of probe modality (p=.80).

Although Experiment 4 was identical to Experiment 2b except for the use of single-feature probes, several significant interactions were revealed, including a significant interaction between articulation condition and probe type (F=39.91, MSE=.79, η_p^2=.58). Post-hoc Neuman-Keuls analyses showed that capacity estimates in the letter probe trials (M=2.97) were significantly higher than those in the location probe trials (M=2.50) in the silent condition, but that location estimates (M=2.37) are significantly higher than letter estimates (M=1.94) during articulatory suppression. Importantly, this analysis also failed to reveal a significant difference between the mean location estimates in the silent and articulation conditions (p=.24), indicating that when spatial locations are maintained as separate representations from a cross-domain stimulus, concurrent articulation does not significantly impair memory for them.

As in Experiment 1, significant interactions involving the set size factor were observed: two-way interactions between probe modality and set size (F=6.51, MSE=.83, η_p^2=.18) and articulation condition and set size (F=4.22, MSE=.73, η_p^2=.13) reached statistical significance. These interactions seem to be mainly attributable to the similarity

in capacity estimates at set size 2, a ceiling effect. The 3-way interaction was also significant (F=6.03, MSE=.58, η_p^2=.17), which, like the two-way interactions involving set size, seems to be due to more pronounced interaction of articulation condition and probe modality at larger set sizes. Post-hoc Neuman-Keuls analyses showed that in the silent conditions, the verbal probe capacity estimates reached a plateau at set size 4 (comparisons between set sizes 4, 5, and 6 were non-significant, ps from .43-.93) whereas the spatial probe capacity estimates seemed to gradually increase at 5 or more objects (comparisons of set sizes 3, 4, and 5 were non-significant, ps from .052-1, but set size six significantly higher than all others). In the articulation conditions, both the verbal and spatial capacity estimates seem to plateau; for the verbal conditions, set sizes 5 and 6 did not significantly differ (p=.27) and estimates at set size 5 are significantly *lower* than those at set size 4. For the spatial conditions, set sizes 4, 5, 6 did not significantly differ (ps from .08-.83), although they appear to increase slightly.

Experiment 4's results may be compared with the new letter and new location conditions of Experiment 2b; in these conditions, the stimulus presentations were exactly the same, but in Experiment 2b, the task required maintenance of the binding between letters and spatial locations. A repeated measures ANOVA was carried out on mean capacity estimates with articulation condition (silent or "the, the,"), probe type (letter or location change), and set size (2, 3, 4, 5, or 6 items) as factors, with Experiment (2b and 4) as a between-subjects variable. No main effect of experiment was observed (p=.24), and interactions of probe type and experiment were non-significant (p=.18), indicating that mean capacity estimates were similar when binding maintenance was required (Experiment 2b) versus when it was not (Experiment 4). Complete ANOVA results can

be found in Table 8. The critical result indicates that the significant interaction between articulation condition and probe type differed between Experiments 2b and 4: in Experiment 2b, concurrent articulatory suppression impaired both new letter and new location trials whereas in Experiment 4, concurrent suppression only impaired letter change trials and actually improved location change trials. A separate 2-way ANOVA with factors of experiment (2b and 4) and set size (2, 3, 4, 5, and 6) was carried out to compare only letter change trials in the articulatory suppression conditions across experiments. This analysis showed that mean capacity estimates in Experiment 4, in which binding maintenance was not required, were significantly lower than in Experiment 2b, in which binding maintenance was required. This suggests that maintaining the verbal information bound with spatial locations helped preserve it during concurrent articulatory suppression.

Discussion

Considered with Experiments 2a and 2b, Experiment 4 shows that verbal and spatial stimuli presented as cross-domain objects *can* be separately maintained when the cross-domain information is not needed for the task. Under these circumstances, concurrent articulatory suppression does not significantly impair memory for spatial locations, but does significantly impair memory for letters. Furthermore, a cross-experiment comparison suggested that no more feature information was maintained when letters and spatial locations are separately held versus when they are held in a bound format, except that for verbal information, more information might be preserved during concurrent suppression if letters are maintained in a bound format with spatial locations. This suggests that how representations are maintained depends on how they are encoded,

but that it is possible to maintain similar amounts of feature information in integrated or unintegrated format.

General Discussion

Summary

The series of experiments described above yields several new findings about how cross-domain objects are maintained in working memory. Experiment 1 showed that stimuli from several sources can interfere with memory for cross-domain stimuli, and that even making a simple judgment (compared with a more attention-demanding choice judgment) about these stimuli could lead to impaired memory for cross-domain objects. Experiment 1 also revealed a robust effect of feature-change in a cross-domain visual change detection task, namely that changing a letter feature resulted in higher estimates of total working memory capacity than changing a spatial location feature or changing the binding between two features. Experiments 2a, 2b, and 3 replicated this effect, and also showed that a simple concurrent articulatory suppression task impaired cross-domain memory, even in cases when remembering the spatial locations alone would have been sufficient for making a correct response. Finally, Experiment 4 confirmed that concurrent articulatory suppression does not impair memory for spatial locations when they are not maintained as part of integrated cross-domain objects.

Storage of Cross-Domain Objects in Working Memory

These data can provide partial answers to several critical questions about domain-general working memory storage and cross-domain binding. One of these questions concerns the relationship between domain-general storage and attention. Two prominent theories of working memory that posit domain-general storage, Baddeley's updated

multiple-component model (2000) and Cowan's Embedded Process Model (1999) both posit a strong relationship between the domain-general store and attention (or executive processes in Baddeley's terminology). Consistently, the evidence reported in the four studies above demonstrates that memory for cross-domain bindings is sensitive to interference from a variety of sources.

Another critical question is whether cross-domain materials are held in memory as separate features with abstract links between them, or rather as object files, similar to those described by Kahneman, Treisman, and Gibbs (1992). The fact that when bound objects are to-be-remembered, spatial locations do not seem to be separately maintained suggests that the cross-domain associations are maintained as components of cross-domain objects, rather than as links between separately-maintained features. However, this point bears further testing.

If it is the case that integrated features are stored as objects in a domain-general store and if there are also domain-specific feature stores in working memory, then new letter and new location conditions should have shown a clear advantage over recombination trials in Experiments 1, 2a, 2b, and 3, because in new letter and new location trials, maintenance of extra features should have increased the chance of having enough information to correctly reject new letter and new location probes. This seemed to be the case for new letter trials, which always produced higher estimates of total working memory capacity than recombination trials. However, this was not the case for new location trials, which did not generally produce higher estimates of total working memory capacity than recombination trials. This implies that *no spatial information is stored independently of the binding information*. No data from any of the experiments in this

paper support the proposition that the spatial feature information in these memory arrays is maintained independently when the cross-domain associations are to-be-remembered. If the spatial arrangement of the stimuli were simultaneously maintained, then estimates of total working memory capacity on the new location trials would be decidedly better than those for the recombination trials, especially during concurrent articulatory suppression, and this is clearly not the case. This finding might be surprising, given the support in the literature for a working memory component specialized for holding fairly complex visuo-spatial patterns (Baddeley & Lieberman, 1980; Logie, Zucco, & Baddeley, 1993; Phillips, 1983) and ultimately any conception of working memory storage will need to accommodate those findings too. But it appears that the addition of verbal information to a spatial pattern, and the instructions to remember verbal-spatial associations, drastically change the way that the spatial material is held in mind.

The absence of evidence for separate memory of spatial locations when cross-domain binding is encouraged is consistent with the findings of Zimmer, Speiser, and Seidler (2003), who showed that memory for the spatial locations of objects was not impaired by a concurrent spatial tapping task, though it clearly impaired Corsi-task location memory. Zimmer et al surmised that storage of locations in a Corsi task requires different resources than storing locations of objects, and suggested that object locations were maintained in the episodic buffer, or some other domain-general working memory store, along with other object features, thereby avoiding within-domain spatial interference.

Referencing Figure 3, which describes how information from these displays should be stored according to the updated multiple-component model, there are several

findings that cannot be accommodated by this model of working memory storage. As mentioned above, there is no evidence in these studies that any spatial information is maintained independently of the bound letter-location objects. Also, articulatory suppression impaired accuracy on recombination trials. These trials should only have relied on the domain-general store, which was supposed to operate independently of the phonological store and rehearsal system. Even the updated multiple-component model of working memory is difficult to impose on the cross-domain memory studies reported here.

