Examining the role of attention during feature binding in visuospatial working memory

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Abstract

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The current experiments address the enduring debate regarding the role of attention in feature binding in visuospatial working memory by considering the nature of the to-be-bound features, i.e., whether they are intrinsic (integrated within the object, such as its color and shape) or extrinsic (not part of the object, such as its spatial location). Specifically, arrays of different-colored shapes in different locations were followed by probed recall: One feature of the probed object prompted recall of one of its remaining two features (e.g., a shape probe prompts recall of color, with the probe displayed at the center of the screen [i.e., without spatial information]) to test the retention of intrinsic (shape, color) and extrinsic (location) features. During the retention interval, we manipulated attention via disruption (Experiment 1) and retro-cues (Experiment 2) to determine their impacts on binding errors, as estimated from a three-parameter mixture model fit to recall error (i.e., the distance between the target and response). Disrupting central versus peripheral attention in Experiment 1 did not respectively increase extrinsic and intrinsic binding errors as predicted, but disrupting central attention reduced target memory of the extrinsic feature relative to a no-disruption baseline. Guiding attention via extrinsic and intrinsic retro-cues in Experiment 2 did not respectively reduce extrinsic and intrinsic binding errors as predicted, but we observed retro-cue benefits to target memory that did not distinguish between extrinsic and intrinsic features. Thus, this work highlights that attentional resources aid target memory, with no consistent distinction between intrinsic and extrinsic features.

Keywords: working memory, attention, feature binding, retro-cues

Significance

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Is attention necessary to bind together bits of information that are briefly held in working memory? We addressed this question through a novel paradigm that manipulated whether features probed for recall are extrinsic (not part of an object, e.g., location) or intrinsic (part of an object, e.g., color or shape) while disrupting or guiding attention to those features. We found that manipulating attention impacted target recall largely regardless of whether the features were intrinsic or extrinsic to the target. This suggests that the use of attention in working memory does not distinguish between intrinsic and extrinsic feature binding.

Fundamental questions of human memory concern how individuals are able to focus their attention and hold in mind no-longer perceptually available items and how features of that item (e.g., color, shape, orientation and relationship to other items in mind) are integrated together into a cohesive representation. Working memory (WM) has been an instrumental concept for understanding these questions given its ascribed role in maintaining and manipulating information in service to goal-related cognition. For example, in a typical visuospatial WM study, participants are often asked to briefly maintain an array of multi-feature objects (e.g., red circle, green triangle, blue square) to be immediately retrieved thereafter (e.g., via change detection, determining whether the probe of a red triangle was presented). A prominent yet still unresolved question in the literature concerns whether integrating the features of these objects, or feature binding, relies on attention or is relatively automatic (Allen et al., 2006; Baddeley et al., 2011; Elsley & Parmentier, 2009; Hitch et al., 2020; Vogel et al., 2001; Wheeler & Treisman, 2002). In the current study, we investigated this issue through two predominant methods of manipulating attention in the WM literature: disrupting attention and guiding attention.

Disrupting Attention and Feature Binding

A great deal of prior research has followed the logic that if feature binding requires attention, then an attention-demanding task should more strongly disrupt the maintenance and recall of bindings (e.g., remembering a red circle) compared to individual features (e.g., remembering red and circle individually). Much of this research has demonstrated that attentionally-demanding tasks (e.g., judging tones, counting backwards) similarly impair the recall of individual features and their bindings, thus suggesting that feature binding may not require additional attentional resources (Allen et al., 2006, 2012; Langerock et al., 2014; Morey & Bieler, 2013; Vergauwe et al., 2014). However, other research has reported contradictory findings. For example, some work has suggested that attention-demanding tasks do indeed impair feature binding disproportionately compared to individual features, thus suggesting that feature binding in WM requires additional attentional resources (Brown & Brockmole, 2010; Elsley & Parmentier, 2009; Zokaei et al., 2014). What may cause such a discrepancy?

First, the nature of the to-be-bound features may be an important factor in whether feature binding requires attention. A great deal of the prior work supporting the notion that feature binding is automatic has used color-shape bindings. According to Ecker and colleagues (2013), such *intrinsic* feature bindings (i.e., information belonging to an object) can be distinguished from *extrinsic* feature bindings (i.e., relational, contextual information of an object, such as its spatial location). This distinction between intrinsic and extrinsic feature binding has also been referred to as conjunctive versus relational binding, respectively (Kirmsse et al., 2018; van Geldorp et al., 2015). Ecker and colleagues suggested that binding of intrinsic features (e.g., color, shape, orientation) may be automatic in WM, whereas binding of extrinsic features (e.g., spatial/temporal context) may require additional, effortful attentional resources. Consistent with this assertion, some prior work has indeed shown a role of attention for extrinsic bindings (Ecker et al., 2013; Elsley & Parmentier, 2009), whereas attentionally-demanding tasks have no differential impact on intrinsic feature binding (e.g., color-shape bindings) compared to retaining the individual features, as explained previously (e.g., Allen et al., 2006, 2012). Conversely, other work has suggested that visual interference can impact visual WM (Teng & Kravitz, 2019), especially intrinsic feature bindings (Ueno et al., 2011). Thus, it may be the case that disrupting central attention specifically impairs extrinsic binding but not intrinsic binding, whereas disrupting peripheral, visual attention impairs intrinsic binding for visuospatial features. This distinction may occur if extrinsic features are prioritized and provide the foundation for intrinsic information to be automatically encoded.

For example, Schneegans and Bays (2017) demonstrated that intrinsic features may rely on spatial-temporal context in order to become feature-bound representations in WM (see also Pertzov & Husain, 2014).

A second potential source of discrepancy concerns the measurement of feature binding. Much of the cited previous research has used change detection, wherein participants are presented with a test probe that may be the same as what had been presented or a lure, such as a recombination of features. A potential problem with this approach is that using observed performance may only offer a coarse measure of feature binding that is conflated with extraneous processes like guessing. For example, a participant may correctly identify a red circle had been presented, but it is unclear whether this indicates correct intrinsic binding or other processes, such as guessing. Instead, measuring recall using a continuous scale (e.g., recalling the precise color or location of a probe) allows decomposition of the participants' observed recall error (e.g., the deviation of the recalled color from the true target color) according to a mixture of underlying components. Most relevantly, Bays and colleagues' (2009) model assumes three sources of error: memory for the target item with a certain precision, memory for one of the presented but unprobed items (henceforth, binding errors), or random guessing when no memory is available. Previous work applying this mixture model to recall has indicated that binding errors may be more common when recalling extrinsic versus intrinsic features (Schneegans & Bays, 2017) or when attentional demands are high (Zokaei et al., 2014). For example, Zokaei and colleagues (2014) showed that varying the demand of an unrelated visual search task during the retention interval of a visuospatial WM task primarily impacted binding errors, whereas precision and random guessing were largely unaffected. Thus, the parameter estimate representing binding errors when applying a mixture model may be more sensitive than observed performance in determining the role of attention in feature binding.

