THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Maintaining binding in working memory: Comparing the effects of intentional goals and incidental affordances

OPEN ACCESS

Running head: INTENTIONAL BINDING IN WM

Maintaining binding in working memory: Comparing the effects of intentional goals and

incidental affordances

Candice C. Morey

University of Groningen

Address correspondence to:

Candice C. Morey

Experimental Psychology

Grote Kruisstraat 2/1

9712 TS Groningen, The Netherlands

Phone (Netherlands): +31 050 363 6254

Phone (USA, via Skype): 1 573 234 6251

Email: c.c.morey@rug.nl

Word count (including references): 5,314 (Abstract: 141)

Date submitted: 21 June, 2010

Date re-submitted: 9 December, 2010

Abstract

Much research on memory for binding depends on incidental measures. However, if encoding associations benefits from conscious attention, then incidental measures of binding memory might not yield a sufficient understanding of how binding is accomplished. Memory for letters and spatial locations was compared in three within-participants tasks, one in which binding was not afforded by stimulus presentation, one in which incidental binding was possible, and one in which binding was explicitly to be remembered. Some evidence for incidental binding was observed, but unique benefits of explicit binding instructions included preserved discrimination as set size increased and drastic reduction in false alarms to lures that included a new spatial location and an old letter. This suggests that substantial cognitive benefits, including enhanced memory for features themselves, might occur through intentional binding, and that incidental measures of binding might not reflect these advantages.

Word count: 141

Keywords: binding, working memory, attention

Memory for binding: Comparing the effects of intentional goals and incidental

affordances

Much research on binding, the grouping of otherwise unrelated features into a

unified object, depends on inferences about incidental binding. Incidental binding

describes evident memory for a relationship between features when learning that

relationship was not an explicit task goal. Incidental binding is sometimes observed as the

faster recognition of studied versus unstudied combinations of features or differences in

blood flow during tasks where binding was afforded compared with tasks in which

binding was implausible (Nyberg, Habib, McIntosh, & Tulving, 2000; Prabhakaran,

Narayanan, Zhao, & Gabrieli, 2000). Methods examining incidental rather than

intentional binding are logically appealing because they allow direct comparisons

between two recognition tasks, which can be identical except for the format of the

stimulus presentation. These methods presume that some binding occurs without

intention, and also that the processes underlying incidental binding are similar to those

underlying intentional binding. I reconsider these presumptions, which are frequently

assumed by researchers studying binding, by directly comparing behavioral performance

on three similar tasks designed to differ in how strongly binding is afforded by the

stimulus presentation and instructions.

One influential binding study was carried out by Prabhakaran, Narayanan, Zhao,

and Gabrieli (2000). Prabhakaran et al. compared behavioral responses and BOLD

activation between two conditions, one in which to-be-remembered letters were presented

in a central location while to-be-remembered locations surrounded the letters (*Separate*)

and another in which the letters were displayed occupying the locations (*Bound*).

Recognition decisions were the same in both tasks; after a brief delay, a single letter appeared on the screen, in a location, and participants were to respond affirmatively if both the probe letter and location were represented at study, and negatively if either the letter or location were not. This task did not require explicit memory for binding; memory for both feature dimensions was sufficient for correct responding. However, binding was possible in the *Bound* condition and some measures indeed suggested that binding occurred. In the *Bound* condition, positive probes could be congruent, including a letter and location presented together at study, or recombined, including two features from study presentation recombined from different letter-location pairs. Prabhakaran et al. found that participants responded significantly faster to congruent positive probes than to recombined ones, suggesting that participants remembered bindings. This inference allowed Prabhakaran et al. to interpret unique BOLD activation in the anterior prefrontal cortex during the *Bound* trials as evidence of a domain-general working memory store, capable of holding letter-location representations. This research was cited by Baddeley (2000) as key evidence leading to the supposition of the domain-general episodic buffer, which could conceivably store cross-domain object representations.

Despite the elegance of the incidental binding research design, it could be problematic to make inferences about processes and mechanisms underlying binding using a task that does not explicitly require binding. Other evidence suggests that binding does not necessarily occur whenever stimulus presentation affords it (e.g., Cowan, Saults, & Morey, 2006; Morey, 2009). For example, Morey (2009) compared memory for bound displays of letter-in-location stimuli, manipulating whether participants were always tested with a single feature or instead whether binding was tested. When binding was

never tested, articulatory suppression did not affect memory for spatial locations, but when binding was tested, articulatory suppression impaired performance even on trials in which a new, unstudied location (i.e., a location lure), was tested. This indicates that given the same study display, participants may remember features differently when binding is required. When attention is paid to binding at study, memory representations may differ compared to circumstances in which binding is ignored.

