

# Retrieval from long-term memory reduces working memory representations for visual features and their bindings

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**Abstract** The ability to remember feature bindings is an important measure of the ability to maintain objects in working memory (WM). In this study, we investigated whether both object- and feature-based representations are maintained in WM. Specifically, we tested the hypotheses that retaining a greater number of feature representations (i.e., both as individual features and bound representations) results in a more robust representation of individual features than of feature bindings, and that retrieving information from long-term memory (LTM) into WM would cause a greater disruption to feature bindings. In four experiments, we examined the effects of retrieving a word from LTM on shape and color–shape binding change detection performance. We found that binding changes were more difficult to detect than individual-feature changes overall, but that the cost of retrieving a word from LTM was the same for both individual-feature and binding changes.

**Keywords** Working memory · Binding · Features · Objects · Short-term memory

Mental representations of objects are created by binding together an object's individual features, and studying this binding process is useful for understanding perception (Treisman & Gelade, 1980), as well as working memory (Wheeler & Treisman, 2002). Perceptually binding visual features into unified objects requires the deployment of visuospatial attention (Treisman & Gelade, 1980); in the absence of attention, illusory conjunctions may occur (e.g., perceiving a blue ball and a red square as a red ball and a blue square). It has been a matter of some debate whether attention must be maintained on these objects in order for the features to remain bound in

working memory (WM), or whether the features automatically remain bound in WM (Allen, Baddeley, & Hitch, 2006; Brown & Brockmole, 2010; Fougny & Marois, 2009; Gajewski & Brockmole, 2006; Johnson, Hollingworth, & Luck, 2008; Morey & Bieler, 2013; van Lamsweerde & Beck, 2012; Wheeler & Treisman, 2002; Yeh, Yang, & Chiu, 2005).

The *attention hypothesis* proposes that shifts of attention disband the feature binding representations, although individual features can be stored in WM without sustained attention (Brown & Brockmole, 2010; Fougny & Marois, 2009; Wheeler & Treisman, 2002). Although some empirical evidence supports the attention hypothesis (Brown & Brockmole, 2010; Fougny & Marois, 2009), a large amount of evidence supports the hypothesis that attention is *not* required to maintain the feature bindings in WM (Allen et al., 2006; Delvenne, Cleeremans, & Laloyaux, 2010; Gajewski & Brockmole, 2006; Johnson et al., 2008; van Lamsweerde & Beck, 2012; Yeh et al., 2005). For example, shifting visual attention via invalid retro-cues or eye movements (Gajewski & Brockmole, 2006; van Lamsweerde & Beck, 2012) does not impair memory for feature bindings more than individual features, and valid retro-cues do not benefit feature bindings more than individual features (Delvenne et al., 2010). In addition, secondary attention-demanding tasks, such as visual search (Johnson et al., 2008) and backward counting (Allen et al., 2006; Allen, Hitch, Mate, & Baddeley, 2012), do not impair memory for feature bindings more than for individual features.

However, even if attention is not required to remember feature bindings, detecting feature swaps (e.g., a red square and a blue circle become a blue square and a red circle) can be more difficult than detecting the appearance of a novel feature (Allen et al., 2006; Fougny & Marois, 2009; Wheeler & Treisman, 2002). Binding memory offers a useful avenue for understanding the process of WM by investigating whether bindings and features are subject to different WM processes

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(Baddeley, Allen, & Hitch, 2011). That is, is there a difference between the ways that bindings and features are retained in WM? If this difference is not due to attention, some other component of WM that differs between binding and feature representations may offer insight into the mechanism of WM. For example, memory for features versus objects has been studied to investigate whether the unit of WM is an object or individual features (Delvenne et al., 2010; Gajewski & Brockmole, 2006; van Lamsweerde & Beck, 2012; Wheeler & Treisman, 2002; Yeh et al., 2005), as well as to explore the function of the episodic buffer, a domain-general storage buffer within a multicomponent WM model (Allen et al., 2006).

Within the framework of a modification of the Baddeley & Hitch (1974) multi-component WM model, it has been suggested that WM may store both object-based and feature-based representations (Baddeley et al., 2011), which could account for the disparity in the literature that supports both object-based (Luck & Vogel, 1997; Luria & Vogel, 2011; Vogel, Woodman, & Luck, 2001) and feature-based (Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011; Fournie & Alvarez, 2011; Wheeler & Treisman, 2002) representations in WM. In this project, we explored the possibility that WM stores both object-based and feature-based representations (the *multiple-representations hypothesis*) and that bindings are more likely to be replaced by new information introduced into WM as a result. According to the multiple-representations hypothesis, if object-based representations are overwritten, the feature-based representations can act to preserve memory for individual features, but not for feature bindings (Baddeley et al., 2011).

Baddeley et al. (2011) proposed that initially, visual feature bindings are formed in the domain-specific visuospatial sketchpad (without attention: Allen et al., 2006), and then these bound (although not necessarily complete) object representations are fed forward into the domain-general episodic buffer. Therefore, it is possible that while the episodic buffer contains only the bound objects, the visuospatial sketchpad continues to retain “copies” of only the individual features.