Guiding Attention and Feature Binding

Alongside the substantial number of studies that have explored the role of attention in feature binding via disrupting attention, another approach is to manipulate attention through instructions to prioritize some memoranda. For example, presenting retro-cues during the retention interval to indicate the to-be-tested item of the previously presented stimulus array provides a means of understanding how no-longer perceptually presented information is brought into the focus of attention (see Souza & Oberauer, 2016 for review). Retro-cue studies often show a retro-cue benefit, such that retro-cues improve visuospatial WM performance compared to a no-cue or neutral-cue baseline, thereby demonstrating the benefits of attention in WM. Furthermore, the retro-cue benefit seems specific to reducing binding errors (Souza, 2016), thus evidencing the importance of attention to facilitate binding in WM. There is some evidence that the retro-cue benefit is weaker for intrinsic (e.g., shape) compared to extrinsic (e.g., spatial-location) retro-cues (Arnicane & Souza, 2021; but see Heuer & Schubö, 2016). This may indicate that intrinsic retro-cues are less effective overall than extrinsic retro-cues or perhaps are just less effective for extrinsic bindings compared to intrinsic bindings, but this has not yet been explicitly tested. Coupled with the aforementioned research pointing to a potential distinction between the effects of disrupting central versus peripheral attention on extrinsic and intrinsic binding, respectively, these findings suggest a dissociation in how guiding attention may impact different types of feature binding in WM. Explicitly investigating this dissociation would provide novel insight into the long-standing theoretical puzzle regarding how representations are established in WM.

Current Study

The current study clarifies the role of attention in feature binding in WM by investigating whether manipulating attention via disruption (Experiment 1) and retro-cues (Experiment 2) differently impacts the maintenance of intrinsic and extrinsic feature bindings (Table 1). Both experiments required participants to maintain a set of multi-feature objects (i.e., different-colored shapes) presented in random locations around an invisible circle, followed by probed recall of one of the items. Participants were prompted to recall one of the features based on one of the two remaining features (e.g., a shape probe may prompt recall of color, with the probe displayed at the center of the screen [i.e., without spatial information]). Experiment 1 disrupted different types of attention (central versus perceptual) whereas Experiment 2 manipulated focused attention via different types of retro-cues (intrinsic [color, shape], extrinsic [spatial]). Both experiments had a no-disruption/no-cue baseline condition. Recall error was fit with a hierarchical Bayesian three-parameter mixture model (Bays et al., 2009; Oberauer et al., 2017) to estimate latent cognitive parameters underlying observed memory performance, most relevantly, the parameter reflecting binding errors.

We hypothesized that if extrinsic and intrinsic feature binding are distinguishable, then a central-attention demanding task should increase binding errors when recalling extrinsic features, but not intrinsic features, whereas a peripheral-attention demanding task should increase binding errors when recalling intrinsic features, but not extrinsic features (Experiment 1). Furthermore, extrinsic retro-cues should reduce binding errors compared to a no-cue baseline, whereas there should be no impact of intrinsic retro-cues on binding errors when recalling extrinsic features (Experiment 2). However, if there is no distinction between extrinsic and intrinsic binding and both are automatic, then binding errors should be similar regardless of the nature of the attentional demand (Experiment 1) or retro-cue (Experiment 2).

Table 1

Hypotheses and Predictions for Each Feature Binding Type.

Feature binding type	Hypotheses	Experiment (E) Predictions
Extrinsic	Central attention may be required to selectively maintain extrinsic bindings	(a) Disrupting central attention should selectively increase extrinsic binding errors but not intrinsic binding errors relative to a no-disruption baseline (E1).
	Benefits of guiding attention may be specific to extrinsic binding.	(b) Guiding attention via extrinsic retro-cues should reduce extrinsic binding errors but not intrinsic binding errors relative to a no-cue baseline (E2).
Intrinsic	Domain-specific, peripheral attention may be required to selectively maintain intrinsic features.	(c) Disrupting peripheral attention should selectively increase intrinsic binding errors but not extrinsic binding errors relative to a no-disruption baseline (E1).
	If intrinsic binding errors are reduced during the presentation of an intrinsic retro-cue, then attention is required for intrinsic feature binding.	(d) Guiding attention via an intrinsic retro-cue should reduce intrinsic binding errors relative to a no-cue baseline (E2).

Experiment 1

Method

Participants. We recruited 24 unique participants per experiment from Prolific in exchange for UK£7.50 per hour of participation. Participants in both experiments were British, aged 18-35, and had normal or corrected-to-normal hearing and vision and normal color vision. Participants in both experiments were required to pass an initial color blindness test; those who did not pass it were not allowed to proceed further in the experiment.[1] Participants provided informed consent and were fully debriefed in both experiments. The experiments were approved by the University of Essex ethics committee and are in accordance with the Helsinki ethical

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[1] Note that we did not define what we meant by "pass" at stage 1. The Ishihara color blindness test (e.g., http://www.colorvisiontesting.com/ishihara) that we used typically requires 100% pass rate (e.g., Loaiza & Souza, 2019) and thus we used this criterion for participants to proceed further with the experiment.

guidelines (World Medical Association, 2013). Table 2 shows the final sample details, with details of the exclusions explained further on in the next sections. The anonymized raw data of all the participants are available on the OSF.

Table 2

Sample Details and Exclusions

	Exp. 1	Exp. 2
Total N attempted	61	52
N exclusions:	37	28
1. Failed to pass the first color blindness/visual/auditory screening phase*	30	10
2. Restarted in the middle of the experiment*	0	4
3. Assigned to a counterbalance order that was already complete*	1	10
4. Incomplete data (e.g., from leaving the experiment)*	6	8
Final N for analysis after exclusions	24	24

* Note that these may not sum to the total N excluded given that participants could fall under more than one category for exclusion.

We determined the sample size and the number of trials per condition by simulating 150 experiments based on the parameter estimates derived from fitting a hierarchical Bayesian three-parameter mixture model to the raw data of Souza and Oberauer (2017, Experiment 1A) and Souza (2016), whose designs we closely follow in Experiments 1 and 2, respectively. For the sake of brevity, the rationale, analysis scripts, and results of the simulations for both Experiments 1 and 2 can be found on the OSF.