Whether attention is strictly necessary for remembering binding remains an open question (cf. Allen, Baddeley, & Hitch, 2006; Wheeler & Treisman, 2002), one whose ultimate answer will be no doubt be influenced by the methods used to measure memory for binding. There are currently some reasons for supposing that incidental and intentional binding might reflect at least partially distinct processes. Dissociations between a bottom-up, perceptually-based kind of binding and top-down association learning have been observed (Colzato, Raffone, & Hommel, 2006). A distinction is sometimes made between grouping and unitization, where grouping refers to explicit formation of associations and unitization refers to implicit representation (Graf & Schacter, 1989). Explicit memory for binding is thought by some to rely on recollective processes, rather than familiarity (Diana, Yonelinas, & Ranganath, 2008; Yonelinas, 2002), and recollection is thought to reflect controlled processes (Jacoby, 1991) rather than automatic ones.

Assuming this is accurate, then it is difficult to say what behaviors Prabhakaran et al. (2000) actually measured in their *Bound* task. Their results could reflect incidental binding of letter identities to their attended locations (Treisman & Zhang, 2006, who argue that such binding occurs), or their results could reflect intentional strategies

adopted by their participants to attend to and remember letter-location bindings.
Differentiating between these possibilities is crucial if progress is to be made in
understanding how and under what circumstances attention impacts memory for binding.
Both Prabhakaran et al.'s behavioral results and neuroimaging results are puzzling if it is
assumed that maintenance of binding was the unique difference between the *Bound* and
Separate conditions. Behaviorally, binding conveyed little cognitive advantage; accuracy
was significantly better in the *Bound* condition compared to the *Separate*, but only
slightly so. Furthermore, recent neuroimaging evidence is inconsistent with assumptions
about storage of letter-location binding arising from Prabhakaran et al.'s research.
Prabhakaran et al. suggested that their unique anterior PFC activation reflected a working
memory store capable of maintaining cross-domain object representations. However,
subsequent event-related studies of anterior PFC function, which are better able to isolate
activation due to storage rather than other cognitive processes, have not implicated the
anterior PFC in storage operations (Campo et al., 2005; DePisapia, Slomski, & Braver,
2007), suggesting that any differences between the *Bound* and *Separate* tasks in
Prabhakaran et al.'s study might not have been attributable to the unique use of a domain-
general store in the *Bound* condition.

The following experiment was carried out to replicate the behavioral findings of
Prabhakaran et al. (2000) and to examine how explicit instructions to remember binding
might affect memory for letters, spatial locations, and their binding. Participants
completed three letter and location memory tasks. Two of these tasks were constructed to
be similar to the *Separate* and *Bound* conditions of Prabhakaran et al. (referred to here as
Separate Presentation and *Bound Presentation*). In a third task, (called *Binding*

Recognition), letters were presented in locations as in the *Bound Presentation* task, but participants were instructed to respond affirmatively to a letter-location probe only if the letter and location were presented together at study. Therefore, in the *Binding Recognition* task, memory for binding was necessary for making a correct response whereas in the *Bound Presentation* task, an accurate response was possible without explicit memory for binding.

Possibly, simply presenting features in *Bound* format provides genuine behavioral advantages compared to presenting features in the disconnected, *Separate* format. If so, this experiment will help to elucidate those advantages. However, it is also important to know whether top-down attention to binding qualitatively changes the memory representation, possibly conveying different advantages or incurring different costs. Much recent research on binding makes use of methods similar to Prabhakaran's, with binding manipulated through stimulus presentation only (e.g., Elsley & Parmentier, 2009; Guérard, Tremblay, & Saint-Aubin, 2009). Inference will sometimes depend on knowing whether memory for binding was implicit or explicit, and if implicit, understanding how similar incidental and intentional memory for binding truly are. To better gauge how much information was maintained during binding compared with separate feature memory, I manipulated the amount of to-be-remembered information, varied from 3 letters and locations, which is within typical estimates of working memory capacity (Cowan, 2001) to 5 letters and locations, which should slightly exceed working memory capacity (at least for spatial locations or letter-location objects). Remembering these features as bound objects instead of separate features should decrease the effect of increasing the amount of to-be-remembered information. Differences between behavioral

performance during intentional versus incidental binding tasks, compared with performance during a task where binding is implausible, may be taken to reflect whether binding, or at least the same kind of binding, is really occurring in these conditions.

Method

Participants

Thirty-three students enrolled at the University of Groningen participated. The data of two participants were excluded due to chance responding in at least one task, leaving *N*=31 (9 males and 22 females, 20-26 years old).