In support of this idea, Ueno, Allen, Baddeley, Hitch, and Saito (2011) found that encoding new information into WM resulted in a disproportionate impairment to feature bindings. Specifically, when irrelevant (i.e., to-be-ignored) visual stimuli were presented after the offset of the memory display (“suffixes”), change detection performance was impaired if these suffixes were part of the potential “memory set” used throughout the experiment. This impairment was greater for bindings than for individual features. The authors suggested that the new perceptual information disrupted representations in WM and that binding representations were more likely to be eliminated, possibly because there are multiple levels of feature representations (both as individual features and as object representations), but only a single level of binding representation (the object representation).

In the present study, we investigated the hypothesis that bound representations are retained in domain-general storage buffers, while unbound feature copies are retained only in domain-specific visual storage buffers (Baddeley et al., 2011). This was accomplished by having participants retrieve words from long-term memory (LTM) while simultaneously retaining visual information in WM. Retrieving words from LTM should occupy domain-general WM storage and has been shown to negatively affect visual change detection (Ricker, Cowan, & Morey, 2010). Therefore, the impact of retrieving words on memory for visual information is a useful test of the possible contents of domain-general storage: That is, does retrieving information from LTM disrupt memory more for feature bindings than for individual features?

Participants were required to memorize two lists of words and remember the list identity of each word before starting the visual WM task portion of the experiment. For the visual WM task, they had to remember either the shape or the color–shape bindings (in separate blocks) of objects in a memory display. While retaining visual information in WM, they heard words from one of the two lists and determined which list the word belonged to (these “retrieval” trials were intermixed with trials in which participants responded to a tone, or heard no stimuli and gave no response). The controlled search from LTM required by the retrieval task occupies WM capacity (Unsworth & Engle, 2007), and should therefore recruit the same domain-general storage space as the visual information (Ricker et al., 2010). The prediction that retrieval from LTM would disrupt visual WM is consistent with either a multicomponent model of WM with a domain-general component (the episodic buffer; Baddeley et al., 2011) or a single-component model in which there is only one, domain-general storage (Cowan, 2001). However, the prediction that retrieval from LTM will specifically impair feature bindings because individual feature copies are retained in domain-specific storage is specific to a multicomponent model of WM (Baddeley et al., 2011), in which feature copies are retained in domain-specific storage. Importantly, retrieval from LTM offers a way of testing storage without requiring that participants attend to new visual information.

A strict interpretation of Baddeley et al. (2011), in which only feature-based representations remain in the visuospatial sketchpad after object-based representations are fed into the episodic buffer (the *multiple-representations hypothesis*), suggests that occupying the episodic buffer should result in a specific impairment to change detection for feature bindings. We note that unlike previous studies that have utilized backward counting (Allen et al., 2006) or visual search (Johnson et al., 2008) as secondary tasks, which are meant to tax *attention* processes specifically, retrieving a word from LTM should occupy *storage* space in WM (Ricker et al., 2010). Although this may certainly also tax attention resources (e.g., a central executive), this task is unique in that it is designed to

test how the occupation of storage specifically affects memory for features and their bindings.

Four experiments were conducted that differed in (1) encoding time, (2) interstimulus interval (ISI) duration, and (3) the distribution of auditory-task trials (see Table 1). In Experiment 1, we utilized an encoding time of 500 ms, which had also been used by Cowan, Blume, and Saults (2013) and Ricker et al. (2010), and an ISI duration of 1,500 ms. In Experiment 2, a longer encoding time was used (2,000 ms; Ueno et al., 2011) to test whether short encoding times might specifically impair binding consolidation, leading to lower performance overall and a failure to adequately detect further impairments from the secondary task. Although short encoding times do not necessarily prevent complete representations (Cowan et al., 2013), longer encoding times may allow focused attention to be allocated to each individual item, which can facilitate durable binding representations (van Lamsweerde & Beck, 2012). In Experiment 3, we used the same encoding time as in Experiment 1 (500 ms), but increased the length of the ISI to 3,200 ms to ensure that participants had adequate time to give a response, so that they were not still responding to the secondary task when the test display of the change detection task appeared. In Experiment 4, we introduced a blocked design, such that the “no-load” secondary-task trials were completed either at the beginning of the experiment, prior to learning the list words, or at the end of the experiment, at which point participants were instructed that the list words were no longer important. The purpose of this experiment was to test whether the task instructions produced a sufficient attentional load prior to encoding to reduce binding perception, resulting in poor WM representations of bindings.

