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# Neither separate nor equivalent: Relationships between feature representations within bound objects

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ABSTRACT

Evidence suggests that binding, or encoding a feature with respect to other features in time and space, can convey cognitive advantages. However, evidence across many kinds of stimuli and paradigms presents a mixed picture, alternatively showing cognitive costs or cognitive advantages associated with maintaining bound representations. We examined memory for colored letters drawn from similar and distinct color sets under circumstances that encouraged or discouraged the maintenance of color-letter binding. Our results confirmed previous change recognition research showing feature recognition improvement under explicit instructions to maintain binding. Color memory improved during binding, showing a reduced detrimental effect of feature similarity on retrieval, particularly when the letter served as the retrieval cue for a letter-color object. We found that feature recognition improved when two conditions were met: 1) relationships between features were to-be-remembered, and 2) the feature conjunction was relevant at test. Our results further suggest that this feature advantage arises because the encoded relationship between the features facilitates retrieval, not because features and objects are represented simultaneously in separate buffers.



## 1. Introduction

The *binding problem* refers to the difficulty of elegantly explaining how features of various types and qualities, which elicit activation in disparate neural regions, meld to produce the percept of a unified object containing all these qualities. A further puzzle arises when one attempts to explain how these percepts are then represented in memory, which is known to be liable to severe limits (e.g., Cowan, 2001). How do disparate features become associated in memory, and does this process convey cognitive advantages or induce cognitive costs?

Several extant theories approach the binding problem from various levels of analysis. For very recently-perceived stimuli and their organization, Kahneman, Treisman, and Gibbs (1992) suggest that online perception is assisted by the formation of object files, which they describe as temporary representations that link aspects of an object at one time to its characteristics at a later time. Some construct like an object file seems necessary to explain how some visual image is perceived as having the same identity despite appearing successively in different locations, or even with different semantic identities. For example, Kahneman et al. describe the crowd's gradual identification of a flying object as Superman; first it was labeled a bird and then a plane before correct identification occurred, but each of these labels clearly refers to the same object in the environment, which is presumably represented in some stable manner even as some of its attributes change. The principles of the object file hypothesis have been applied to the formation of coherent multi-modal object identities and responses across time (e.g., Zmigrod, Spapé, & Hommel, 2009) as well as to the association of component features of an object (Moore, Stephens, & Hein, 2010). A sufficient condition for the initial loading of component features into an object file is their appearance at the same location at the same moment in time (Van Dam & Hommel, 2010; Xu, 2002). According to Kahneman et al., prior knowledge of similar objects (or long-term memory for the same object token) has no bearing on the creation of an object file, although certainly recognition of the correspondence between an attended object and the same previously encountered object can occur. Importantly though, to Kahneman et al. the object file is a temporary structure that supports perceptual organization and search of memory for recently viewed objects, requiring no link to more permanent knowledge.

Object files could however form the basis for more stable, persistent associations of features. With their Type-Token model, Zimmer and Ecker (2010) suggest that perceptual object files can become memorial object tokens, which can ultimately be consolidated and retrieved whole. Object tokens are believed to include an object's intrinsic features (Ecker, Maybery, & Zimmer, 2013) and are thought to underlie feelings of familiarity in recognition memory (Ecker,

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Zimmer, & Groh-Bordin, 2007). The biological mechanism believed to generate object token encoding is the synchronized firing of cell assemblies coding for each feature (Tallon-Baudry & Bertrand, 1999), and interestingly, modeled limits in the number of distinct synchronized groupings that may be simultaneously distinguished correspond to observable behavioral limits in memory (Cowan, 2001; Raffone & Wolters, 2001). The supposition that repeated occurrences of these groupings should lead to more stable memorial representations is in line with the concept of Hebbian learning (e.g., Hebb, 1961). Thus the concepts of object files and tokens lie at the junction between perception and memory, at the very heart of the debate over how external information comes to persist in the mind.

Also occupying this nexus of perception and memory is the concept of working memory, which refers to the collection of memory and attention processes involved in real-time thinking. In any specific moment, memories that are activated for use may be considered the contents of working memory. Naturally, a comprehensive theoretical framework describing working memory should be able to explain how relationships between features are maintained. For the multi-component model of working memory (Baddeley, 1986; Baddeley & Hitch, 1974), explaining the effects of long-term knowledge on short-term memory (such as chunking; Cowan, Chen, & Rouder, 2004) or results suggesting that binding can occur between novel combinations of verbal and visual–spatial features (Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000) posed major problems. Regarding verbal chunking, the multi-component model described a working memory system that is distinct from long-term memory, with no explicit means for interaction between new and old memories. Regarding cross-domain binding, verbal and visual–spatial representations were purportedly maintained in separate buffers, with no proposed storage mechanism capable of bridging them. Therefore the multi-component model could not explain how verbal labels and visual imagery (such as a name and a face) could come to be associated, nor could it explain why short-term memory for materials that are part of some learned structure was consistently superior to short-term memory for novel or unrelated information.