An accurate and complete model of working memory storage should be able to accommodate the following findings from the cross-domain memory experiments reported above:

1. Interference from many sources impairs memory for cross-domain objects.
2. Letter feature changes are detected more accurately than location feature changes, which are detected no more accurately than recombinations.
3. Articulatory suppression impairs letter, location, and binding change detection when letter-location objects are to-be-remembered, but when letters and locations may be remembered separately, articulatory suppression only impairs memory for letters and does not impair memory for spatial locations.
4. Working memory capacity for verbal and spatial materials is similar whether binding is required or not.
5. With concurrent articulatory suppression, letter change detection is more accurate if binding memory is required than if it is not.

These data pose two critical problems for the multiple-component model (Baddeley, 2000): 1) the multiple-component model posits an independent domain-specific spatial store that does not seem to supplement cross-domain objects, and 2) the multiple-component model allows for no relationship between the domain-specific phonological loop and the domain-general store. The other model of working memory that proposes domain-general storage linked to attention is Cowan's Embedded Process Model (1999). This model of working memory posits a focus of attention (which functions as a limited-capacity domain-general store) within a field of activated mental representations, but offers no formal hypotheses about the mechanisms included in this activated memory. In Figure 10, a possible representation of the results of the studies described above is imposed onto the Embedded Process Model. If it is supposed that the activated memory portion of the Embedded Process Model includes some sort of verbal rehearsal loop (the evidence favoring the existence of such a mechanism is quite strong), then the results observed here can be accommodated by the model. When cross-domain binding is required, a limited number of cross-domain objects are maintained in the focus of attention, which is thought to be limited to 3-4 objects. This number is consistent with the capacity estimate data observed in the studies presented here (See Tables 3, 5, and 6). Letters that form the objects in the focus of attention are rehearsed in the loop (represented by the dotted lines) along with the isolated letters that are activated in memory. In this case, concurrent articulatory suppression impairs memory for letter-location bindings in the focus of attention as well as activated letter features. When cross-domain binding is not required, letters and spatial locations seem to be separately stored, possibly with spatial locations always stored in the focus of attention, and letters in a

verbal rehearsal loop in activated memory. In this case, concurrent articulatory suppression does not impair memory for spatial locations, but still impairs memory for the letters.

Assuming, as Kahneman et al suggested (1992), that objects are defined at encoding by the focusing of attention to a particular level of hierarchy, then the domain-general focus of attention might contain a broad representation that lacks specific details at lower levels (e.g., only spatial locations of objects) or alternatively, the focus of attention may contain objects with finer details (e.g., letters in spatial locations). (Refer to Figure 1.) Applied to the studies described here, the same store could be supposed to maintain spatial features or verbal-spatial objects. In Experiment 4, when the bindings between letter and spatial locations were irrelevant, objects may have been defined by a more broadly-focused attention, without respect to verbal features; memory for these objects was therefore unimpaired by articulatory suppression. In Experiments 1-3 on the other hand, objects might have been defined more narrowly, encompassing letter and location information, and therefore interfacing with a passive verbal store. In these cases, articulatory suppression would impair memory for verbal-spatial objects, as observed. Cowan's description of the focus of attention (2005) allows for this difference in object storage.

Can a model of working memory storage including only a verbal and a general store accommodate other data in the working memory literature? As described in the introduction, a great deal of research has reported strong within-domain dual-task interference and weak or non-existent cross-domain dual-task interference; this is the strongest evidence favoring the domain-specific stores of Baddeley and Hitch (1974). A

model including a passive verbal store and rehearsal mechanism and an attentional domain-general store would predict no interference in some cases, particularly those in which the verbal dual-task component is passive (e.g., maintaining a short list of words or digits). However, if the verbal task requires more attention, this model of working memory storage predicts that interference would occur. This explanation possibly reconciles Morey and Cowan's (2004, 2005) findings of cross-domain interference with dual-task working memory studies that failed to find cross-domain interference. In Morey and Cowan's (2005) study of interference between verbal digit lists and visuospatial color-square stimuli, different effects of speech on visual working memory were observed. They observed that a visual working memory task was not impaired by concurrent articulatory suppression alone, and not much impaired by a concurrent memory load, but clearly impaired by a spoken memory load. Neither speech alone nor an unspoken memory load were sufficient to significantly impair visual working memory, but speaking a memory load did result in poorer visual working memory. It could have been the case that at some combination of task difficulties, speaking the verbal memory load made verbal digit memory a less passive task, forcing it to make more use of the active focus of attention and thereby competing with visual memory storage. This model predicts interference between two effortful tasks, regardless of their stimulus modalities.

Though he spoke of visual memory specifically, Phillips' (1983) explanation of working memory is quite similar to the one advocated here. He and his colleagues (especially Phillips and Christie, 1977) demonstrated that many verbally-dependent "executive" tasks interfered with visual memory. The characteristics Phillips attributed to a visual short-term store, namely that it is related to attention and that verbalization can

interfere with it but not necessarily aid it, seem quite apt for describing a domain-general store with the dynamic properties of Cowan's focus of attention (2001, 2005). A major difference between this idea of a flexible storage device, where Baddeley and colleagues might propose multiple devices, is that instead of supposing that because the same stimuli (spatial locations) can be held in different forms they must be held by different stores (e.g., sometimes in visuospatial sketchpad, sometimes in episodic buffer), it supposes that one store can be used in a variety of ways, including in its interactions with other information processing structures. This is an important consideration when adding components to a model of working memory; with each additional component, potential interactions among the components multiply if they are not truly independent, which they do not seem to be.

Predictions for Working Memory with a Flexible Central Store

If the working memory system were supposed to have two stores, one for the passive rehearsal of auditory or verbal materials and one for the more effortful maintenance of material from any modality, studies showing only within-domain dual-task interference might be reconciled with those that show cross-domain interference as well. For simple memory tasks, this model would predict that verbal and spatial information could be simultaneously maintained with minimal interference. However, if the verbal and spatial tasks were both very effortful, demanding attention for successful completion, then cross-domain interference might be observed. This is clearly the case in many of the studies of concurrent cross-domain dual-tasks in which interference has been observed (Cowan & Morey, in press; Morey & Cowan, 2004, 2005). Furthermore, a

model of working memory that posited that all visuospatial memory required attention for extended storage could reconcile some of the findings of Allen, Baddeley, and Hitch (2006) with the predictions of Wheeler and Treisman (2002). Allen et al observed no additional effect of dividing attention on the memory for binding of visual features than on memory for the visual features themselves, contradicting Wheeler and Treisman's proposition that attention is needed to maintain conjunctions but that features can be simultaneously maintained in parallel stores. If both visual features and visual bindings are maintained in an attentional store, then memory for both might be affected by divided attention.

Similarly, differences in memory for single-feature and multi-feature objects that are sometimes observed could be due to the hierarchy at which the items were encoded. Future research on visual binding will compare object and feature maintenance when integrated and unintegrated representations are encouraged. Note that this explanation of working memory maintenance allows that binding in the visual domain may *not* depend on verbal rehearsal mechanisms. A model of working memory that posits this flexible store would predict that without concurrent articulatory suppression, more cross-domain objects could be maintained than multi-feature visual objects, because verbal rehearsal might enhance cross-domain memory but not necessarily visual object memory: it is true that many studies have found no effect of articulatory suppression on working memory for visual materials, neither for features (Experiment 4 here) nor visual objects (Luck & Vogel, 1997). Such a model would also predict though, that cross-domain and visual objects would compete for storage.

A critical test of the model proposed above would compare cross-domain stimulus conditions in which the relevance of the binding information to the test stimulus varied. In separate blocks of trials, the proportion of letter-location probes and only-letter or only-location probes would vary. In blocks with low proportions of letter-location probes, mean accuracy on letter-location probes should be significantly lower than mean accuracy in blocks with high proportions of letter-location probes, because in the low-proportion blocks attention would be focused to encode the spatial configurations which are usually tested rather than the narrower letter-location associations.