## Method

### Participants

In all, 37 participants (age  $M = 19.7$ , 28 female, nine male) participated in Experiment 1, 24 in Experiment 2 (age  $M = 19.1$ , 17 female, seven male), 36 in Experiment 3 (age  $M = 21.34$ , 30 female, six male), and 47 (age  $M = 19.08$ , 17 female, 30 male) in Experiment 4. More participants completed Experiment 4 so that we could determine if block order (no-

load first or tone and retrieval first) affected changed the results; however, analysis of variance (ANOVA) results did not reveal an effect of order, so results described are collapsed across load. One participant in Experiment 4 did not complete the demographic information due to computer error on the last experimental trial. Because only the last trial was not completed, data from this participant were included in analysis. Participants reported normal or corrected to normal vision and normal color vision and participated in this experiment for credit in their undergraduate psychology courses.

### Visual stimuli

The same visual stimuli were used for all four experiments. A set of 12 shapes from Fiser and Aslin (2002) and 12 colors were used to create the visual stimuli. Each object subtended approximately  $1.2^\circ$  of visual angle from a viewing distance of 47 cm. Memory displays contained three colored objects, each in one of the eight outer locations of a  $3 \times 3$  invisible grid subtending approximately  $4.3^\circ$  of visual angle. The shapes and colors of the objects in the memory display were randomly determined (without repetition of a color or shape within a display), for a total of 208 memory displays (including practice trials). At test, a single object was presented in the center position of the grid, and participants indicated whether the object was an old or new *shape* or *color–shape binding* (see Fig. 1).

### Auditory stimuli

The same auditory stimuli were used for all four experiments: Eight words spoken by a male voice at the rate of two words/s comprised the auditory stimuli for the retrieval trials. All words were two syllables long and had a familiarity rating between 545 and 700 and an imageability rating between 550 and 700, from the University of Western Australia’s MRC Psycholinguistic Database (Fearnley, 1997). The eight words were divided into two lists that participants were required to memorize (four words in each list). In addition, a 500-ms, 6000-Hz tone with a 40-ms onset envelope and a 20-ms offset envelope was used.

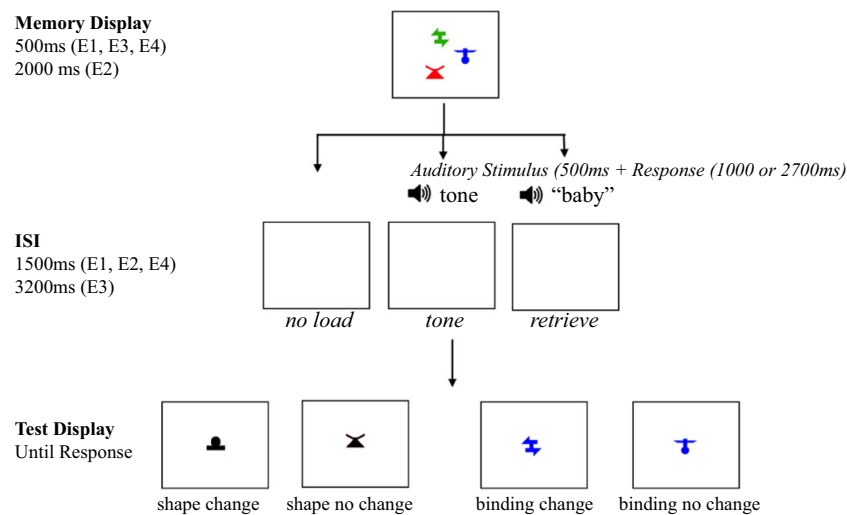
### Procedure

The basic procedure was very similar across all four experiments, which differed in the encoding time (500 or 2,000 ms), the duration of the ISI (1,500 or 3,200 ms), and the distribution of the tone and retrieval trials with the no-load trials (blocked or random); these differences are summarized in Table 1.

First, participants memorized two lists of words and were required to remember the list identity of each word. Then they moved on to the visual WM task: Three memory objects were

**Table 1** Experiment design differences across all experiments

Experiment	Final $n$	Encoding Time	ISI Duration	Auditory Task
1	26	500 ms	1,500 ms	Random
2	29	2,000 ms	1,500 ms	Random
3	20	500 ms	3,200 ms	Random
4	24	500 ms	1,500 ms	Blocked



**Fig. 1** Procedure for all experiments. In Experiment 4, we used tasks identical to those shown here, except that the “no-load” trials were blocked separately from the tone and retrieval trials

presented for 500 ms (Exps. 1, 3, and 4) or 2,000 ms (Exp. 2), followed by a brief ISI (1,500 ms in Exps., 1, 2, and 4; 3,200 ms in Exp. 3), then a single test object. Participants indicated whether the test object was the same as any of the objects in the memory display (either the same shape or the same shape–color binding, depending on the block), or whether it was changed. During the ISI, they completed the auditory task.

The auditory task began immediately after the offset of the memory display. For the auditory task, participants heard (1) a word from one of the two memorized lists (retrieval condition), (2) a tone (tone condition), or (3) nothing (no-load condition). All auditory-task types were randomly intermixed in each block (except for Exp. 4, which blocked no-load trials separately from tone and retrieval trials). The word or tone played for 500 ms, followed by a 1,000-ms delay (2,700 ms in Exp. 3) for participants to give a response. They responded by pressing the spacebar if they heard a tone or a word from the designated list (before each block, participants were instructed to respond if they heard a word from a designated list; e.g., “respond if the word is from List 1, and do not respond if the word is from List 2,” or vice versa). If there was no auditory stimulus or if the presented word did not come from the designated list, participants were instructed not to respond. Participants completed 16 trials for each auditory-task type within each block; all three auditory tasks were randomly distributed within each block (except for Exp. 4).