Apparatus and Stimuli

Stimuli for each trial were randomly selected without replacement from predetermined sets. Letters (B, F, G, H, J, M, Q, R, T, L) were chosen to minimize phonological confusability and because upper- and lower-case exemplars were not visually identical in Times New Roman font. Ten locations were chosen from the perimeter of an imaginary ellipse centered on the screen. The centers of each location were ≥2 cm apart. All locations fell between pixels 398-622 horizontally and 309-457 vertically on a 1024x768 display, enabling participants to see all stimuli at once from a distance of approximately 50 cm.

Stimuli were controlled using E-Prime (Schneider, Eschmann, & Zuccolotto, 2002). Responses were collected with Psychology Software Tools response boxes.

Tasks and Procedure

Participants completed 3 randomly-ordered tasks, each beginning with practice trials (with 3 items) supervised by an experimenter. Correct responses on at least 5 practice trials were necessary to begin the experimental trials. Participants could repeat

the practice session indefinitely, but most participants (*N*=18) never needed to repeat, and

of those remaining, only two ever required more than one repetition of a practice block.

These criteria ensured that participants understood the differences between instructions

for each task, so that simple misunderstanding could not adequately explain accuracy

differences between tasks.

Separate Presentation. In the *Separate Presentation* task upper-case letters were

presented in a centered row and locations indicated with unfilled circles surrounding the

letters (see Panel A of Figure 1). Participants were to consider whether the probe letter

had been present and whether the probe location had been occupied, and reject the probe

if either of these conditions were not met. At test, letter and location probes could be

presented unbound (letter probe presented at the center of the screen and location probe

presented as an unfilled circle) or their presentation could be bound (letter presented at a

stimulus location, within a circle). When the probe appeared in bound format, this task

replicated the *Separate* trials of Prabhakaran et al. (2000).

Bound Presentation. In the *Bound Presentation* task upper-case letters were

displayed within circles representing spatial locations (see Panel B of Figure 1). The

instructions for responding were the same as in the *Separate Presentation* task. The probe

letter and location could appear in bound or unbound format. When the probe appeared in

bound format, this task replicated the *Bound* trials of Prabhakaran et al. (2000), and like

theirs, resulted in the presence of both congruent and recombined targets.

Binding Recognition task. Verbal and spatial stimuli were presented exactly as

described for the *Bound Presentation* task. However in the *Binding Recognition* task,

participants were instructed to reject a probe that included a letter and a spatial location

that were not bound together during study. As in the *Separate Presentation* and *Bound*

Presentation blocks, probe stimuli could appear in unbound or bound format.

In all tasks, proportions of targets and lures were equal. Lure types also occurred

in equal proportions within each task block. All tasks included letter and location lures,

which included one familiar feature from the study display and one unstudied feature.

The *Bound Presentation* task included two types of targets (in equal proportions),

congruent targets in which the letter and location were bound together at study and

recombined targets, in which the tested letter and location were both present at study but

were not bound together. In the *Binding Recognition* task, a probe with a letter and

location that were present but not bound together at study was a recombination lure. The

Separate and *Bound Presentation* blocks contained 64 trials each (32 targets and 32 lures,

with equal proportions letter and location lures), and the *Binding Recognition* block

contained 96 trials (48 targets and 48 lures, with equal proportions recombination, letter,

and location lures), so that both the number of letter and location lures and the overall

proportions of lures and targets was constant across tasks.

Procedure. Instructions emphasized accuracy over speed, and these instructions

were reinforced by requiring performance to a criterion during the practice session. Trial

events are represented in Figure 1. The participant initiated a trial by pressing the button

on the response box marked *Next*. A fixation "+" appeared for 1000 ms, followed by the

study presentation, which remained onscreen for 1500 ms for 3 letters and 3 locations, or

2500 ms for 5 letters and locations in order to keep encoding time per object constant.

After a blank 5000-ms retention interval, a probe letter and location appeared, and

remained until the participant responded by pressing the button labeled *Yes* for a target or the button labeled *No* for a lure.

Analyses

My analysis of these data occurs in two parts. In the first, I sought to replicate the findings of Prabhakaran et al. (2000), especially the latency differences they uncovered in the *Bound Presentation* task. I therefore conducted comparisons between the *Separate* and *Bound Presentation* tasks on both accuracy and latency data, and compared probe conditions within the *Bound Presentation* task. I also compared overall discrimination and correct rejections of lures across all three tasks, to determine whether behavioral performance during a letter-location memory task that affords binding is more similar to performance on a letter-location memory task that does not afford binding or more similar to an explicit letter-location binding task. Because of near-ceiling performance in some experimental conditions, arcsine transformations were applied to proportions correct before inferential analyses (though mean proportions correct are reported for ease of interpretation). Whenever ANOVA assumptions of sphericity were violated, the Greenhouse-Geisser correction was applied. The threshold for declaring statistical significance was always $p<.05$.