Another critical test would compare the effects of an attention-demanding visual memory task on verbal memory. Varying the passiveness of a concurrent verbal memory task differentially impaired a visual working memory task (Morey & Cowan, 2005): the more passive the verbal task, the less it impaired visual memory accuracy. However, the reverse situation should not be true if this model is correct, because all visuo-spatial tasks require the domain-general store; interference would be determined only by the need of the domain-general store for completion of the verbal memory task. The study cited by Farmer et al (1986) provides a possible illustration: recall that a spatial reasoning task was unaffected by articulatory suppression but a verbal reasoning task, which seemed effortful, was in some conditions impaired by a concurrent spatial task.

Another direction for future research is in memory for sequentially-presented cross-domain items. This was examined in Experiment 3, which did not reveal any striking effects of serial position by change trial type. However, Experiment 3's design was not ideal for discerning effects of serial position, as probe recognition is not a sensitive measure of serial position effects. (Experiment 3 was similar in design to Allen,

Baddeley, and Hitch's (2006) Experiment 5.) Phillips (1983) described a robust, one-item recency position in serial position curves for visual items which differed from the serial position effects of phonological materials such as word lists, which exhibit a characteristic pattern of fewer errors at the beginning and end of the lists for a few items, rather than only one. Because of Phillips' data, I suspect that different serial position curves for new letter trials compared with new location and recombination trials may yet be observed. This finding would provide additional support for the proposed model of working memory storage if it further distinguished the processes associated with memory for verbal lists from those associated with spatial memory or cross-domain binding. It may also be the case that spatial locations are stored in a different representation when they are linked to verbal materials or when they are serially presented than when they are not. This hypothesis could also be more explicitly tested by comparing effects of articulatory suppression on memory for simultaneous and sequentially-presented letter-location information when, as in Experiment 4, the binding between these features does not need to be remembered. Theories positing a domain-general sequential rehearsal mechanism (i.e., the object-oriented episodic record of Jones et al, 1996) might predict greater effects of articulatory suppression on sequential spatial memory than on simultaneous spatial memory.

Alternative Explanations and Caveats

The data presented here do not prompt an immediate expulsion of a separate visuospatial store from all models of working memory that propose one. There is at least one explanation why I might not have observed any contribution from a visuospatial store

to overall working memory capacity: it is possible that representations in the visuospatial store decay more quickly verbal representations, or instead are more susceptible to interference, possibly from overwriting from subsequently-presented stimuli or the test stimuli themselves (Wheeler & Treisman, 2002). In the studies reported here with simultaneous presentation and no intervening stimuli (Experiments 2a and 2b), any interference should have been minimal because only one letter-location object, rather than a whole array, was used to probe memory contents. It seems to be the case that visual sensory memories (iconic memories, Sperling 1960) decay more quickly than auditory ones (Darwin, Turvey, & Crowder, 1972; although see Cowan, 1988). However, it should be noted that proponents of Baddeley's visuospatial sketchpad model of visual working memory have consistently argued that it is similar in composition to the phonological loop system (there is a "highly seductive symmetry", according to Logie, 1995, p. 93), with its own rehearsal or refreshing mechanisms (typically involving hand or eye movements) for maintaining information and possibly a dissociation of visual and spatial materials. It is certainly the case that a limited amount of visual information can be retained longer than items in iconic memory (Logie, 1995; Phillips, 1983), so it is presumably fair to argue that if some spatial features were stored separately in a domain-specific visual store, at least a portion of this representation would have survived a 3000-ms retention interval to contribute to estimates of total working memory capacity. These possible objections could be taken themselves as evidence against a spatial memory system comparable to the well-specified phonological loop of Baddeley's model (1986): the potential objection that visuospatial representations are more fragile than auditory

ones simply reinforces the need for attention and visual working memory to be integrated.

Other evidence in the working memory literature suggests close relationships between spatial memory and central executive function or cross-domain memory and attention, and these may ultimately describe the same relationship. Miyake and colleagues (2001) have shown that measures of visuospatial working memory relate closely to measures of executive functioning. Possibly related to this is Cowan et al's (2006) finding that cross-domain memory correlates with memory tasks thought to measure the capacity of the focus of attention, but only when the cross-domain memory task restricts contributions from verbal rehearsal. These findings further support the notion that a visual or domain-general working memory store and attention are closely related, but do not necessarily mean that they form an integrated structure.

It may seem unfair to have omitted concurrent spatial or motor suppression from the experiments presented here. Manipulation of concurrent articulatory suppression was added to Experiments 2a and 2b because of the advantage observed for new letter trials with respect to new location and recombination trials in Experiment 1. If total working memory capacity estimates for new location trials had also exceeded those for recombination trials, some concurrent spatial or motor task might also have been used in an attempt to eliminate contributions from both within-domain stores. It is unknown what affect a concurrent spatial or motor task might have on cross-domain memory; however, given that interference was observed from multiple sources in Experiment 1, I suspect that a concurrent spatial task would also impair cross-domain memory. Across many studies, the effects of spatial analogues to verbal articulatory suppression on verbal and

spatial memory tasks have not been as consistent as the effects of simple articulatory suppression; also, many tasks that have been used to approximate verbal suppression in the spatial domain do not seem truly similar to articulatory suppression (e.g., visual object tracking, which seems much more attention-demanding than simple articulatory suppression). Studying the effects of concurrent spatial tasks on cross-domain memory is one possible direction for future research.

It is possible that non-spatial visual features might behave differently in working memory storage or as components of cross-domain objects than spatial ones have. Easily discriminable colors and shapes might be more easily grouped into familiar categories (Olsson & Poom, 2005) than spatial locations. Studies of cross-domain memory with different stimuli could suggest other configurations of working memory stores and their interactions than those observed in these experiments, and offer new ideas about relationships between components of information processing.

Another promising direction for understanding domain-general working memory is in neuroimaging research. Prabhakaran et al's (2000) finding of unique right anterior PFC activation during conditions of memory for integrated letter-location stimuli similar to those used here was considered compelling evidence for the inclusion of a domain-general store in working memory (Baddeley, 2000). fMRI techniques used to judge whether regions are limited by capacity or stimulus complexity (Todd & Marois, 2005; Xu & Chun, 2005) in the visual domain may be applied to cross-domain stimuli. Studies of attentional filtering of memory stimuli may also be enhanced with data from fMRI, by determining whether other regions collaborate with a store in a situation in which irrelevant stimuli should be kept out of mind. Recent work in neuroimaging has shown

that techniques have advanced beyond regional exploration, and that information about localization can be used to restrict cognitive theories of working memory (cf. Chein, Ravizza, & Fiez, 2003).

Conclusions

The data presented in this paper suggest more complex interactions between components of working memory than any current model fully describes. The explanation offered, that the contents of a flexible, general store can be enhanced by verbal rehearsal when part of the contents are verbal but not when only non-verbal material must be maintained, does not fit perfectly with any prominent model of working memory. Baddeley's domain-general store, the episodic buffer (2000), is not supposed to interact directly with the domain-specific phonological apparatus. Another domain-general store, Cowan's focus of attention, does offer this kind of flexibility, but this model has remained agnostic to other proposed components of working memory that seem appropriate for explaining the data observed here and elsewhere in the working memory literature. However, Cowan's description of the focus of attention is consistent with the proposition that a single, flexible store maintains some objects with help from another information processing component, and other types of materials without this assistance and can focus broadly or narrowly to capture objects for maintenance.

These data join a small but perhaps growing field of studies of integrated verbal and visuospatial materials in working memory and a represent a short advance in understanding of how these items are maintained in working memory. As more information on integration of cross-domain stimuli in working memory becomes

available, the prevailing emphasis may shift from segregation of representations to their integration.

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VITA

Candice Coker Morey was born in Jacksonville, FL on September 19, 1978 to Charles and Deborah Coker. She was raised in Lakeland, FL where she graduated from Harrison Center for the Visual and Performing Arts, on the campus of Lakeland High School, in 1997. Candice studied psychology and music at Florida State University, attaining her Bachelor of Science degree in psychology, magna cum laude, in April, 2001. Candice began graduate study toward her Master of Arts and Doctor of Philosophy degrees at the University of Missouri-Columbia in Fall, 2001. She continued her career in cognitive psychology and neuroscience research as a post-doctoral fellow at Washington University in St. Louis.

Table 1.