Materials and Procedure. The stimuli and the open-source scripts for all the experiments are available on the OSF, and a short example can be tried at this link: https://tinyurl.com/RegReportAPP. Both experiments were conducted online through lab.js (Henninger et al., 2021) hosted on the JATOS server Mindprobe (https://jatos.mindprobe.eu; Lange et al., 2015). After a brief demographic questionnaire, participants took part in two practice phases of the visual and auditory tasks, respectively, that served as the later attention disruption in the critical task. Participants who did not pass either practice phase were not allowed to proceed further as it suggested that they did not have sufficient visual or auditory abilities to complete the experiment.[2] Thereafter, participants completed three blocks of a visuospatial WM task, with four practice trials preceding each block and 150 critical trials presented per block (50 of each probe-target type, randomly intermixed)[3]. Each trial began with a fixation cross presented for 500ms followed by an array of six colored shapes simultaneously presented in random locations around an invisible circle for 1000ms. The color, shape, and location features of each item were randomly sampled from 360° of continuous values, with a minimum of 15° of separation in each feature domain from the other memoranda in the array: The colors were sampled along a circle in the CIELAB color space (with L = 70, a = 20, b = 38, and radius = 60), the shapes were drawn randomly from a shape wheel (Li et al., 2020), and the locations were drawn randomly along an invisible circle (radius = 150[4]).

Following Souza and Oberauer (2017, Experiment 1), the nature of the retention interval (2500ms in total) varied according to the attention disruption manipulation: During the no-disruption block, the retention interval remained blank with the fixation cross at the center of the screen. During the peripheral-attention disruption block, the fixation cross altered its shade from white to light grey for 100ms during 50% of the trials at least 500ms after the offset of the memory array and 900ms before the onset of the retrieval phase; participants were instructed to detect whether the fixation cross changed its shade by pressing the spacebar (Figure 1). During the central-attention disruption block, participants were asked to indicate whether two successively

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[2] Note that we did not define what we meant by "pass" at stage 1, and thus we decided that at least 80% correct was required given that this is a typical exclusion criteria in dual-task WM experiments (e.g., Ricker & Vergauwe, 2022).

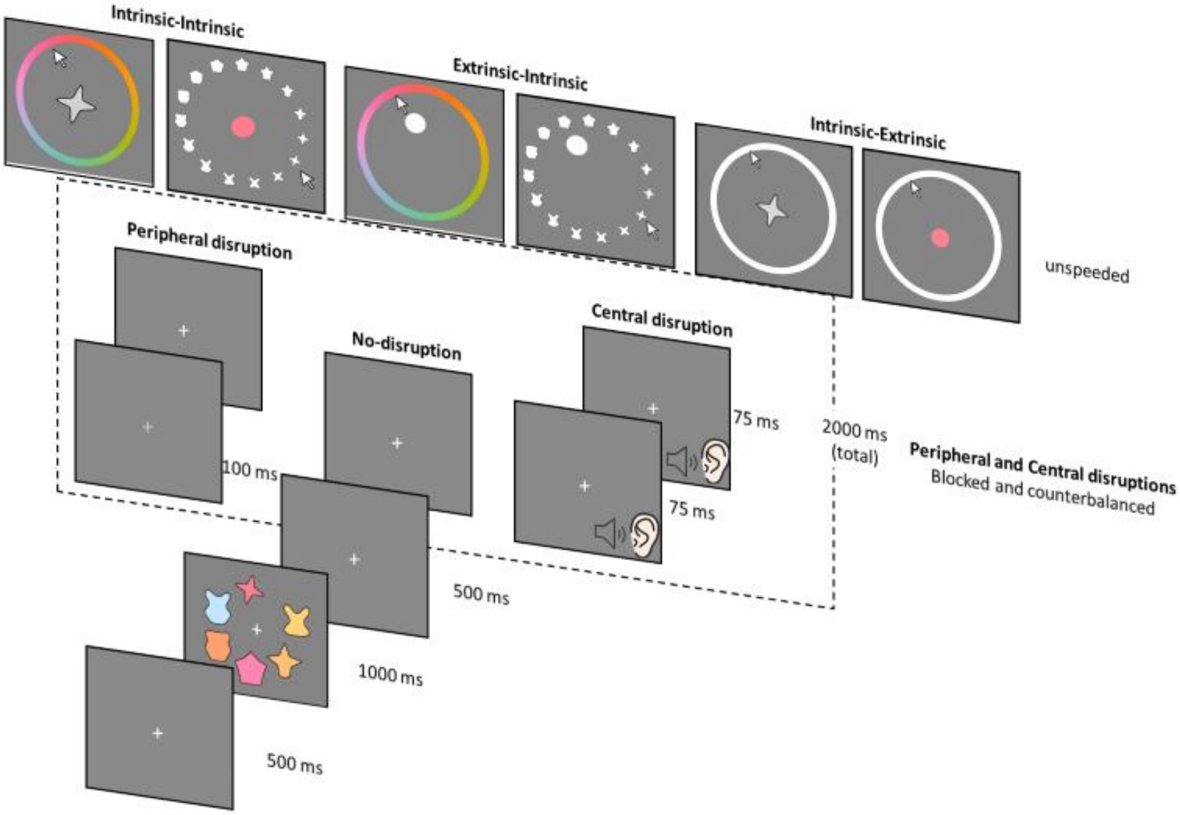
[3] Note that due to a server upload error, there were several participants for whom some trials were missing at random (*N* = 1 and 3 in Experiments 1 and 2, respectively). We decided to include participants who had at least 80% of trials per cell of the design.

[4] Note that we had written radius = 40 here at stage 1, but this was a typo. A radius of 150 is typical (e.g., Loaiza & Souza, 2019) and allowed better spacing of the memoranda in the array.

presented tones (75ms each) were of a lower (600 Hz) or higher (675[5] Hz) pitch by pressing the left- and right-arrow keys, respectively. The first tone was presented 500 ms after the offset of the memory array, with participants allowed 925ms to respond before the second tone was presented with a 925ms response period.

Figure 1

Example Trial Sequence from Experiment 1 that Varied Attention Disruption (None, Peripheral, Central) and Probe-Target Type (Intrinsic-Intrinsic, Extrinsic-Intrinsic, Intrinsic-Intrinsic).



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[5] Note that we had written 610 Hz in the revised stage 1. However, all the participants failed the first screening phase, suggesting that it was impossible to distinguish tones presented at 600 and 610 Hz. We conducted an additional pilot experiment (see OSF and Online Supplementary Materials (OSM)) to determine that 600 and 675 Hz, with additional opportunities for feedback and practice during the screening phase, would make the task challenging albeit still possible for participants.