After an initial analysis, I excluded the unbound probe trials from further analysis, in order to simplify the report of results. Contrary to my expectations, the effect of this manipulation did not significantly differ between the *Separate* and *Bound Presentation* tasks (Task x Probe format, $p=.26$). I chose to report results for only the bound probes, so as to remain consistent with Prabhakaran et al.'s (2000) design, but collapsing across probe format reveals results similar to the ones I report.

Results

Does incidental binding occur when stimuli afford it?

Is there strong evidence of binding during the *Bound Presentation* task, as Prabhakaran et al. (2000) argued? This could manifest itself as more accurate responses in the *Bound* than in the *Separate Presentation* task, which Prabhakaran et al observed. Mean proportions correct for all tasks and conditions are given in Table 1. A 3-way ANOVA including task (*Bound Presentation* and *Separate Presentation*), probe condition (target, letter lure, or location lure), and set size (3 or 5) revealed significant main effects of probe condition ($F(2,60)=40.88$, $MSE=.16$, $\eta_p^2=.58$), and set size ($F(1,30)=16.30$, $MSE=.07$, $\eta_p^2=.35$). The effect of task did not reach criterion for statistical significance ($p=.07$), and neither did any interactions (ps between .08 and .30). The difference between overall accuracy in the *Bound* ($M=.84$, $SEM=.01$) and the *Separate Presentation* tasks ($M=.81$, $SEM=.01$) was comparable to that observed by Prabhakaran et al (.885 for *Bound* and .857 for *Separate*, with 4-item displays). One might also ask whether judgments were more accurate for congruent than recombined targets in the *Bound Presentation* task. An advantage for congruent targets would be consistent with the assumption that incidental binding occurred in the *Bound Presentation* task. A 2-way ANOVA including each probe condition (congruent target, recombined target, letter lure, or location lure) and set size of arcsine-transformed proportions correct in the *Bound Presentation* task showed a main effect of probe condition ($F(3,90)=15.35$, $MSE=.14$, $\eta_p^2=.34$), but a Bonferroni-corrected comparison between congruent targets ($M=.89$, $SEM=.03$) and recombined targets ($M=.82$, $SEM=.03$)

was non-significant (p=.45). A main effect of set size was also observed (F(1,30)=19.74, MSE=.05, η_p^2=.40); their interaction was non-significant (p=.30).

Prabhakaran et al.'s strongest evidence came from latency differences, particularly between the congruent and incongruent targets in the *Bound Presentation* task. Trimmed mean response times for correct responses only are given in Table 2 (*N*=28 after trimming). Correct responses faster than 300 ms and slower than 7000 ms (more than 5 SDs from the mean, < 2% of all responses) were excluded. First a 3-way ANOVA performed on trimmed mean response times with task (*Separate Presentation*, *Bound Presentation*), set size (3, 5), and probe condition (targets, letter lures, location lures) was carried out to examine any differences between the *Separate Presentation* and *Bound Presentation* tasks that might reflect incidental binding in the *Bound Presentation* task. No main effect of task (p=.995) or any significant interactions between the task factor and other variables were observed (*p*s from .35-.93), which might have reflected incidental binding in the *Bound Presentation* task. A separate 2-way ANOVA of the *Bound Presentation* task only, with set size and probe condition (congruent targets, recombined targets, letter lures, and location lures) as factors, was carried out in a further search for evidence that incidental binding might have occurred when it was afforded. Main effects of set size (F(1,27)=16.22, MSE=242214, η_p^2=.38) and probe condition (F(3,81)=6.30, MSE=371307, η_p^2=.19) were found (no significant interaction, p=.41). In this analysis, the main evidence for binding observed by Prabhakaran et al. was clearly replicated: recombined targets (*M*=2251, *SEM*=148) produced significantly slower responses than in all other conditions, including congruent targets (*M*=1829, *SEM*=93).

In the *Bound Presentation* task, for which binding was possible but not necessary, modest evidence for incidental binding was observed. Specifically, response times to congruent targets were faster than to recombined targets. However, if incidental binding occurred and conveyed behavioral advantages supposedly associated with binding, one might also have expected interactions between task and other variables, possibly set size, indicating that more information was maintained during binding memory than during dual-feature memory. These interactions never reached statistical significance. Even overall differences in accuracy between the *Bound* and *Separate Presentation* tasks did not significantly differ, though the size of the difference between these conditions was similar to the statistically significant difference observed by Prabhakaran et al. (2000). Considering the entire pattern of comparisons between the *Separate* and *Bound Presentation* tasks, bound presentation did not afford much of an advantage. To consider whether the assumption that binding should afford behavioral advantages is reasonable, I next compare performance on the *Binding Recognition* task with performance on the *Separate* and *Bound Presentation* tasks.