Descriptive Statistics for Judgment Tasks, Experiment 1

	Choice		Simple	
	Accuracy	Latency	Accuracy	Latency
Single Task				
Color	.95(.04)	522.72(67.30)	.99(.01)	235.63(30.10)
Location	.98(.03)	484.57(70.52)	.99(.02)	263.99(40.28)
Tone	.89(.11)	569.57(75.21)	.99(.02)	260.19(61.85)
Letter	.99(.02)	814.95(82.56)	.98(.02)	458.82(74.42)
Dual Task				
Color	.94(.08)	625.92(83.70)	1.00(.01)	336.97(71.83)
Location	.96(.04)	601.84(91.33)	.99(.02)	360.52(67.28)
Tone	.88(.11)	685.71(90.92)	.99(.02)	343.78(92.39)
Letter	.95(.04)	871.56(76.04)	.96(.03)	472.04(90.04)

Note. Reported means (with standard deviations). N=23. Longer reaction times for the letter judgment task are due to longer onset in letter sound files than in tone sound files. Accuracy means include all trials for all participants included in the sample, and latency measures include only correct responses.

Table 2.

Descriptive Statistics for Letter-Location Memory Task, Experiment 1

	RT task instructions	
Concurrent Judgement Task:	Choice	Simple
Control (memory task only)		
New Letter	.95(.08)	.95(.07)
New Location	.74(.23)	.80(.18)
Recombination	.77(.23)	.79(.22)
No change	.87(.10)	.85(.10)
Color task		
New Letter	.93(.10)	.94(.12)
New Location	.67(.23)	.76(.19)
Recombination	.69(.25)	.78(.19)
No change	.82(.12)	.83(.13)
Location task		
New Letter	.91(.15)	.94(.12)
New Location	.71(.20)	.80(.20)
Recombination	.71(.21)	.75(.20)
No change	.79(.14)	.77(.16)
Tone task		
New Letter	.87(.19)	.95(.08)
New Location	.70(.20)	.76(.17)
Recombination	.71(.24)	.76(.25)
No change	.80(.13)	.84(.13)
Letter task		
New Letter	.95(.09)	.94(.09)
New Location	.74(.17)	.73(.18)
Recombination	.79(.21)	.81(.17)
No change	.79(.13)	.79(.15)

Note. Raw proportions correct (with standard deviations). Choice and simple reaction time instruction trials were collected in separate blocks, each with their own blocks of single-task control trials. N=23.

Table 3.

Estimates of Working Memory Capacity, Experiment 1

	RT task instructions	
Concurrent Judgement Task:	Choice	Simple
Control (memory task only)		
New Letter	3.27(0.58)	3.21(0.59)
New Location	2.43(1.11)	2.60(0.83)
Recombination	2.56(1.15)	2.56(1.05)
Color task		
New Letter	3.01(0.73)	3.09(0.81)
New Location	1.97(1.15)	2.38(0.94)
Recombination	2.02(1.14)	2.46(0.95)
Location task		
New Letter	2.79(1.00)	2.84(0.99)
New Location	2.01(1.06)	2.28(1.03)
Recombination	2.01(1.12)	2.08(1.25)
Tone task		
New Letter	2.65(1.09)	3.14(0.79)
New Location	2.01(1.02)	2.37(0.91)
Recombination	2.02(1.10)	2.39(1.30)
Letter task		
New Letter	2.96(0.70)	2.93(0.90)
New Location	2.13(0.94)	2.09(0.95)
Recombination	2.30(1.00)	2.41(1.12)

Note. Mean capacity estimates, calculated with Cowan's formula (Cowan et al, 2005), (with standard deviations). Choice and simple reaction time instruction trials were collected in separate blocks, each with their own blocks of single-task control trials. N=23.

Table 4.

Descriptive Statistics for Letter-Location Memory Task, Experiments 2a and 2b

Experiment 2a	Set Size				
	2	3	4	5	6
Silent					
New Letter	.98(.04)	.96(.08)	.96(.08)	.95(.09)	.88(.10)
New Location	.87(.14)	.83(.15)	.90(.11)	.84(.14)	.86(.17)
Recombination	.96(.07)	.91(.13)	.86(.12)	.85(.15)	.81(.18)
No Change	.91(.10)	.88(.13)	.86(.13)	.79(.15)	.73(.17)
Articulatory Suppression					
New Letter	.93(.11)	.94(.09)	.88(.14)	.80(.18)	.80(.16)
New Location	.86(.15)	.80(.18)	.76(.18)	.79(.16)	.85(.16)
Recombination	.88(.14)	.83(.15)	.78(.20)	.71(.17)	.79(.18)
No Change	.85(.14)	.82(.14)	.75(.18)	.67(.17)	.58(.17)
Experiment 2b					
Silent					
New Letter	.99(.03)	.98(.06)	.97(.06)	.92(.09)	.89(.12)
New Location	.92(.12)	.87(.15)	.88(.15)	.85(.12)	.87(.12)
Recombination	.93(.11)	.86(.14)	.91(.11)	.86(.10)	.84(.13)
No Change	.93(.07)	.92(.07)	.88(.11)	.81(.14)	.74(.16)
Articulatory Suppression					
New Letter	.94(.10)	.93(.10)	.94(.10)	.84(.14)	.82(.17)
New Location	.86(.12)	.86(.15)	.85(.14)	.83(.17)	.82(.17)
Recombination	.92(.11)	.86(.17)	.80(.19)	.76(.17)	.73(.17)
No Change	.90(.09)	.85(.10)	.78(.12)	.68(.17)	.58(.19)

Note. Proportion correct (with standard deviations). The only difference in the design of Experiments 2a and 2b was that in 2b, the stimuli were circled. Experiment 2a N=28; Experiment 2b N=26.

Table 5.

Estimates of Working Memory Capacity, Experiments 2a and 2b

Experiment 2a	Set Size				
	2	3	4	5	6
Silent					
New Letter	1.79(.23)	2.49(.59)	3.26(.71)	3.71(.98)	3.66(1.32)
New Location	1.56(.36)	2.10(.66)	3.05(.66)	3.17(1.07)	3.56(1.43)
Recombination	1.74(.24)	2.34(.70)	2.89(.74)	3.19(1.26)	3.29(1.70)
Articulatory Suppression					
New Letter	1.56(.41)	2.28(.62)	2.51(.90)	2.37(1.31)	2.33(1.33)
New Location	1.43(.40)	1.88(.56)	2.05(.96)	2.33(1.24)	2.62(1.14)
Recombination	1.46(.44)	1.96(.67)	2.18(1.10)	1.92(1.19)	2.31(1.25)
Experiment 2b					
Silent					
New Letter	1.84(.17)	2.69(.30)	3.37(.48)	3.62(.83)	3.77(1.17)
New Location	1.71(.31)	2.36(.53)	3.00(.73)	3.26(.91)	3.65(1.18)
Recombination	1.72(.30)	2.34(.47)	3.15(.52)	3.33(.80)	3.48(1.14)
Articulatory Suppression					
New Letter	1.68(.30)	2.35(.51)	2.88(.59)	2.59(1.15)	2.41(1.42)
New Location	1.53(.33)	2.12(.55)	2.52(.78)	2.52(1.34)	2.41(1.52)
Recombination	1.65(.28)	2.12(.59)	2.33(.92)	2.18(1.27)	1.84(1.50)

Note. Mean capacity estimates (with standard deviations). The only difference in the design of Experiments 2a and 2b was that in 2b, the stimuli were circled. Experiment 2a N=28; Experiment 2b N=26.

Table 6.

Descriptive Statistics and Capacity Estimates for Letter-Location Memory Task, Experiment 3

Proportions Correct	Probe Serial Position			
	1	2	3	4
Silent				
New Letter	.94(.09)	.94(.10)	.94(.07)	.95(.07)
New Location	.81(.18)	.80(.14)	.79(.18)	.81(.14)
Recombination	.82(.13)	.74(.20)	.79(.18)	.82(.18)
No Change	.84(.10)	.81(.13)	.82(.14)	.87(.10)
Articulatory Suppression				
New Letter	.90(.10)	.83(.17)	.87(.12)	.88(.10)
New Location	.80(.17)	.79(.17)	.77(.20)	.82(.18)
Recombination	.72(.20)	.75(.13)	.72(.20)	.77(.16)
No Change	.76(.17)	.70(.14)	.73(.14)	.80(.11)
Capacity Estimates				
Silent				
New Letter	3.13(.63)	2.98(.84)	3.04(.74)	3.29(.54)
New Location	2.61(.80)	2.44(.87)	2.41(.90)	2.74(.77)
Recombination	2.64(.74)	2.19(1.10)	2.43(1.09)	2.75(1.03)
Articulatory Suppression				
New Letter	2.62(.88)	2.11(1.02)	2.37(.84)	2.69(.58)
New Location	2.21(.90)	1.96(.92)	1.97(.95)	2.46(.84)
Recombination	1.91(1.05)	1.81(.81)	1.79(1.06)	2.26(.80)

Note. Proportions correct and capacity estimates by articulatory suppression condition, memory trial type and probe serial position (with standard deviations). Silent group N=24; Articulatory suppression group N=20.