To address these problems, Baddeley (2000) proposed a new module for the multi-component model, the episodic buffer, which provided a store capable of holding information retrieved from secondary memory or from either of the domain-specific storage buffers. Originally, the episodic buffer was believed to be accessible only via the central executive (consistent with assumptions that binding requires attention, e.g., feature integration theory, Treisman & Gelade, 1980). However, tests of this hypothesis interpreted within the framework of the multi-component model violated this assumption. Specifically, Allen, Baddeley, and Hitch (2006) found that performing concurrent processing tasks, which should reduce the availability of the central executive for engaging in binding, had no more impact on memory for binding between visual features than on memory for the visual features only, a result that has been replicated many times over (e.g., Allen, Hitch, Mate, & Baddeley, 2012; Delvenne, Cleeremans, & Laloyaux, 2010; Morey & Bieler, 2013). In an updated exposition of the episodic buffer model, Baddeley, Allen, and Hitch (2011) proposed that features represented in the domain-specific short-term stores are passed to the episodic buffer. Instead of supposing that attention acts in a top-down manner to select information for representation in the episodic buffer, they proposed a filtering mechanism that can be tuned toward features meeting specified criteria. An explicit assumption of the updated framework is that features are represented in two ways, as disassociated representations in their domain-specific buffers and as components of object files, which reside in the episodic buffer.

The episodic buffer construct is not in conflict with the proposition that object files are created during perception and become memorial object tokens. Within the episodic buffer, Baddeley et al. (2011) accept the premise that features could be organized into object files. However, it is not obvious that the multi-component working memory framework is necessary to explain differences between memories for objects and features. The episodic buffer is part of a framework that complicates predictions about perception and memory; it is thus necessary to consider whether the extra complexity it brings is really essential.

A unique assumption about feature storage during binding made in Baddeley's updated model is that when participants endeavor to maintain the binding between verbal and visual features, those features are represented twice within the working memory system. This assumption distinguishes the multi-component working memory system from frameworks that consider the contents of working memory as the most highly-activated portions of secondary memory (e.g., Cowan, 2005; Oberauer, 2009), which do not explicitly propose separate buffers for short-term maintenance. Moreover, this unique assumption provides a potential explanation for the cognitive advantages sometimes observed when participants undertake a memory task involving cross-domain binding. Intent to maintain verbal–spatial binding has been shown to improve recognition memory performance for individual features compared to a task that does not require binding (Morey, 2011), and also to change how domain-specific properties of an interfering task affect various memoranda. Morey (2009) tested memory for visually-presented letters and spatial locations in two groups of participants, one in which memory for the letter or location features (but never their binding) was always tested, and one in which binding was always tested, but in a manner that allowed inference about component feature memory. Both groups completed half of their trials with concurrent articulatory suppression. Unsurprisingly, memory for letters was always impaired by articulatory suppression. However, participants in the binding group were better able to recognize letter features during suppression than participants in the feature group, suggesting that something about encoding letter-location associations helped to preserve letter representations from interference from articulation. One way to explain this result is to suppose that during the binding task letters were stored both in the phonological loop and as components of object files in the episodic buffer, and those maintained in the episodic buffer were shielded against interference from concurrent articulation.

However, there are other phenomena that seem inconsistent with the idea that features are stored in two forms during a binding task: under some circumstances cross-domain binding can also induce cognitive costs. Morey (2009) also found that even though memory for spatial locations in the feature group was never impaired during suppression, memory for spatial locations in the binding group was impaired by articulatory suppression (see also Kessels & Postma, 2002). Similarly, Guérard, Tremblay, and Saint-Aubin (2009) found that memory for sequences of spatial locations was impaired if the spatial locations were marked by phonologically similar letters compared to phonologically distinct letters. Guérard, Morey, Lagacé, and Tremblay (2013) recently confirmed that while phonological similarity in a serial letter-location list impairs spatial memory, manipulating spatial complexity does not affect memory for the letters. These outcomes show that during binding, visual–spatial features can become vulnerable to sources of distracting information that typically exert selective interference on verbal memories. These outcomes are consistent with the proposition that during binding, features are stored in connection with each other, and that these connections may reduce within-domain feature interference while increasing cross-domain interference. However, it is not clear that these outcomes are consistent with the idea that visual–spatial features are stored twice during a memory task that requires verbal-spatial binding in the manner described by Baddeley et al. (2011).

To attempt to resolve these contradictions, we aimed to test the effects of maintaining cross-domain binding on verbal and visual feature storage. We first set out to replicate previous results suggesting that binding can improve feature recognition memory, generalizing these effects to a context in which spatial location was not a to-be-remembered element. In Experiments 1 and 2, we used change detection tasks to measure recognition memory for colored letters, with conditions that enabled comparisons of feature memory during binding and feature