Does intentional memory for binding differ from incidental memory for binding?

How does discrimination in the *Binding Recognition* task, in which binding maintenance was an explicit task goal, compare with that of the *Separate Presentation* and *Bound Presentation* tasks? In order to fairly compare across all three tasks, which each had the same 50/50 division of targets and lures but different definitions of what constituted a target or lure, nonparametric A' values were calculated. A' models discrimination, correcting for response biases, but imposes no other assumptions on the values (Macmillan & Creelman, 2004). Assuming performance is better than chance,

$$A' = \frac{1}{2} + \frac{(H - F)(1 + H - F)}{4H(1 - F)} \qquad (1)$$

where H equals the hit rate, or the proportion of correct responses to targets, and F equals

false alarm rate, or the proportion of incorrect responses to lures. A' values were entered

into a 2-way ANOVA, with task (*Binding Recognition*, *Bound Presentation*, or *Separate*

Presentation) and set size as factors. Significant main effects of task ($F(2,60)=10.15$,

$MSE=.01$, $\eta_p^2=.25$) and set size ($F(1,30)=9.03$, $MSE=.01$, $\eta_p^2=.23$) were observed; their

interaction was non-significant ($p=.17$). Discrimination was significantly higher in the

Binding Recognition task ($M=.94$, $SEM=.01$) than in both the *Separate Presentation* task

($M=.87$, $SEM=.02$) and the *Bound Presentation* task ($M=.91$, $SEM=.01$); Bonferroni-

corrected comparisons between *Bound Presentation* and *Separate Presentation* ($p=.08$)

were non-significant.

Lures that included one studied feature and one new feature occurred across all

tasks, enabling some direct comparisons of proportions correct across tasks. A 3-way

ANOVA with task, set size, and lure type (letter or location lure) as factors uncovered

significant main effects of task ($F(2,60)=11.10$, $MSE=.09$, $\eta_p^2=.27$), set size

($F(1,30)=6.53$, $MSE=.08$, $\eta_p^2=.18$), and lure type ($F(1,30)=105.50$, $MSE=.12$, $\eta_p^2=.78$). A

significant 2-way interaction between task and set size ($F(2,60)=3.39$, $MSE=.06$, $\eta_p^2=.10$)

qualifies these effects, providing a possible explanation of improved discrimination

observed in the *Binding Recognition* task. This pattern is depicted in Figure 2. In the

Separate and *Bound Presentation* tasks, recognition typically decreased as set size

increased, but in the *Binding Recognition* task, recognition of lures did not decrease as set

size increased. This interaction suggests that intentional binding might enhance memory

for the features being bound. The effect is clearest for the location lures (i.e., old letters

presented in new locations), though the 3-way interaction between task, set size, and lure type which would show that the same pattern does not hold for letter lures does not reach the criterion for statistical significance (p=.065). Morey (2009) showed a similar advantage for letter lures, which might arise if participants remember the all letter identities on a trial. This is certainly plausible for displays of 3-5 letters, considering that working memory capacity for verbal lists tends to be higher than 5 (e.g., Miller, 1956).

<div align="center">Discussion</div>

Intentionally encoding verbal-spatial relationships seemed to bring about a substantial improvement in accuracy of responses, compared with responses in a similar task which only afforded a possibility to maintain bindings, but did not actually require maintenance of bindings. Though some evidence of binding was observed in the *Bound Presentation* task, comparable to the *Bound* condition of Prabhakaran et al. (2000), discrimination accuracy in this task did not show the same pattern of improvement with respect to a *Separate* memory task as responses in the *Binding Recognition* task. Evidence for improved recognition under binding instructions does not depend on a simple main effect, which might be interpreted as reflecting a generic increase in effort during the *Binding Recognition* block[1]. Instead, an interaction between task instructions and set size suggests that intentionally maintaining binding may enhance memory for

---

[1] One could argue that the *Binding Recognition* task required more effort than the others because more information was to-be-remembered. One could as easily argue that the *Bound* and *Separate Presentation* tasks required more effort because two judgments were necessary on every trial, whereas in the *Binding Recognition* task, it was possible to consider the decision at probe one judgment. At the end of each session, participants were asked to indicate which task they found most fatiguing and most difficult. More participants found the *Bound Presentation* task to be most fatiguing (N=13) and most difficult (N=17) than the *Binding Recognition* task (Ns=11 and 6 respectively). One should not draw serious conclusions from participant's perceptions of their performance, which could be influenced by their perceived accuracy in each task or even mis-remembered, but note that these responses are at least inconsistent with the assumption that participants felt that the binding instructions added an extra cognitive burden.

component features themselves and help to preserve discrimination accuracy as information load increases.