During the retrieval phase, participants were probed with one feature from one item of the memory array to prompt recall of one of the item's two remaining features. For each probe-target type, retrieval occurred along a continuous color, shape, or location wheel (depending on the to-be-recalled target feature), wherein participants used a mouse to click along the corresponding wheel[6]. For the intrinsic-intrinsic probe-target condition, the participants were probed with either the color (presented as a circular dot) or shape (presented in dark grey) at the center of the screen in order to recall the item's corresponding shape or color, respectively. For the extrinsic-intrinsic probe-target condition, participants recalled the color or shape feature when probed with the location of the corresponding item (i.e., a dark-grey circular disk appearing in the location of the probed item). Finally, for the intrinsic-extrinsic probe-target condition, participants recalled the location of the probed item with either the color (presented as a circular dot) or shape (presented in dark grey) at the center of the screen. The recall attempt was unspeeded, and the instructions emphasized that participants should prioritize accuracy over speed in their responses. After the practice trials and every 10 test trials, participants received feedback about their average recall accuracy (expressed as a percentage of their mean reproduction error, i.e., 100 – 100 * mean error/180)[7] and, depending on the block, their average accuracy on the disruption task. There was an inter-trial interval of 1000ms followed by a screen that said "Ready?" to which participants pressed the spacebar to proceed to the next trial. Participants were offered a break twice during each block, after every 50 trials.

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[6] Recall error was slightly underestimated by about 3° in Experiment 2 due to a programming error. Given that this error was unsystematic, the general pattern of results from Experiment 2 is unlikely to be affected.

[7] For several participants in Experiment 2, the recorded recall error of the shape target was systematically off by 90°. This was corrected during analysis and did not affect the experiment except that these participants' feedback was slightly incorrect.

Design. The experiment followed a 3 (attention disruption: none, peripheral, central) x 3 (probe-target type: intrinsic-intrinsic [color-shape, shape-color], extrinsic-intrinsic [location-color, location-shape], intrinsic-extrinsic [color-location, shape-location]) within-subjects design. The attention disruption manipulation was blocked and counterbalanced[8] across participants, with the nature of the probe-target type varying randomly within each block.

Data Analysis. The analysis scripts to reproduce the results for all the experiments are available on the OSF. For each experiment, observed recall error data collected was fit with a three-parameter hierarchical Bayesian mixture model (Loaiza & Souza, 2019; Oberauer et al., 2017). The model assumes that the distribution of observed responses reflects the contributions of (1) the probability that the tested feature is held within WM with a (2) specific precision, and (3) the probability of misbinding or (4) guessing when the participant has not stored the information in WM. Our hypotheses pertained to binding errors, or the probability of recalling non-target but presented features from the array. The model was fit using rjags (Plummer, 2016) via Markov Chain Monte Carlo sampling. We verified good convergence and conducted posterior predictive checks to ensure appropriate model fit. We report posterior estimates of each parameter in Figures 2, 4, and 5, and the posterior differences between the conditions for each parameter (and their 95% HDIs) in Tables 3 and 4.

Results and Discussion

Table 3 and Figure 2 summarize our results. When recalling the extrinsic feature (i.e., the intrinsic-extrinsic condition), binding errors were *lower* in the central (estimated difference = -0.32 [-0.51, -0.31]) and peripheral (estimated difference = -0.22 [-0.43, -0.01]) conditions

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[8] Note that there were instances in both experiments where participants were inadvertently assigned to a counterbalance order that had already been completed (e.g., in Experiment 1, six counterbalance orders required four participants each to equal 24 total participants, but one additional participant was assigned to one of the orders). In these instances, these additional participants were excluded from analysis in both experiments (see Table 2).

compared to the no-disruption baseline. Closer inspection of Figure 2C reveals that this result may reflect an artifact of particularly high binding errors at baseline in the intrinsic-extrinsic condition. Furthermore, there was no credible effect of disrupting central attention when probed with the extrinsic feature (i.e., the extrinsic-intrinsic condition; estimated difference = 0.00 [-0.26, 0.28]). These results thus conflict with our first hypothesis, instead showing that disrupting central attention did not have any specific detrimental effect on binding errors of extrinsic features.

Figure 2

Posterior Parameter Estimates of the Bayesian Hierarchical Mixture Model for the Probability of Target Memory (A), Memory Precision (B), Probability of a Binding Error (C) and Probability of Guessing (D) in Experiment 1. Larger Dark Circles Indicate Group Means, Smaller Faded Circles Indicate Individual Means, and the Error Bars Show the 95% HDIs of the Posterior.