**Training phase** Participants completed a comprehensive training phase before moving on to the experimental phase of the experiment. First, they learned how to complete the change detection task, followed by eight practice trials (four each of shape change and binding change trials). Next, participants memorized the two lists of words, followed by a recognition test with feedback. Participants had to correctly

identify the source of each word twice before proceeding. Next, participants learned how to complete the secondary auditory task, followed by 12 practice trials. Finally, they completed 12 dual-task trials. Once participants had completed the training, they moved forward to the experimental phase.

**Experimental phase** Participants completed four blocks of the visual WM task: two shape change detection blocks and two binding change detection blocks. Participants completed 48 trials in each block, half with a change and half with no change. In two of the blocks (one each for shape and binding changes), participants were instructed to respond to List 1, and in the other two blocks they were instructed to respond to List 2. Prior to each block, they viewed instructions that told them which type of change to detect (binding or shape) and which list to respond to (1 or 2). In addition, between trials, participants viewed a screen with a reminder of the change type and list instructions (e.g., “Shape Change + List 1”). The order of the blocks was counterbalanced between participants.

In Experiments 1, 2, and 3, all secondary-task types were randomly intermixed in each block. In Experiment 4, the no-load trials were blocked separately from the tone and retrieval trials (all no-load trials at either the beginning or the end). If the no-load trials were blocked at the beginning, participants learned the list words after completing the no-load trials.

## Results

Across all experiments, some participants performed very poorly, showing only chance performance in either the change detection or auditory task. It is possible that including these participants would reduce the sensitivity of the tests by creating floor effects. This was a particular concern for the binding change type, for which performance was already lower than

for shape change detection. We therefore excluded low performers by using the following procedure.

Thresholds for exclusion were determined separately for each experiment. Average change detection performance (across all conditions) and average auditory-task performance (across all conditions) were calculated for each participant. Any participant who performed lower than one *SD* below the grand average for either the change detection or auditory task was excluded. In Experiment 1 (short ISI, short encoding, random auditory-task distribution), the exclusion criteria were 58% correct for the change detection task and 77% correct for the auditory task: Four participants were excluded due to low performance in the change detection task only, four for low performance in the auditory task only, and three for low performance in both, for a total of 11 excluded participants (see Table 1). In Experiment 2 (long encoding time), the exclusion criteria were 63% for the change detection task and 81% for the secondary task: One person was excluded due to low performance in the change detection task, one due to low auditory-task performance only, and two due to low performance in both tasks, for a total for a total of four participants excluded. In Experiment 3, the exclusion criteria were 55% for the change detection task and 79% for the secondary task: Three participants were excluded due to low performance in the change detection task only, one in the auditory task only, and three in both, for a total of seven excluded participants. In Experiment 4 (blocked auditory task), the exclusion criteria were 60% for change detection and 73% for the auditory task. This resulted in excluding eight participants apiece for change detection and the auditory task only, and seven for low performance on both, resulting in a total of 23 participants excluded. Across all experiments, if the assumption of sphericity was violated, a Greenhouse–Geisser correction was applied.

To determine whether retrieving words from LTM had a negative effect on visual WM and whether this effect was specifically greater for binding changes, we completed a 2 (change type)  $\times$  3 (auditory-task type) repeated measures ANOVA with Change Type (shape, binding) and Auditory-Task Type (no load, tone, retrieval) as within-subjects factors. If retrieving words from LTM negatively impacted the representation of visual information, change detection performance should be lower in the retrieval conditions than in the no-load and tone conditions. In addition, if the secondary task negatively impacted bindings more than individual features, we should observe an interaction between change type and auditory task. All data were analyzed in terms of proportions correct,  $d'$ , and  $K$  (Cowan, 2001). All results were the same, regardless of the dependent variable; therefore, the statistics presented below are based on proportions correct, although all three variables are displayed in Fig. 2. For the raw proportions correct in both tasks, please see Tables 2 and 3.

## Change detection task

*Experiment 1* We found a main effect of change type,  $F(1, 25) = 37.14, p < .001, \eta_p^2 = .60$  (shape > binding,  $p < .001$ ), a main effect of auditory task,  $F(2, 50) = 37.14, p < .001, \eta_p^2 = .42$  (no load vs. tone  $p = .42$ ; no load and tone both > retrieval, both  $ps < .001$ ), and a significant interaction,  $F(2, 50) = 3.18, p = .05, \eta_p^2 = .11$ . The interaction, however, was caused by shape change detection being more negatively impacted by retrieval, which was in the opposite direction from the predicted interaction.<sup>1</sup> Furthermore, whereas shape change detection marginally decreased from no load to tone ( $p = .06$ ), there was no change in performance from no load to tone for binding changes ( $p = .55$ ).