These results, along with similar findings examining binding between visual features (Colzato et al., 2006) and between verbal items (Graf & Schacter, 1989) are consistent with a dissociation between the processes underlying incidental and intentional binding. This body of research suggests that, whatever the modality of the to-be-remembered stimuli, binding can occur on multiple levels, perhaps according to the suggestion of Colzato et al., that binding first occurs as a temporary link between activated features, and can become a more stable, integrated representation. A similar reconciling hypothesis was suggested by Wheeler and Treisman (2002) to explain why they observed a cost for remembering multi-feature visual objects, contrary to the results of Luck and Vogel (1997). The present research suggests that the process of forming a stable representation does not occur automatically; rather, attention to feature association during encoding plays an important role in facilitating the formation of a stable object representation. However, this study does not eliminate the possibility that some initial link between activated features occurs automatically. Distinguishing between these levels of binding might explain why binding is sometimes unimpaired by concurrent tasks (as in Allen, Baddeley, & Hitch, 2006; Allen, Hitch, & Baddeley, 2009). If some binding occurs automatically, participants in tasks with very short retention intervals might rely more on these temporary representations, which are believed to either remain intact for as long as 5000 ms or vanish completely from memory (Zhang & Luck, 2009). In the present study, memoranda were tested after a 5000-ms delay, thus instructions to

maintain and recognize binding might have been further reinforced by the need to maintain the representation over several seconds.

However, it is also possible that the modest evidence for binding in the *Bound Presentation* task reflects intentional binding on the part of a sub-set of participants. The possibility that only some participants adopt an explicit binding strategy is a serious problem for interpreting the results of implicit tests of memory for binding. In at least one instance, performing a concurrent task has been shown to impair binding measured implicitly with a task similar to Prabhakaran et al.'s (2000). Elsley and Parmentier (2009) compared response times for congruent and incongruent targets during performance of a concurrent task, and found that compared to single-task performance, performing a secondary tone memory task eliminated any implicit evidence of binding memory. As in the Prabhakaran et al. study, this design limits the inferences that can be made about the nature of cross-domain binding, because it is impossible to know whether participants intentionally encoded letter-location associations. These results could be taken as evidence that even incidental cross-domain binding requires attention, but it could also have been the case that the observed binding effect was due to an intentional binding strategy adopted by a sub-set of the sample, and that this process was affected by a concurrent, attention-demanding task. Using implicit measures of binding, it is impossible to distinguish between these possibilities, but using explicit measures of binding, such a comparison would be possible.

Prabhakaran et al.'s (2000) demonstration of cross-domain binding provided strong support for Baddeley's proposal of a domain-general, attention-driven episodic buffer (Baddeley, 2000). The results of the present research support some domain-general,

attentional component in working memory (or alternatively a unitary working memory model, such as that of Cowan (2005) or Jones, Beaman, & Macken (1996)) even more strongly. The finding that performance does not decrease at set size 5 for bound representations is consistent with the idea that as these features are grouped, more features may be maintained for the same cognitive cost. This is exactly what should happen if a domain-general store maintains stable representations of bound objects, or chunks of grouped features, (Cowan, 2001), and is consistent with Baddeley's hypotheses about how information is maintained by the episodic buffer (Repovš & Baddeley, 2006), namely that attentional resources should be required either for integrating feature information, maintaining representations, or both. This pattern was only observed when binding was necessary for successful task completion, not when binding was merely possible. This strongly suggests that the application of attention is necessary for these cognitive advantages to appear. Concurrently-presented verbal and spatial stimuli can also be maintained separately, not necessarily as bound object representations (Cowan et al., 2006; Morey, 2009); to observe the expected cognitive advantages of binding, it is necessary to foster circumstances that demand or reward explicit memory for binding, rather than rely on participants to voluntarily adopt a strategy of attending to bindings afforded at stimulus presentation.

In conclusion, measures of incidental binding do not seem to reflect potential cognitive advantages of encoding features as bound objects. Measures of incidental binding might reflect somewhat different processes than measures of intentional binding, but because implicit tests of binding allow for multiple strategies, it is difficult to

unambiguously interpret the results of these tests. One solution to these difficulties is to

measure binding explicitly.

Acknowledgments

References

Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: General, 135*, 298-313.

Allen, R. J., Hitch, G. J., & Baddeley, A. D. (2009). Cross-modal binding and working memory. *Visual Cognition, 17*, 83-102.