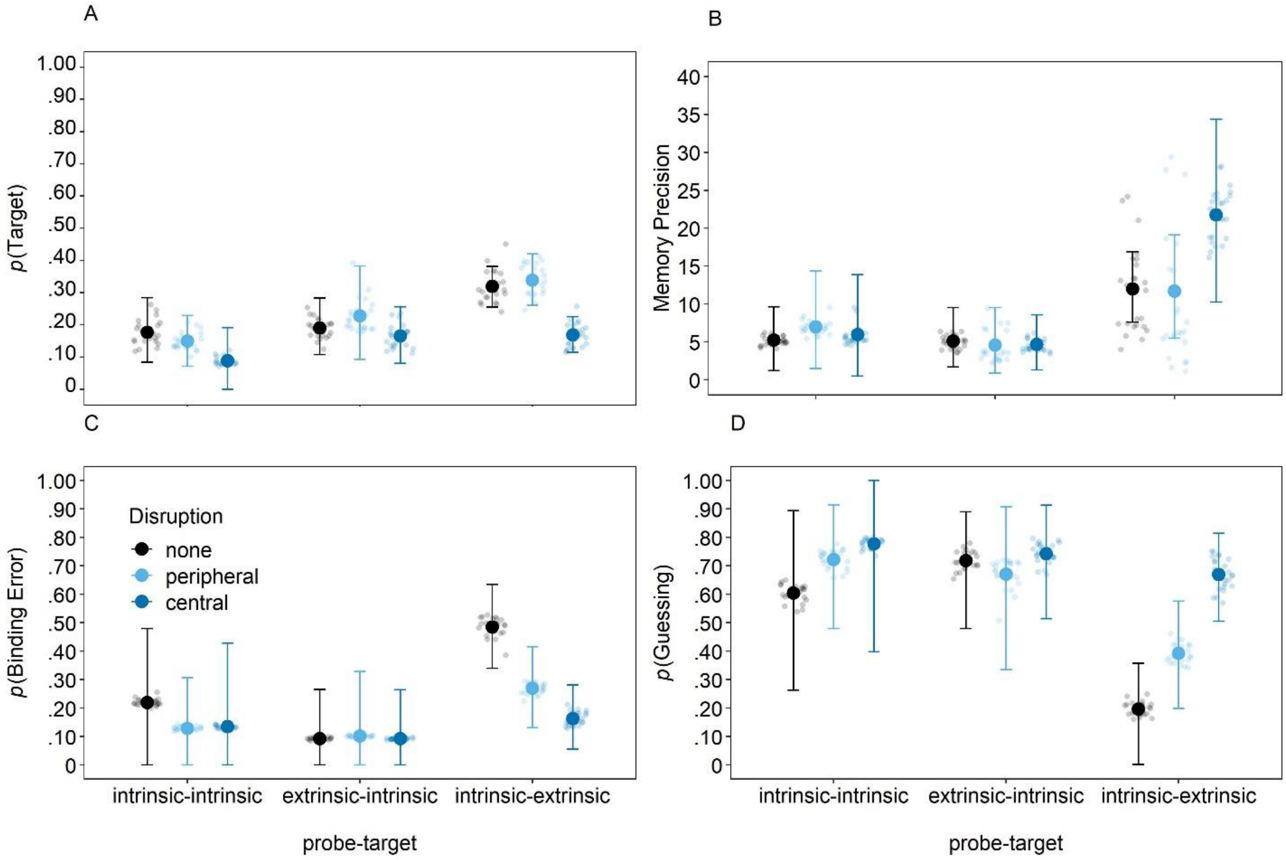


Table 3

Summary of Mean Differences [and 95% HDIs] in Each Memory Parameter Across Experiments.

Exp.	Probe-target type	Baseline/None vs.	*P*(Target)	*P*(Binding error)	*P*(Guessing)	Precision
1	Intrinsic-intrinsic	Central	-0.09 [-0.24, 0.06]	-0.09 [-0.48, 0.32]	0.17 [-0.32, 0.70]	0.73 [-7.46, 10.47]
		Peripheral	-0.03 [-0.16, 0.11]	-0.09 [-0.44, 0.24]	0.12 [-0.31, 0.56]	1.75 [-6.37, 11.29]
	Extrinsic-intrinsic	Central	-0.02 [-0.16, 0.10]	0.00 [-0.26, 0.28]	0.02 [-0.34, 0.36]	-0.44 [-6.38, 5.43]
		Peripheral	0.04 [-0.13, 0.23]	0.01 [-0.30, 0.34]	-0.05 [-0.50, 0.38]	-0.55 [-7.33, 6.49]
	Intrinsic-extrinsic	Central	**-0.15 [-0.24, -0.07]**	**-0.32 [-0.51, -0.13]**	**0.47 [0.23, 0.71]**	9.77 [-2.82, 23.46]
		Peripheral	0.02 [-0.08, 0.12]	**-0.22 [-0.43, -0.01]**	0.20 [-0.07, 0.47]	-0.30 [-8.59, 8.74]
2	Intrinsic-intrinsic	Color cue	**0.42 [0.30, 0.53]**	-0.01 [-0.20, 0.15]	**-0.41 [-0.63, -0.14]**	4.55 [-4.79, 12.63]
		Shape cue	**0.41 [0.29, 0.53]**	0.00 [-0.21, 0.17]	**-0.41 [-0.65, -0.14]**	2.79 [-6.90, 11.13]
		Location cue	**0.46 [0.31, 0.59]**	0.00 [-0.22, 0.23]	**-0.46 [-0.71, -0.18]**	-4.36 [-13.12, 2.93]
	Extrinsic-intrinsic	Color cue	**0.28 [0.15, 0.41]**	-0.13 [-0.36, 0.06]	-0.15 [-0.42, 0.14]	5.68 [-0.06, 10.74]
		Shape cue	**0.30 [0.17, 0.42]**	-0.08 [-0.33, 0.12]	-0.22 [-0.50, 0.08]	5.85 [-0.17, 11.59]
		Location cue	**0.26 [0.11, 0.42]**	-0.05 [-0.32, 0.20]	-0.21 [-0.53, 0.14]	0.76 [-5.51, 6.28]
	Intrinsic-extrinsic	Color cue	**0.22 [0.10, 0.35]**	-0.16 [-0.40, 0.06]	-0.06 [-0.35, 0.25]	1.53 [-1.46, 4.50]
		Shape cue	0.08 [-0.03, 0.20]	0.10 [-0.14, 0.34]	-0.19 [-0.48, 0.12]	1.48 [-1.46, 4.22]
		Location cue	**0.57 [0.47, 0.65]**	**-0.26 [-0.47, -0.08]**	**-0.30 [-0.54, -0.03]**	**5.06 [1.98, 7.98]**

Note. Effects in boldface font indicate credible effects.

Furthermore, there were no credible effects of either central (estimated difference = -0.09 [-0.48, 0.32]) or peripheral (estimated difference = -0.09 [-0.44, 0.24]) disruption on binding errors when only the intrinsic features were relevant (i.e., the intrinsic-intrinsic condition). However, given the prior results that central attention disruption had no impact on extrinsic features, we do not interpret these intrinsic feature results too strongly. Overall, we failed to observe support for our hypotheses that disrupting central versus peripheral attention would differently impact binding errors of intrinsic and extrinsic features.

Although our hypotheses focused on binding errors, we also report on target memory (Figure 2A), memory precision (Figure 2B), and guessing (Figure 2D). Disrupting central attention impaired target memory (estimated difference = -0.15 [-0.24, -0.07]) and increased guessing (estimated difference = 0.47 [0.23, 0.71]) relative to a no-disruption baseline in the intrinsic-extrinsic condition. There were no other credible effects of disruption. Thus, the effects of disrupting central attention for recalling an extrinsic feature (i.e., location) appeared to be specific to target memory and guessing rather than binding errors as we had initially predicted.

To be certain that participants did not simply give up during the task, we verified that proportion accuracy on the peripheral (*M* = 0.95, *SD* = 0.10) and the central (*M* = 0.92, *SD* = 0.05) attention disruption tasks was very high. Coupled with the forthcoming results of Experiment 2, it is thus more likely that randomizing shape and location as additional encoded features alongside color, as well as intermixing the different probe-target conditions, likely yielded a more challenging task overall for participants. We return to the theoretical implications of this in the General Discussion. Notwithstanding, the current results suggest that disrupting central versus peripheral attention did not impact binding errors as we had predicted, but disrupting central attention may specifically impact target memory and guessing when recalling extrinsic features.