*Experiment 2* Here we found a main effect of change type,  $F(1, 19) = 43.30, p < .001, \eta_p^2 = .70$  (shape > binding,  $p < .001$ ), a main effect of auditory task,  $F(2, 38) = 23.70, p < .001, \eta_p^2 = .56$  (no load vs. tone,  $p = .914$ ; tone > retrieval,  $p < .001$ ), but no interaction,  $F(2, 38) = 0.23, p = .80, \eta_p^2 = .01$ .

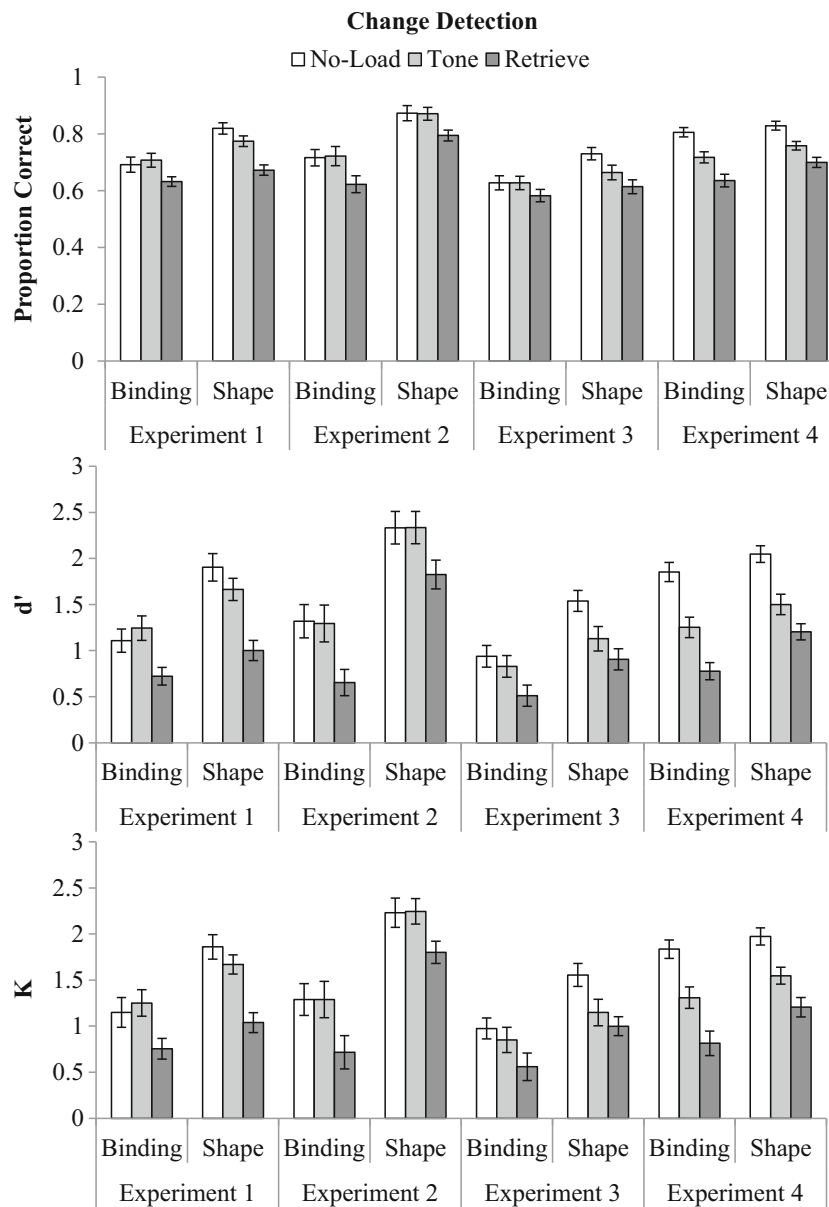
*Experiment 3* As in Experiment 2, the main effects of change type,  $F(1, 28) = 12.17, p = .002, \eta_p^2 = .30$  (shape > binding,  $p = .002$ ), and auditory task,  $F(2, 56) = 16.54, p < .001, \eta_p^2 = .37$  (no load > tone,  $p = .002$ ; tone > retrieval,  $p = .04$ ) were significant, but the interaction was not,  $F(2, 56) = 1.05, p = .36, \eta_p^2 = .04$ .<sup>2</sup>

*Experiment 4* As in the two previous experiments, main effects of change type,  $F(1, 34) = 28.50, p < .001, \eta_p^2 = .46$  (shape > binding,  $p < .001$ ), and auditory task,  $F(2, 68) = 53.77, p < .001, \eta_p^2 = .61$  (no load > tone > retrieval, all  $ps < .001$ ), were observed, but the interaction was not significant,  $F(2, 68) = 1.63, p = .20, \eta_p^2 = .05$ .