Baddeley, A. D. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences, 4*, 417-423.

Campo, P., Maestu, F., Ortiz, T., Capilla, A., Santiuste, M., Fernandez, A., & Amo, C. (2005). Time modulated prefrontal and parietal activity during the maintenance of integrated information as revealed by magnetoencephalography. *Cerebral Cortex, 15*, 123-130.

Colzato, L. S., Raffone, A., & Hommel, B. (2006). What do we learn from binding features? Evidence for multilevel feature integration. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 705-716.

Cowan, N. (2005). *Working Memory Capacity*. New York, NY: Psychology Press.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*, 87-185.

Cowan, N., Saults, J. S., & Morey, C. C. (2006). Development of working memory for verbal-spatial associations. *Journal of Memory and Language, 55*, 274-289.

De Pisapia, N., Slomski, J. A., & Braver, T. S. (2007). Functional specializations in lateral prefrontal cortex associated with the integration and segregation of information in working memory. *Cerebral Cortex, 17*, 993-1006.

Diana, R. A., Yonelinas, A. P., & Ranganath, C. (2008). The effects of unitization on familiarity-based source memory: Testing a behavioral prediction derived from neuroimaging data. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34*, 730-740.

Jones, D.M., Beaman, P., & Macken, W. J. (1996). The object-oriented episodic record model. In (S. Gathercole, ed.) *Models of Short-term Memory* (pp. 209-238). London, U.K.: Erlbaum.

Elsley, J. V., & Parmentier, F. B. R. (2009). Is verbal–spatial binding in working memory impaired by a concurrent memory load? *The Quarterly Journal of Experimental Psychology, 62*, 1696-1705.

Graf, P., & Schacter, D. L. (1989). Unitization and grouping mediate dissociations in memory for new associations. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 930-940.

Guérard, K., Tremblay, S., & Saint-Aubin, J. (2009). Similarity and binding in memory: Bound to be detrimental. *The Quarterly Journal of Experimental Psychology, 62*, 26-32.

Jacoby, L. L. (1991). A process dissociation framework: Separating automatic from intentional uses of memory. *Journal of Memory and Language, 30*, 513-541.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*, 279-281.

Macmillan, N. A., & Creelman, C. D. (2004). *Detection Theory: A User's Guide* (2nd ed.). Mahwah, NJ: Lawrence Erlbaum.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*, 81–97.

Morey, C. C. (2009). Integrated cross-domain object storage in working memory: Evidence from a verbal-spatial memory task. *The Quarterly Journal of Experimental Psychology, 62*, 2235-2251.

Nyberg, L., Habib, R., McIntosh, A. R., & Tulving, E. (2000). Reactivation of encoding-related brain activity during memory retrieval. *Proceedings of the National Academy of Sciences of the United States of America, 97*, 11120-11124.

Prabhakaran, V., Narayanan, K., Zhao, Z., & Gabrieli, J. D. E. (2000). Integration of diverse information in working memory within the frontal lobe. *Nature Neuroscience, 3*, 85-90.

Repovš, G., & Baddeley, A.D. (2006). The multi-component model of working memory: explorations in experimental cognitive psychology. *Neuroscience, 139*, 5-21.

Schneider, W., Eschmann, A., & Zuccolotto, A. (2002). *E-Prime User's Guide*. Pittsburgh, PA: Psychology Software Tools, Inc.

Treisman, A., & Zhang, W. (2006). Location and binding in visual working memory. *Memory & Cognition, 34*, 1704-1719.

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General, 131*, 48-64.

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language, 46*, 441-517.

Zhang, W., & Luck, S. J. (2009). Sudden death and gradual decay in visual working memory. *Psychological Science, 20*, 423-428.

Table 1

Separate Presentation Task

	Set Size 3	Set Size 5
Targets	.79 (.19)	.77(.22)
Letter Lures	.98 (.06)	.94 (.13)
Location Lures	.74 (.23)	.65 (.25)

Bound Presentation Task

	Set Size 3	Set Size 5
Congruent Targets	.94 (.14)	.86 (.20)
Recombined Targets	.87 (.22)	.81 (.22)
Letter Lures	.96 (.09)	.94 (.15)
Location Lures	.79 (.27)	.64 (.23)

Binding Recognition Task

	Set Size 3	Set Size 5
Targets	.90 (.12)	.87 (.12)
Recombined Lures	.91 (.17)	.89 (.20)
Letter Lures	1.00 (.00)	.98 (.06)
Location Lures	.82 (.22)	.87 (.18)

Note. Mean proportions correct (with standard deviations) for each task, by probe condition and set size. *N*=31.