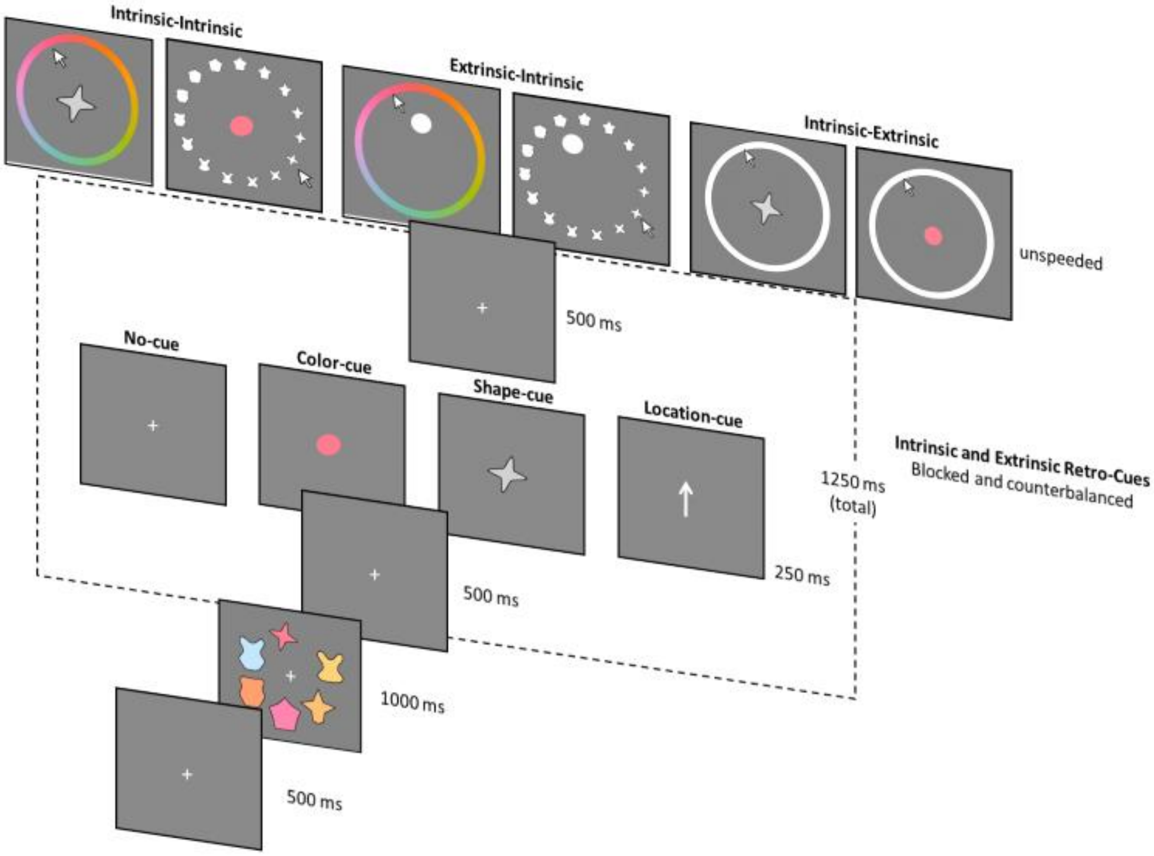
Experiment 2

Method

Materials and Procedure. The materials, procedure, and analysis for Experiment 2 were similar to Experiment 1, except that retro-cues were manipulated during the retention interval (Figure 3). Depending on the block, the retention interval (1250ms) entailed one of four retro-cue conditions. Either the retention interval remained blank with the fixation cross presented at the

Figure 3

Example Trial Sequence from Experiment 2 that Varied Retro-Cues (None, Color, Shape, Location) and Probe-Target Type (Intrinsic-Intrinsic, Extrinsic-Intrinsic, Intrinsic-Intrinsic).



center of the screen (no-cue condition), or a retro-cue was displayed at the center of the screen for 250ms following the offset of the memory array (500ms) and preceding the onset of the retrieval phase (500ms). The retro-cue indicated with 100% validity which of the items from the memory array would be tested. Specifically, either a circular colored-dot (color retro-cue), a dark-grey shape (shape retro-cue), or an arrow pointing to the location of the to-be-tested item (location retro-cue) was presented, depending on the block. There were 50 trials of each retro-cue/probe-target condition.

Design and Data Analysis. The experiment followed a 4 (retro-cue type: none, color, shape, location) x 3 (probe-target type: intrinsic-intrinsic [color-shape, shape-color], extrinsic-intrinsic [location-color, location-shape], intrinsic-extrinsic [color-location, shape-location]) within-subjects design. The retro-cue manipulation was blocked and counterbalanced across participants, with the nature of the probe-target type varying randomly within each block. The analytic approach was the same as Experiment 1.