Table 7.

Descriptive Statistics and Capacity Estimates for Letter and Location Memory, Experiment 4

Proportions Correct	Set Size				
	2	3	4	5	6
Silent					
Letter, Change	.97(.06)	.95(.09)	.90(.16)	.85(.16)	.73(.21)
Letter, Same	.97(.05)	.99(.03)	.93(.11)	.86(.12)	.82(.16)
Location, Change	.92(.11)	.86(.17)	.83(.17)	.78(.17)	.78(.17)
Location, Same	.85(.16)	.84(.18)	.84(.19)	.76(.21)	.80(.16)
Articulatory Suppression					
Letter, Change	.92(.12)	.87(.16)	.76(.17)	.63(.23)	.62(.24)
Letter, Same	.89(.11)	.83(.14)	.83(.18)	.70(.20)	.70(.21)
Location, Change	.89(.12)	.85(.15)	.85(.12)	.78(.17)	.75(.21)
Location, Same	.80(.20)	.85(.17)	.80(.22)	.77(.22)	.76(.26)
Capacity Estimates					
Silent					
Letter Probe	1.88(.14)	2.84(.29)	3.32(.84)	3.56(1.17)	3.30(1.43)
Location Probe	1.53(.38)	2.10(.69)	2.67(1.02)	2.67(1.43)	3.53(1.60)
Articulatory Suppression					
Letter Probe	1.61(.33)	2.11(.67)	2.37(.95)	1.65(1.23)	1.95(1.53)
Location Probe	1.37(.46)	2.11(.68)	2.58(.97)	2.75(1.37)	3.05(1.97)

Note. Mean proportions correct and capacity estimates (with standard deviations) for letter and location probes. N=30.

Table 8.

ANOVA: Mean Capacity Estimates in Experiments 2b and 4 with Articulation Condition, Probe Type, and Set Size as Factors

	MS	F	p	η_p^2
Exp.	7.88	1.39	.24	.03
Error	5.66			
Artic. Supp. Condition	101.59	79.36	.00	.60
AS Condition * Exp.	.12	.10	.76	.00
Error	1.28			
Probe type	3.88	2.89	.09	.05
Probe type * Exp.	2.52	1.88	.18	.03
Error	72.34			
Set Size	69.02	67.48	.00	.56
Set Size * Exp.	.65	.64	.64	.01
Error	1.02			
AS Cond. * Probe	17.92	35.08	.00	.39
* Exp.	11.72	22.93	.00	.30
Error	.51			
AS Cond. * Set Size	8.39	13.29	.00	.20
* Exp.	.52	.82	.51	.01
Error	.63			
Probe type * Set Size	3.67	6.80	.00	.11
* Exp.	1.72	3.18	.01	.06
Error	.54			
AS * Probe * SS	2.20	5.23	.00	.09
* Exp.	1.14	2.71	.03	.05
Error	.42			

Note. Experiment 2b N=26. Experiment 4 N=30.

Figure Captions

Figure 1. Depicts the formation of objects at global or increasingly local levels. The orange circle surrounds the least focused object (two clover like shapes), the green circle surrounds a more focused object (three circles that form one clover-like shape), and the blue circle surrounds the most focused object (one red circle with a black outline).

Figure 2. Letter-location sample stimuli and illustrations of trial types. For new letter and new location trials, participants might respond correctly by only memorizing one of the feature types (e.g., letters or spatial locations). For the recombination trials, participants cannot respond accurately without knowing the correct associations between letters and spatial locations. In Experiments 1 and 3, set size was fixed at 4 letter-location objects. In Experiments 2a, 2b, and 4, set size varied from 2 to 6 letter-location objects.

Figure 3. A sample memory array and the resources available for maintenance according to a three-store model of working memory storage, with domain-specific and domain-general stores, after Baddeley (2000). The contents of the stores are meant to show what information is represented, not necessarily the form in which it is held.

Figure 4. Dual-task trial procedure for Experiment 1. Participants saw a letter-location array to remember, made a sensory judgment, and then responded to a letter-location probe. In this example, the correct letter-location response is “y”, for yes, the object was present in the sample memory array.

Figure 5. Estimated cross-domain memory capacity, by memory task probe trial type and mode of interfering judgment stimulus. N=23, error bars represent the standard error of the mean. The most robust effect was that of probe trial type, where a clear superiority in total working memory capacity in the new letter trials emerged.

Figure 6. Trial events for Experiment 2. A fixation "+" appeared for 1000 ms, then the sample memory array appeared for 125 ms per item (in the case of 3 items depicted here, 375 ms). After a 3000-ms retention interval, a probe stimulus appeared and remained onscreen until the participant responded. The circled stimuli were used in Experiment 2b; in Experiment 2a, the letters were uncircled (see Experiment 1; refer to stimuli in Figures 1 and 2 for examples).

Figure 7. Experiments 2a and 2b, total working memory capacity estimates by articulation condition, probe trial type and memory array size. Error bars represent standard errors of the mean. Experiment 2a N=28; Experiment 2b N=26. Total working memory capacity was highest across array sizes for the new letter trials (as in Experiment 1). Concurrent articulatory suppression reduced capacity in all change trial types.

Figure 8. Experiment 3, total working memory capacity estimates by articulation condition, probe trial type and serial position. Error bars represent standard errors of the mean. N=44. Note that with articulatory suppression, total working memory capacity for new letter trials equals capacity for new location and recombination trials in silent conditions.

Figure 9. Experiment 4, verbal and spatial capacity estimates by articulation condition, probe modality, and set size. Error bars represent standard errors of the mean. N=30. Concurrent articulatory suppression impairs memory for letters (blue graph parameter), but not memory for spatial locations (orange graph parameter).

Figure 10. Storage of verbal-spatial objects and verbal and spatial features, imposed onto Cowan's Embedded Process Model (1999). The dotted line loop represents a verbal rehearsal mechanism.

Figure 1

What is an object file?

An object can be as narrow as one feature or much broader, including many features. Depending on whether attention is focused more broadly or more narrowly, an object can take on many forms:

- Least focused: Good information about overall configuration, poor details of components
- More focused
- Most focused: Good component details, poorer global information