*All experiments* In all of the analyses, the only condition in which an interaction between change type and auditory task emerged (Exp. 1) was created by the secondary task reducing shape change detection more than binding change detection, the opposite of the pattern predicted. Overall, therefore, we found no evidence to indicate that the auditory task impaired binding performance more than shape performance. However, it is possible that a small interaction between change type and auditory task may not have been captured, due to insufficient power. To test this possibility, we collapsed across all four experiments and ran an ANOVA with all (included) participants. As with the individual experiments, we found a main effect of change type:  $F(1, 109) = 93.78, p < .001, \eta_p^2 = .462$

<sup>1</sup> This interaction was not present in an analysis that included all participants; however, all other results were the same.

<sup>2</sup> When all participants were included, we did find an interaction, but this was caused because there was no decrease in the binding change detection task across auditory-task conditions, likely due to floor effects.



**Fig. 2** Performance on the change detection task across all four experiments

(shape > binding,  $p < .001$ ), a main effect of auditory task,  $F(2, 218) = 91.93, p < .001, \eta_p^2 = .46$  (no load > tone >

retrieval, both  $ps < .001$ ), but no interaction,  $F(2, 218) = 0.64, p = .53, \eta_p^2 = .006$ .

**Table 2** Proportions correct for the change detection task

Experiment	<i>M (SE)</i>				
	Change Type		Auditory-Task Type		
	Binding	Shape	No Load	Tone	Retrieval
1	.68 (.02)	.76 (.01)	.76 (.02)	.74 (.02)	.65 (.01)
2	.69 (.02)	.75 (.01)	.79 (.01)	.72 (.01)	.65 (.01)
3	.63 (.02)	.70 (.02)	.71 (.02)	.66 (.02)	.63 (.01)
4	.69 (.03)	.85 (.02)	.80 (.02)	.80 (.02)	.71 (.02)

**Table 3** Proportions correct for the auditory task

Experiment	<i>M (SE)</i>				
	Change Type		Auditory-Task Type		
	Binding	Shape	No Load	Tone	Retrieval
1	.88 (.01)	.89 (.01)	.98 (.01)	.88 (.02)	.79 (.02)
2	.86 (.07)	.88 (.01)	1.00 (.00)	.86 (.02)	.75 (.02)
3	.89 (.01)	.91 (.01)	.94 (.01)	.94 (.01)	.77 (.03)
4	.88 (.01)	.92 (.01)	.99 (.003)	.92 (.01)	.80 (.03)

Auditory task

We then examined auditory-task performance to determine whether it was affected by change type (see Fig. 3). As with change detection accuracy, we completed 2 (change type) × 3 (auditory task) within-subjects ANOVAs. Across all experiments, a main effect of auditory-task type emerged, with performance being highest in the no-load condition, followed by the tone condition, and then the retrieval condition, as expected. Across some experiments, performance on the auditory task was higher when detecting shape rather than binding changes, but this was not consistent. In particular, differences between shape and binding tended to arise from the difference between no-load and tone trials, and not from the retrieval trials: That is, performance was more likely to decrease when responding to a tone if detecting binding rather than shape changes.

*Experiment 1* On average, all included participants were able to respond to the auditory task in the amount of time allotted: 85% of all responses to the auditory task were made prior to the onset of the test display. We found no main effect of change type,  $F(1, 25) = 0.70, p = .41, \eta_p^2 = .03$ , a main effect of auditory task,  $F(1.60, 39.89) = 35.89, p < .001, \eta_p^2 = .59$  (no load > tone > retrieval, all  $ps < .001$ ), and a significant interaction,  $F(1.55, 38.73) = 5.19, p = .009, \eta_p^2 = .17$ .: There was a significant decrease from tone to retrieval for shape changes ( $p < .001$ ) but not binding changes ( $p = .11$ ).

*Experiment 2* Eighty-nine percent of all responses were made within the time limit. We observed a main effect of change type,  $F(1, 19) = 14.90, p = .001, \eta_p^2 = .44$  (shape > binding,  $p = .001$ ), a main effect of auditory task,  $F(1.32, 25.06) = 36.47, p < .001, \eta_p^2 = .66$  (no load > tone > retrieval, all  $ps < .001$ ), and an interaction,  $F(2, 38) = 3.58, p = .04, \eta_p^2 = .16$ . The decrease from no-load to tone was greater when detecting

binding changes (mean difference = .11,  $p < .001$ ) than when detecting than shape changes (mean difference = .04,  $p = .01$ ).

*Experiment 3* Responses were made within the time limit for 97% of all trials. We found a marginal effect of change type,  $F(1, 28) = 3.16, p = .09, \eta_p^2 = .10$ , a main effect of auditory task,  $F(1.21, 33.82) = 46.84, p < .001, \eta_p^2 = .63$  (no load > tone > retrieval, all  $ps < .001$ ), and an interaction,  $F(2, 56) = 12.30, p < .001, \eta_p^2 = .31$ . This interaction was caused by no change in performance from no load to tone when detecting shape changes ( $p = .224$ ), but a significant decrease from no load to tone when detecting binding changes ( $p < .001$ ).