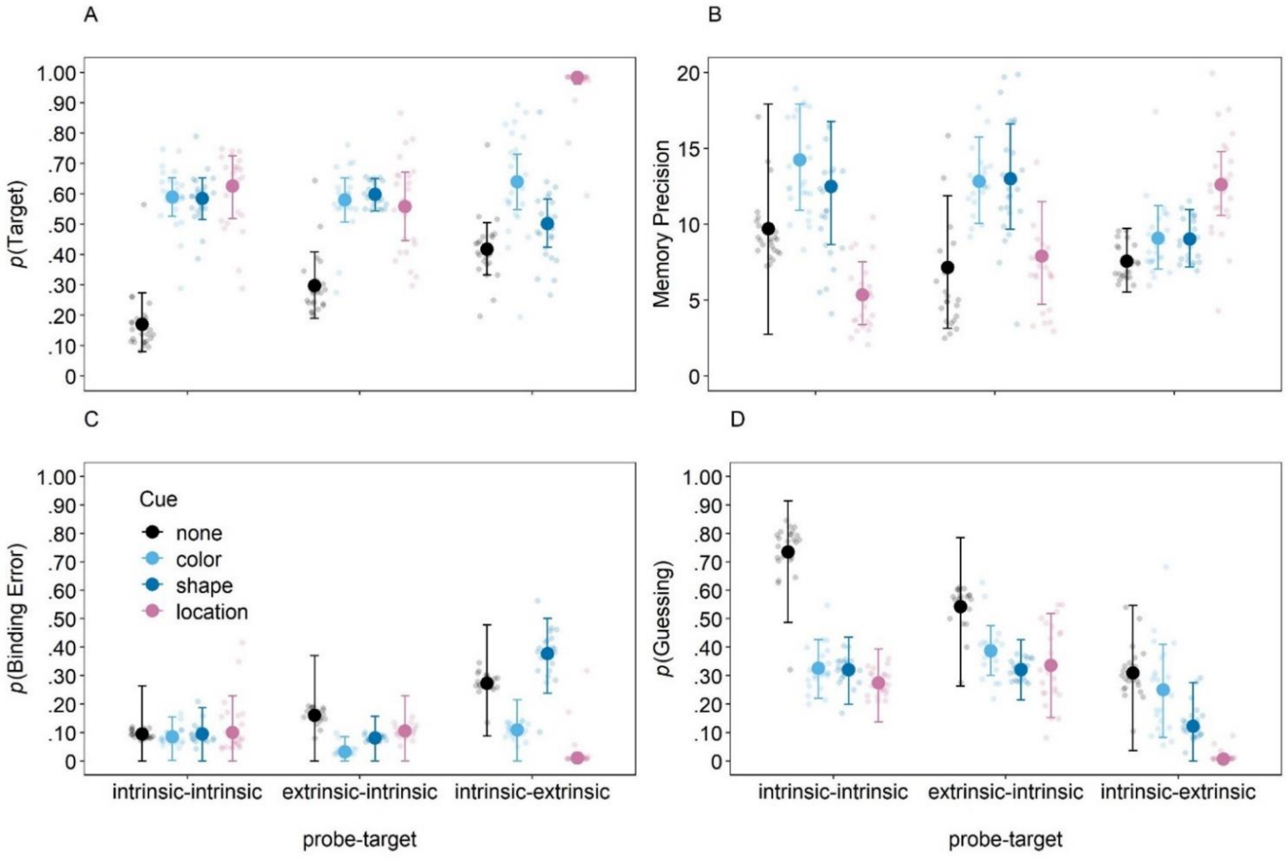
Results and Discussion

Table 3 and Figure 4 summarize our results. We found that extrinsic (i.e., location) retro-cues reduced binding errors in the intrinsic-extrinsic condition compared to the no-cue baseline (estimated difference = -0.26 [-0.47, -0.08]). Although consistent with our hypothesis, in hindsight, we cannot interpret this result given that, in this condition, the retro-cue perfectly matched the target for recall, as was the case in several other conditions (i.e., color retro-cues probing recall of color and shape retro-cues probing recall of shape). We return to this issue in the exploratory analyses section. There were no further credible retro-cue effects in binding errors.

Although our hypotheses focused on binding errors, we once again report on target memory (Figure 4A), memory precision (Figure 4B), and guessing (Figure 4D). Overall, we observed credible retro-cue benefits to nearly all target memory parameters except for shape cues in the intrinsic-extrinsic condition (estimated difference = 0.08 [-0.03, 0.20]). Furthermore, all the retro-cues reduced guessing in the intrinsic-intrinsic condition, but Figure 4D shows that guessing was particularly high in this condition's no-cue baseline. Overall, the benefits of retro-cues were most specific to target memory, and most importantly, their efficacy generally did not discriminate between the nature of the retro-cue (whether intrinsic [color, shape] or extrinsic [location]) nor the nature of the recalled features (intrinsic or extrinsic).

Figure 4

Posterior Parameter Estimates of the Bayesian Hierarchical Mixture Model for the Probability of Target Memory (A), Memory Precision (B), Probability of a Binding Error (C) and Probability of Guessing (D) in Experiment 2. Larger Dark Circles Indicate Group Means, Smaller Faded Circles Indicate Individual Means, and the Error Bars Show the 95% HDIs of the Posterior.



Exploratory analyses. Given our fully-crossed design, there were trials in which the presented retro-cue matched the to-be-recalled target-feature (e.g., presenting a color retro-cue and thereafter recalling color). To understand whether this affected the just-reported confirmatory analysis results, we conducted an additional exploratory analysis that excluded any cue-target matches (i.e., color-cue/color-target, shape-cue/shape-target, location-cue/location-target) and then refit the model for each specific probe-target combination (Figure 5 and Table 4).

We observed that location retro-cues were the most consistently beneficial to target memory, except in the location-color condition (estimated difference = 0.28 [-0.02, 0.59]). Conversely, color and shape retro-cue benefits were specific to the shape-location condition (estimated differences = 0.35 [0.19, 0.50] and 0.15 [0.01, 0.28], respectively). Thus, location retro-cues were effective largely regardless of whether the probe-target features are intrinsic or extrinsic, whereas intrinsic retro-cues (i.e., shape and color) only benefitted recalling extrinsic (i.e., location) features. There were few other retro-cue effects observed in the other memory parameters.

These exploratory results clarify those of the confirmatory analyses by suggesting that what at first appear to be largely consistent retro-cue benefits to target memory, regardless of the type of cue or probe-target condition, are in fact largely driven by location retro-cues when recalling colors and shapes, as well as color and shape retro-cues when recalling a location given a shape probe. This is in line with recent prior work suggesting that intrinsic feature cues, like shape and color, tend to be less effective overall compared to location retro-cues (Arnicane & Souza, 2021). Thus, although there may be something particularly efficacious about location as an extrinsic feature when guiding attention, our results indicate that this efficacy is largely consistent regardless of whether intrinsic or extrinsic features are relevant to recall.

Figure 5

Posterior Parameter Estimates of the Probability of Target Memory (A), Memory Precision (B), Probability of a Binding Error (C) and Probability of Guessing (D) for each probe-target in Experiment 2. Larger Dark Circles Indicate Group Means, Smaller Faded Circles Indicate Individual Means, and the Error Bars Show the 95% HDIs of the Posterior.