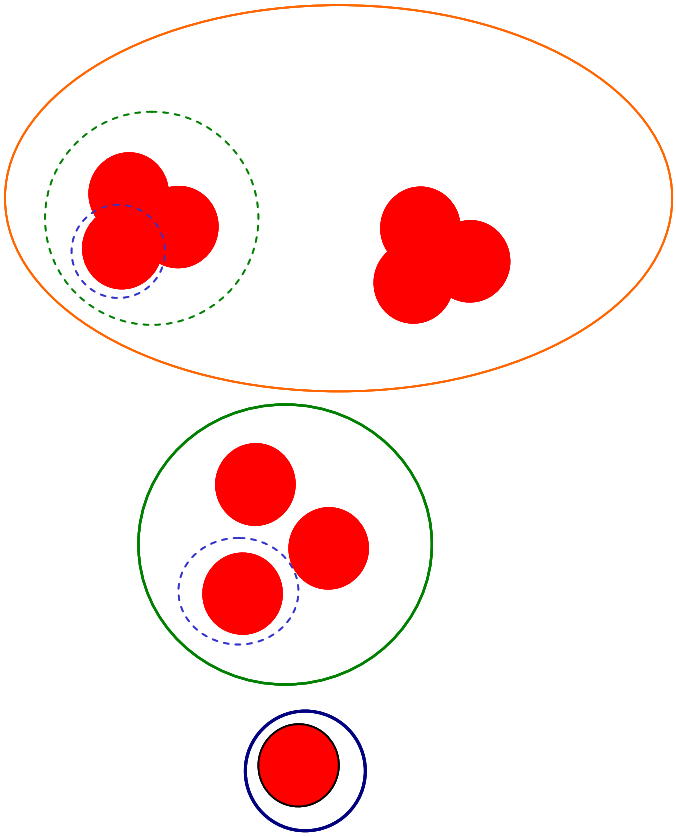


Figure 2

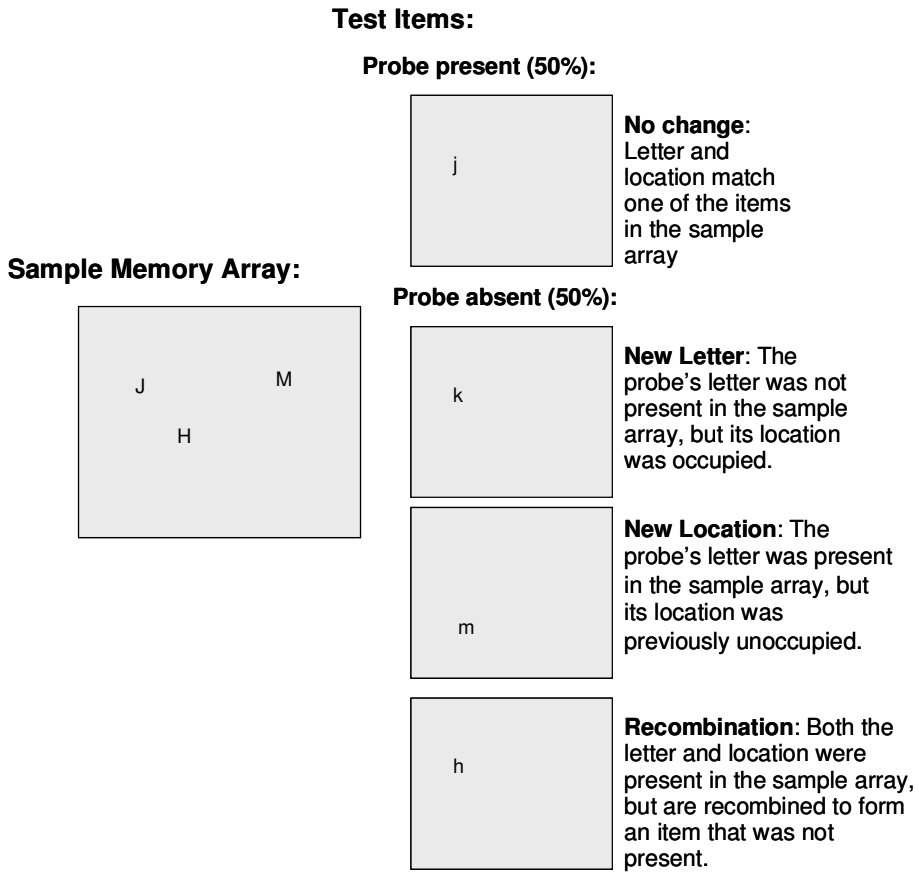

Test Items:
Probe present (50%):
j
No change: Letter and location match one of the items in the sample array
Sample Memory Array:
J
M
H
Probe absent (50%):
k
New Letter: The probe's letter was not present in the sample array, but its location was occupied.
m
New Location: The probe's letter was present in the sample array, but its location was previously unoccupied.
h
Recombination: Both the letter and location were present in the sample array, but are recombined to form an item that was not present.

Figure 3

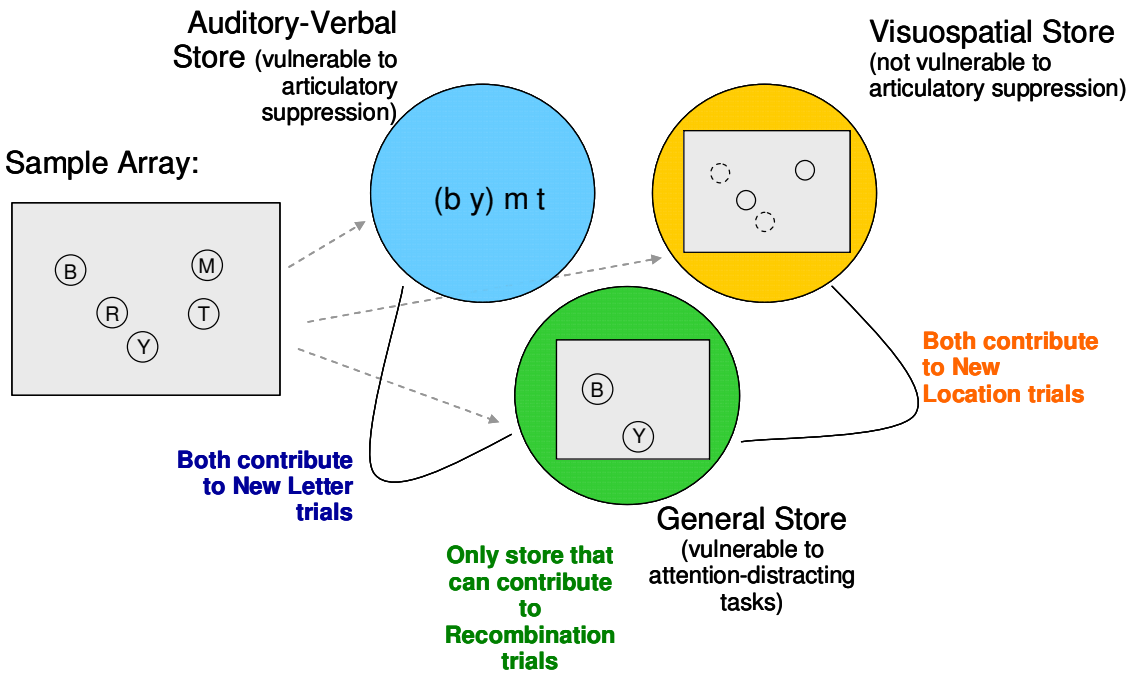

Auditory-Verbal Store (vulnerable to articulatory suppression)
Visuospatial Store (not vulnerable to articulatory suppression)
Sample Array:
B
M
R
T
Y
(b y) m t
B
Y
Both contribute to New Location trials
Both contribute to New Letter trials
Only store that can contribute to Recombination trials
General Store (vulnerable to attention-distracting tasks)