*Experiment 4* Seventy-eight percent of all responses were made within the time limit. No main effect of change type emerged,  $F(1, 34) = 1.80, p = .19, \eta_p^2 = .05$ , although we did observe a main effect of auditory task,  $F(1.64, 57.26) = 86.50, p < .001, \eta_p^2 = .72$  (no load > tone > retrieval, all  $ps < .001$ ), and a significant interaction,  $F(2, 68) = 29.58, p < .001, \eta_p^2 = .47$ . The interaction occurred because there was no change from tone to retrieval when detecting binding changes ( $p = .17$ ), but there was such a change when detecting shape changes ( $p < .001$ ).

Discussion

The results from these experiments show that retrieving words from LTM reduced visual change detection performance, consistent with the idea that visual information is retained in a domain-general storage component of WM (e.g., Baddeley et al., 2011; Cowan, 2001). This was true for shape changes, as had been found by Ricker et al. (2010), as well as binding changes. However, the magnitudes of the effect of LTM retrieval were similar when detecting binding and shape changes. This is inconsistent with the idea that feature

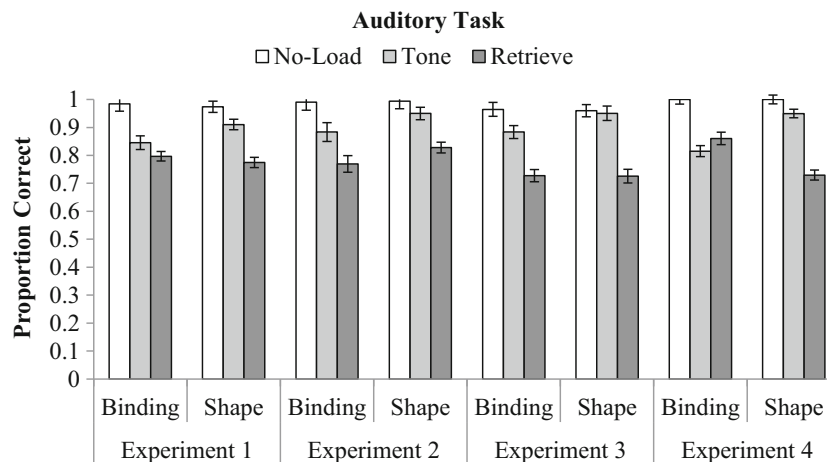


Fig. 3 Auditory-task performance across all four experiments

representations are stored redundantly, whereas binding representations are not, causing bindings to be more vulnerable to disruption than individual features.

Across all experiments, we observed no tendency for the secondary task to negatively impact binding more than shape change detection performance. This was unlikely to be due to floor effects: Even when poor performers were excluded, retrieval never impacted binding more than shape. This was also unlikely to be due to insufficient power; when the data from all four experiments were collapsed, there was still no interaction between change type and auditory load.

### Multiple-representations hypothesis

The multiple-representations hypothesis predicts that WM will hold both feature and object representations. This was most explicitly developed by Baddeley et al. (2011), who proposed that objects serve as the unit of representation in the episodic buffer, whereas individual features are maintained in the visuospatial sketchpad. Whereas the results of this study are consistent with the idea that object-level representations are maintained in WM, the data are inconsistent with the hypothesis that there are also independent feature-level representations. We predicted that if additional “feature” representations were available in WM, then when object representations were lost from the domain-general WM storage space, a greater decrement should be apparent in binding memory than in individual-feature memory. However, the effect of retrieving a word from LTM was the same for both features and their bindings.

A strict interpretation of Baddeley et al. (2011), in which only feature representations reside in the visuospatial sketchpad and only bound representations reside in the episodic buffer, is unlikely to be true, given the data presented here. An alternative interpretation is that there are multiple representations, but that both feature and object representations are stored in the visuospatial sketchpad and episodic buffer. In this case, it might be expected that occupying the episodic buffer would not create a specific impairment for binding representations. However, this does not yield any explanatory power that is greater than that from a single, object-level representation, which is more parsimonious. Alternatively, it has been proposed that the unit of WM is a “hierarchical feature bundle” that is similar to the multiple-copies hypothesis, in that there are both object-level and feature-level representations (Brady, Konkle, & Alvarez, 2011). The results of this study suggest, however, that feature- and object-level representations are not maintained in separate WM storage buffers.

However, we did find that overall change detection performance was lower for feature bindings than for individual features. In addition, whereas Wheeler and Treisman (2002) found that binding performance was not lower than binding

change detection performance when a single object probe was used for a test, the participants in our study performed worse at detecting binding changes with this test.