Table 2
Separate Presentation Task

	Set Size 3	Set Size 5
Targets	1972 (641)	2060(616)
Letter Lures	1652 (561)	1847 (697)
Location Lures	1711 (550)	2168 (865)

Bound Presentation Task

	Set Size 3	Set Size 5
Congruent Targets	1802 (594)	1856 (563)
Recombined Targets	2071 (666)	2432 (1084)
Letter Lures	1659 (593)	2011 (962)
Location Lures	1722 (496)	2015 (743)

Binding Recognition Task

	Set Size 3	Set Size 5
Targets	1581 (436)	1786 (411)
Recombined Lures	1916 (513)	2057 (723)
Letter Lures	1399 (345)	1547 (413)
Location Lures	1566 (371)	1845 (448)

Note. Mean trimmed response times in ms (with standard deviations) for each task, probe condition, and set size. Incorrect responses and correct responses faster than 300 ms and slower than 7000 ms were excluded from analyses. N=28. Participants with no data in any cell after trimming were excluded list-wise as in the corresponding analyses of variance.

Figure Captions

Figure 1. Trial events for the A) Separate Presentation, B) Bound Presentation and Binding Recognition tasks. The probes in the Separate Presentation procedure are targets. In the Bound Presentation procedure, the probes would be targets in the Bound Presentation task (recombined targets) and recombined lures in the Binding Recognition task. On trials with 5 letters and locations, the study display remained onscreen for 2500 ms.

Figure 2. Proportions correct on lure trials in which one feature at test was new. Explicit binding instructions seem to protect against committing false alarms to location lures, as evinced by the comparatively strong performance on location lures in the *Binding Recognition Task*. *N*=31, error bars are standard errors of the mean.
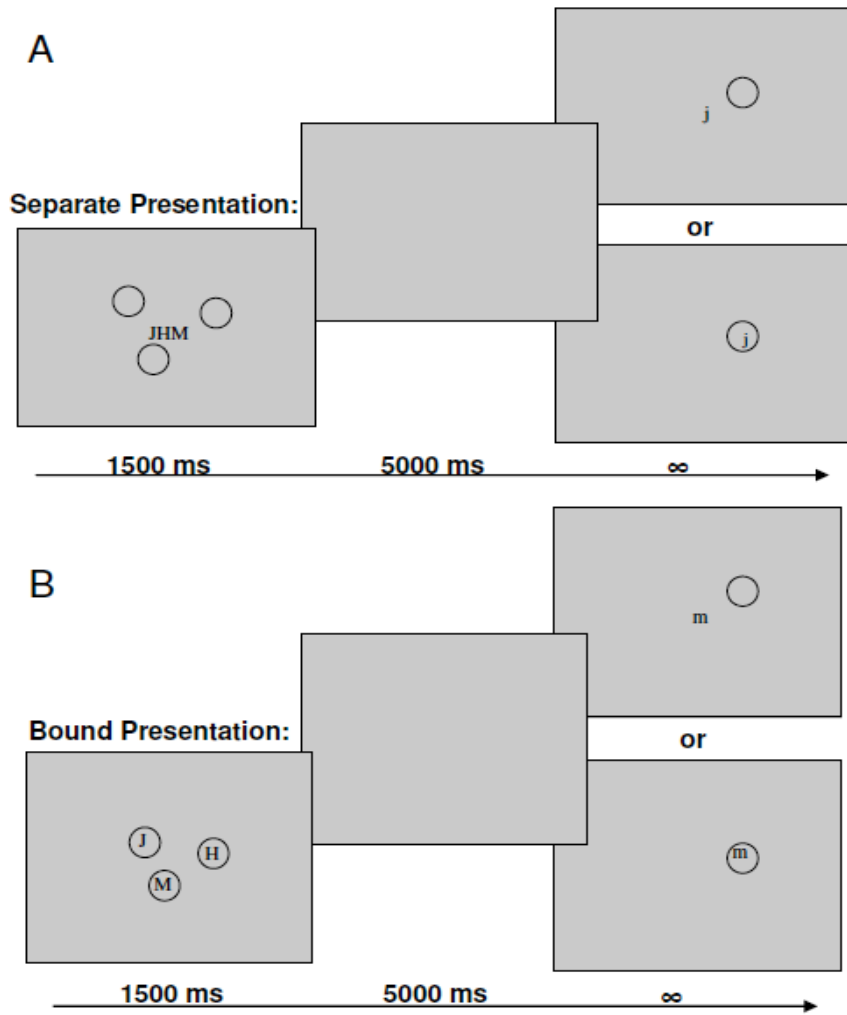
Figure 1

Figure 2