Figure 4

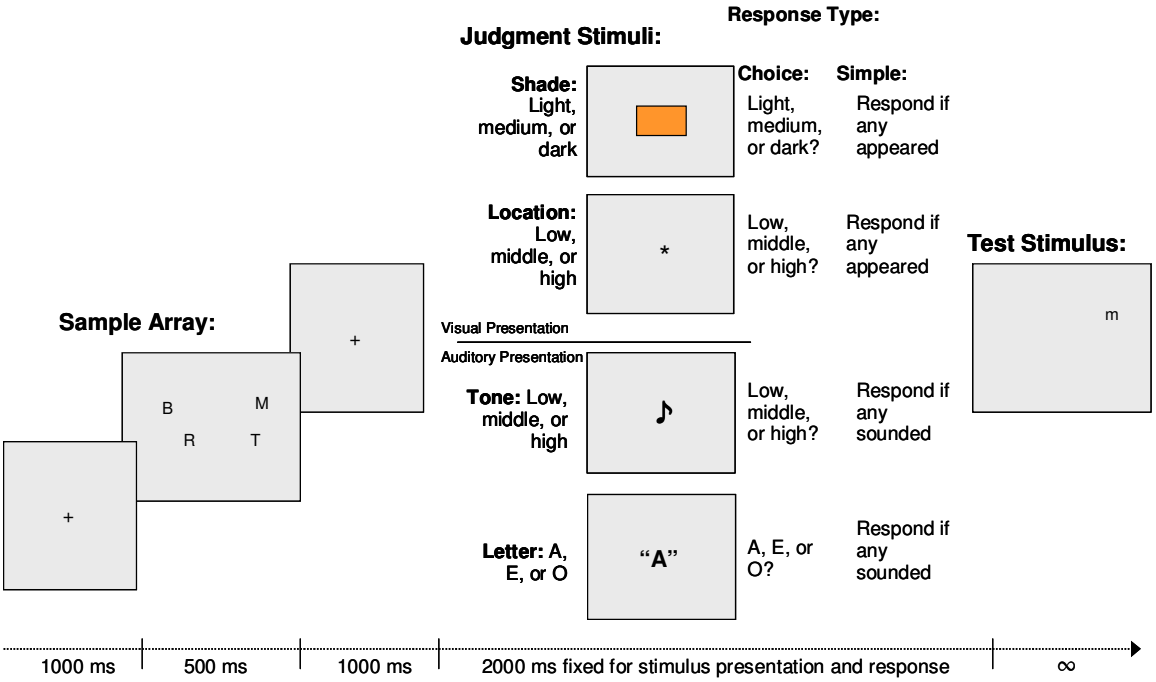

Response Type:
Judgment Stimuli:
Shade: Light, medium, or dark
Choice:
Light, medium, or dark?
Simple:
Respond if any appeared
Location: Low, middle, or high
*
Low, middle, or high?
Respond if any appeared
Test Stimulus:
m
Sample Array:
+
B
M
R
T
+
Visual Presentation
Auditory Presentation
Tone: Low, middle, or high
♪
Low, middle, or high?
Respond if any sounded
Letter: A, E, or O
"A"
A, E, or O?
Respond if any sounded
1000 ms
500 ms
1000 ms
2000 ms fixed for stimulus presentation and response
∞

Figure 5

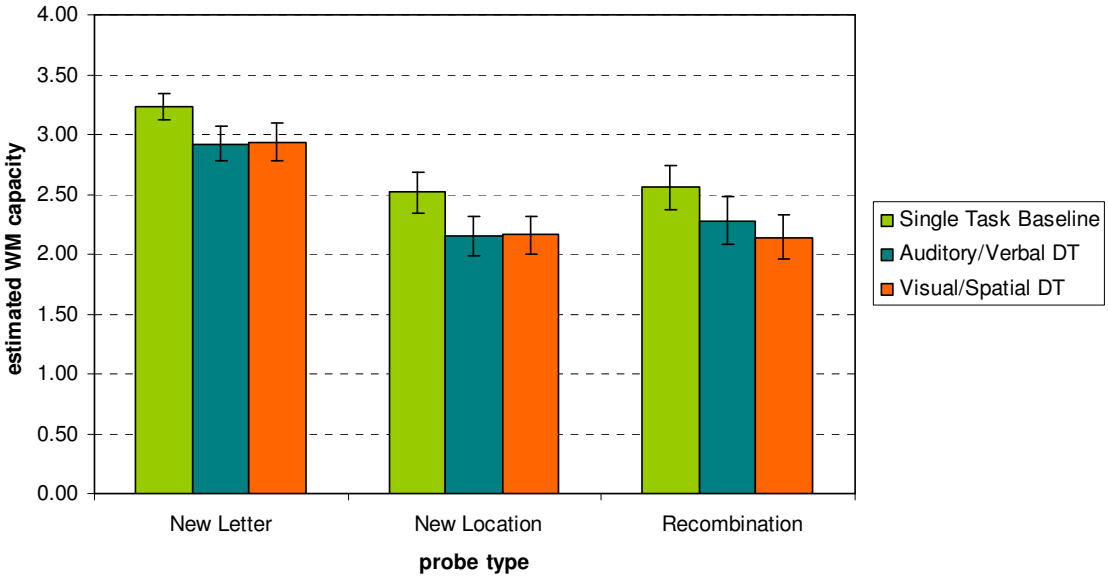

4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
estimated WM capacity
New Letter
New Location
Recombination
probe type
Single Task Baseline
Auditory/Verbal DT
Visual/Spatial DT

Figure 6

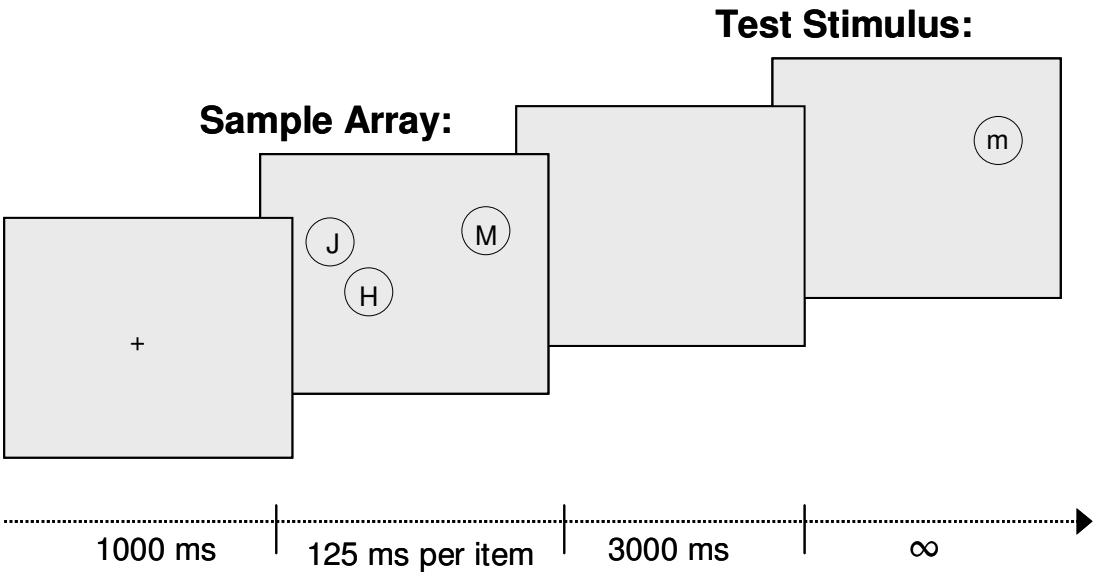

Test Stimulus:
Sample Array:
m
J
M
H
+
1000 ms
125 ms per item
3000 ms
∞

Figure 7

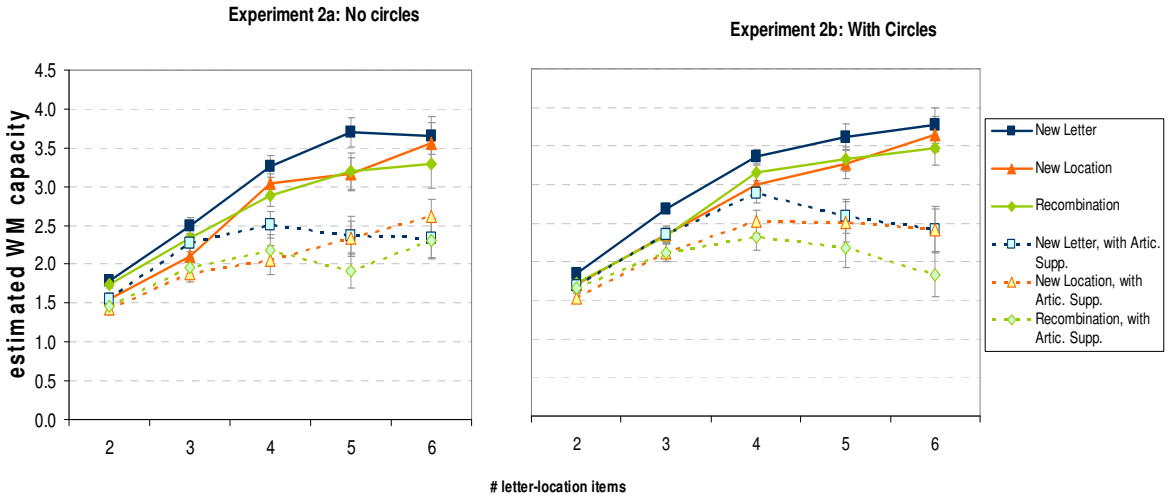

Experiment 2a: No circles
Experiment 2b: With Circles
estimated WM capacity
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2
3
4
5
6
letter-location items
New Letter
New Location
Recombination
New Letter, with Artic. Supp.
New Location, with Artic. Supp.
Recombination, with Artic. Supp.