Difficulty in detecting binding changes may not easily be explained by focusing on the type of representation in WM. Rather, the overall difficulty of binding change detection may be better explained by problems at other phases of the change detection process. Detecting a change across a visual disruption requires several steps (Simons, 2000; Simons & Rensink, 2005): The information must first be attended and encoded into WM, then maintained across a delay, and finally compared to new perceptual input. A failure at any one of these stages can lead to a failure to detect a change (*change blindness*). In the next section, we outline how other stages in the change detection process may contribute to the higher rate of change blindness for feature bindings.

### Why are feature binding changes difficult to detect?

*Encoding failures* One possible explanation for higher change blindness for bindings than for features is that bindings are less likely to be encoded into WM; however, considerable evidence directly contradicts this possibility. For example, our own data in Experiment 2 indicate that longer encoding times did not result in binding performance that was equivalent to shape change detection performance. In addition, Wheeler and Treisman (2002) showed that the disparity between shape and binding change detection performance arises with different types of tests (whole-array or single-object) under the same encoding conditions. In addition, Alvarez and Thompson (2009) showed that performance on a cued-recall test (e.g., being shown a color and asked where it appeared) was higher than a feature-swap test (e.g., being shown colors swapping places and asked to detect whether a swap occurred). These results show that changing the test type affects whether binding changes are more difficult to detect than feature changes, which suggests that change detection performance may hide true binding memory.

However, fully encoded object representations in WM may nonetheless be incomplete (Cowan et al., 2013). Cowan et al. found that, in blocks in which only a single feature change could occur (i.e., participants were told to encode color or shape only), performance was higher for detecting these feature changes (color or shape changes) than in blocks in which color, shape, and binding changes could occur. Therefore, dividing attention to all features at encoding reduced the ability to detect single-feature changes. Binding performance was even lower than shape performance, which tends to have lower change detection performance than color. Furthermore, the number of bindings retained was smaller than would be expected if bindings were equal to the total number of features retained. The results suggest that frequently, only a single feature of an object will be represented in WM, even when the goal is to encode all features of an object. This is in contrast to more strictly object-



based theories of WM that propose that all features are encoded together in WM (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001) at the same rate as the feature that is slowest to encode (Woodman & Vogel, 2008).

The data presented here could be consistent with the hypothesis that some objects (randomly determined) simply do not contain all of the feature information and that both complete and incomplete representations are represented (Cowan et al., 2013). Although this perspective is advantageous in its parsimony, it is not clear what factors would determine whether an object would be represented completely or incompletely in WM. For example, why would representations still be incomplete after a 2,000-ms encoding time? One possibility is that objects with a greater information load consume more capacity than do objects with less information load (Alvarez & Cavanagh, 2004; Cowan et al., 2013; Fougny, Asplund, & Marois, 2010); capacity may be filled by representing, for example, one complete object and two incomplete objects.

In addition, incomplete representations may occur not because of WM capacity limitations, but rather because of a lack of focused attention during encoding. Focused attention may facilitate complete representations (van Lamsweerde & Beck, 2012). However, even with a 2,000-ms encoding time, participants may not choose to overtly shift attention serially among the items. The absence of this kind of serial attention shifting may result in incomplete representations. The present study cannot address which of these mechanisms is the likely reason behind incomplete representations, and indicates an unanswered question for the hypothesis that encoding failures result in overall difficulty in detecting binding changes.

**Comparison errors** Finally, test items are more similar to memory items on binding change trials than on feature change trials, which could lead to more comparison errors on binding change detection trials. This difference could offer a possible explanation for the seemingly discrepant findings that encoding task-irrelevant features that match the potential memory set (Ueno et al., 2011), but not retrieving words from LTM into WM (the present study), results in specific binding impairments. Specifically, the errors occur not in the encoding or maintenance phase, but rather in the comparison and decision-making phase, which may reduce change detection performance (Awh, Barton, & Vogel, 2007), although this possibility is not mutually exclusive from errors at the other stages of processing.

We note that in the present study, participants were required to remember two features in the binding task and only a single feature in the shape task (as in Wheeler & Treisman, 2002); remembering two features at a time may result in an overall decrease in change detection performance, although this pattern is not found consistently (Johnson et al., 2008; Wheeler & Treisman, 2002). Therefore, in our study, the poorer binding performance relative to shape performance could have been

caused simply by an increase in task difficulty when remembering a second feature. However, the data do suggest that both individual features and feature bindings compete with verbal stimuli for the same resources, which is inconsistent with the idea that objects can be overwritten while individual features remain intact.

## Conclusion

The results of the present study demonstrate that word retrieval impairs visual change detection performance for both individual features and feature bindings, which is consistent with the idea that at least part of WM contains a domain-general storage resource (Baddeley et al., 2011; Cowan, 2001). In addition, the results suggest that, once encoded into WM, feature bindings are not maintained in a more vulnerable state than individual features, due to multiple levels of feature representation. Rather, failures to detect binding changes likely arise at another point in processing: in a failure to encode all features of an object, or in confusion during decision-making arising from the similarity between test stimuli and the stimuli in memory. Complementing previous research, the results of the present study suggest that investigating the way that feature bindings are represented in WM can offer insight into the memory's structure.

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