Figure 8

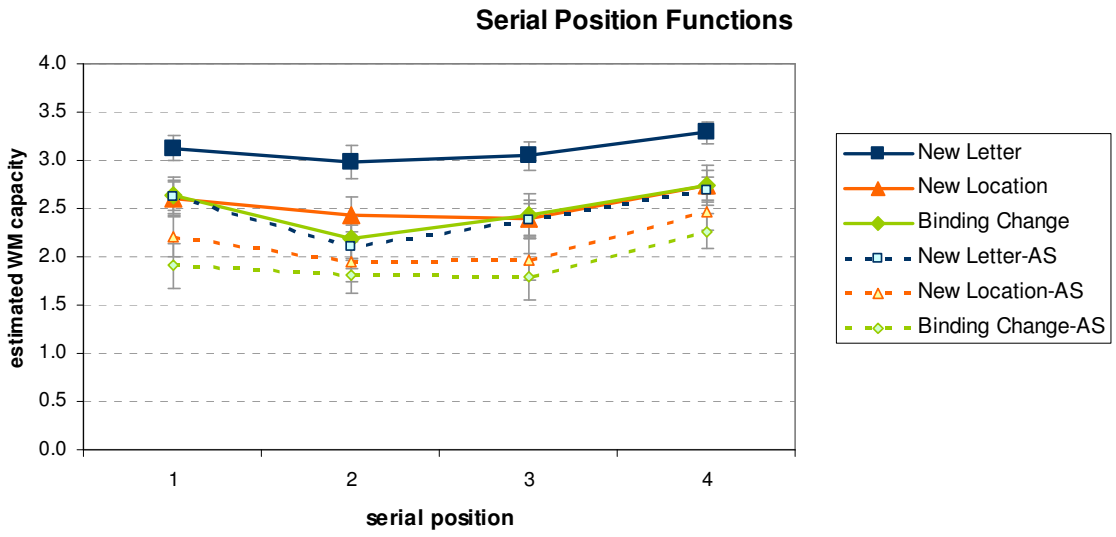

Serial Position Functions
estimated WM capacity
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
2
3
4
serial position
New Letter
New Location
Binding Change
New Letter-AS
New Location-AS
Binding Change-AS

Figure 9

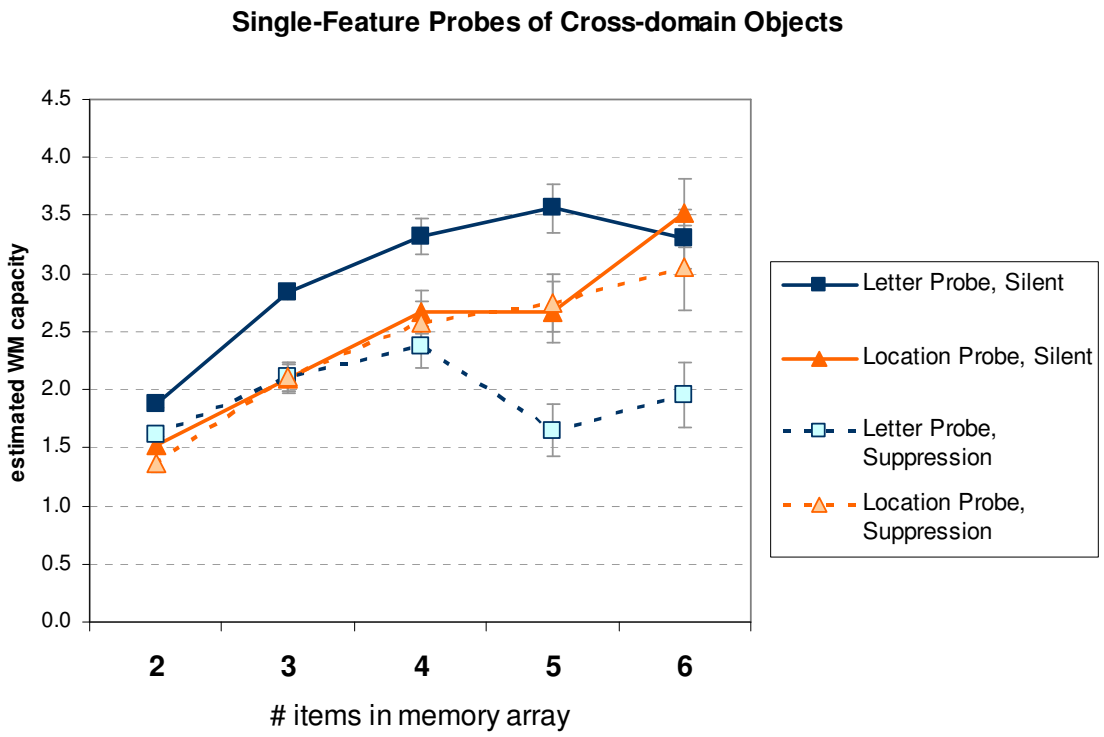
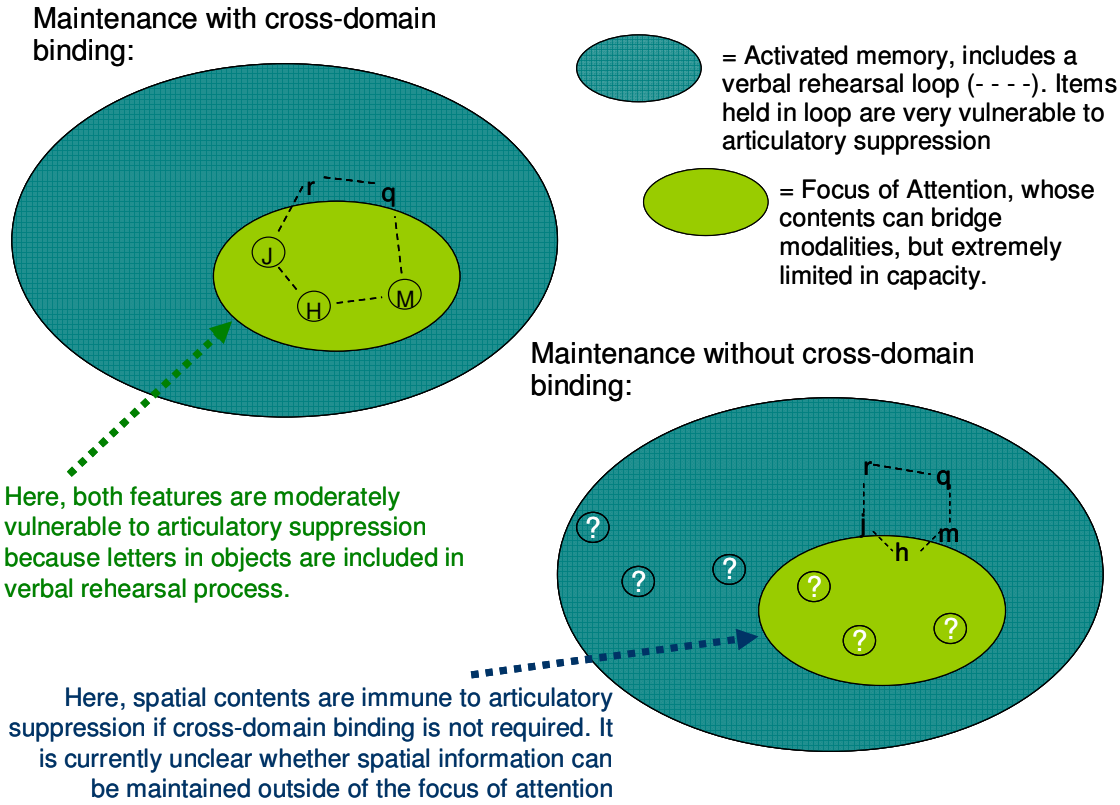

Single-Feature Probes of Cross-domain Objects
estimated WM capacity
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2
3
4
5
6
items in memory array
Letter Probe, Silent
Location Probe, Silent
Letter Probe, Suppression
Location Probe, Suppression

Figure 10


Maintenance with cross-domain binding:
r
q
J
H
M
= Activated memory, includes a verbal rehearsal loop (- - - -). Items held in loop are very vulnerable to articulatory suppression
= Focus of Attention, whose contents can bridge modalities, but extremely limited in capacity.
Maintenance without cross-domain binding:
r
q
l
h
m
?
Here, both features are moderately vulnerable to articulatory suppression because letters in objects are included in verbal rehearsal process.
Here, spatial contents are immune to articulatory suppression if cross-domain binding is not required. It is currently unclear whether spatial information can be maintained outside of the focus of attention