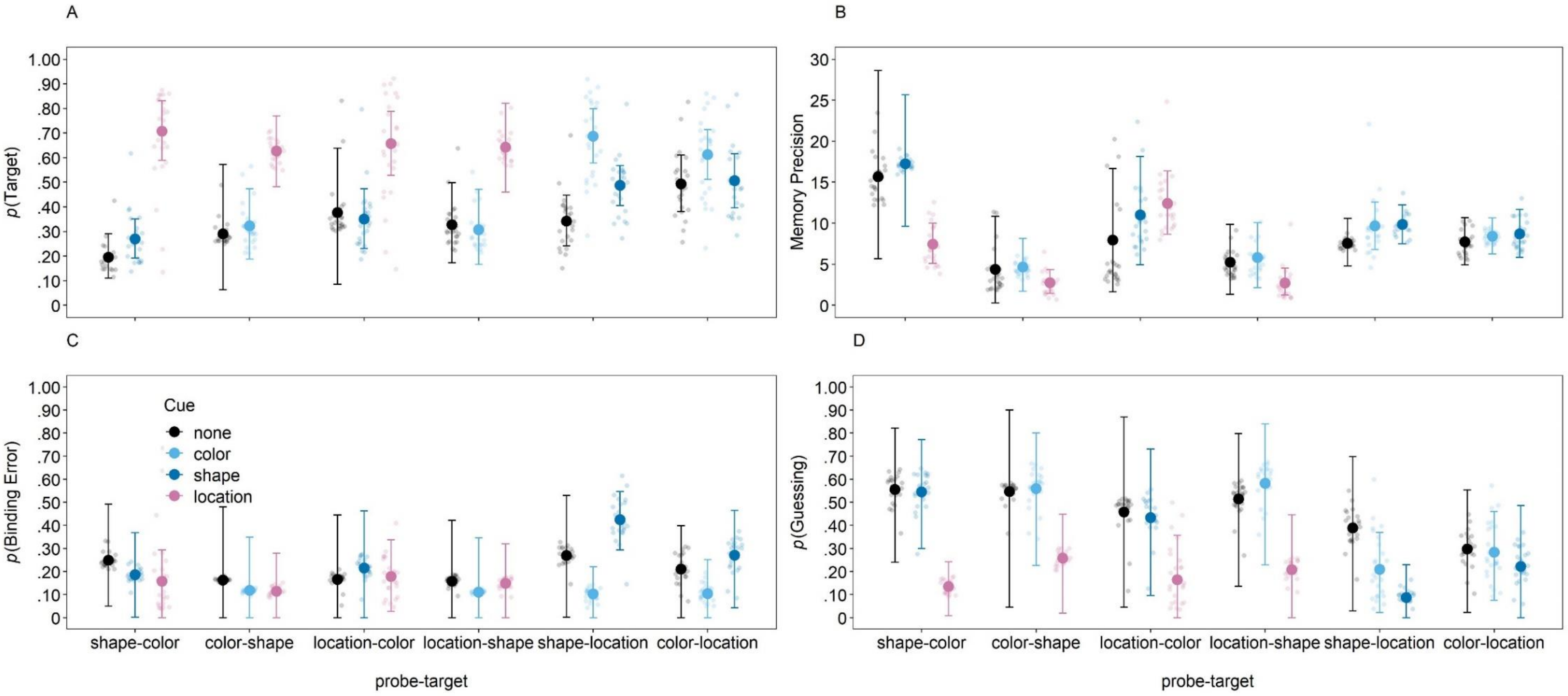


Table 4

Summary of Mean Differences [and 95% HDIs] in Each Memory Parameter for the Exploratory Analyses of Experiment 2.

Probe-Target		Baseline/None vs.	*P*(Target)	*P*(Binding error)	*P*(Guessing)	Precision
Intrinsic-intrinsic	Shape-Color	Shape	0.07 [-0.05, 0.19]	-0.06 [-0.38, 0.24]	-0.01 [-0.40, 0.39]	1.58 [-14.02, 15.68]
		Location	**0.51 [0.36, 0.67]**	-0.09 [-0.38, 0.17]	**-0.42 [-0.72, -0.09]**	-8.22 [-21.23, 2.42]
	Color-Shape	Color	0.03 [-0.29, 0.33]	-0.05 [-0.48, 0.30]	0.01 [-0.48, 0.65]	0.29 [-7.64, 6.85]
		Location	**0.34 [0.02, 0.62]**	-0.05 [-0.43, 0.26]	-0.29 [-0.74, 0.25]	-1.63 [-8.77, 3.38]
Extrinsic-intrinsic	Location-Color	Shape	-0.03 [-0.33, 0.28]	0.05 [-0.37, 0.42]	-0.02 [-0.56, 0.52]	3.07 [-8.97, 13.80]
		Location	0.28 [-0.02, 0.59]	0.01 [-0.32, 0.30]	-0.29 [-0.76, 0.15]	4.47 [-5.33, 12.92]
	Location-Shape	Color	-0.02 [-0.26, 0.21]	-0.05 [-0.39, 0.28]	0.07 [-0.40, 0.54]	0.56 [-5.76, 6.93]
		Location	**0.32 [0.06, 0.55]**	-0.01 [-0.35, 0.30]	-0.31 [-0.72, 0.13]	-2.52 [-7.60, 2.01]
Intrinsic-extrinsic	Shape-Location	Color	**0.35 [0.19, 0.50]**	-0.17 [-0.48, 0.12]	-0.18 [-0.55, 0.22]	2.14 [-1.95, 6.40]
		Shape	**0.15 [0.01, 0.28]**	0.16 [-0.15, 0.45]	-0.30 [-0.66, 0.07]	2.32 [-1.57, 6.02]
	Color-Location	Color	0.12 [-0.04, 0.27]	-0.11 [-0.37, 0.16]	-0.01 [-0.36, 0.31]	0.69 [-3.09, 4.32]
		Shape	0.01 [-0.14, 0.18]	0.06 [-0.26, 0.38]	-0.08 [-0.48, 0.33]	0.97 [-3.35, 5.06]

Note. Effects in boldface font indicate credible effects.

General Discussion

Overall, the results of the current experiments suggest that attention does not discriminate between different types of feature bindings in visual WM as we had predicted. In Experiment 1, we showed that disrupting central and peripheral attention did not respectively increase extrinsic (i.e., location) and intrinsic (i.e., color, shape) binding errors relative to a no-disruption baseline. Instead, disrupting central attention only reduced target memory and increased guessing when recalling the extrinsic feature. Further against the predicted dissociation of extrinsic and intrinsic binding errors, Experiment 2 showed that extrinsic retro-cues were the most effective to increase target memory, regardless of whether the probe-target features were intrinsic or extrinsic. These results thus suggest that manipulating attention impacts target recall in visual WM, with no consistent distinction between intrinsic and extrinsic features in the continuous reproduction paradigm used here.

Before any strong interpretation of the results, it is prudent to compare them first to that of previous similar work, such as Souza and Oberauer (2017), whose Experiments 1A and 1B inspired the design of Experiment 1 and Souza (2016) which inspired the design of Experiment 2. The results of those experiments showed much greater target memory in the no-disruption baseline conditions (Experiment 1A: estimate = 0.54 [0.47, 0.61]; Experiment 1B: estimate = 0.48 [0.39, 0.56]; see OSF for details) compared to the same relative extrinsic-intrinsic condition of our Experiment 1 (estimate = 0.19 [0.11, 0.28]). Target memory was also much lower overall in our Experiment 2 (no-cue location-color estimate = 0.38 [0.09, 0.64]; retro-cue location-color estimate = 0.66 [0.53, 0.79]) compared to the same relative conditions of Souza (2016; no-cue location-color estimate = 0.63 [0.54, 0.72]; retro-cue location-color estimate = 0.87[0.78, 0.95]). It may be that the novelty of the current design, which randomized three different features of color, shape, and location within the same memory array while randomly intermixing different probe-target conditions increased the overall difficulty of the task relative to similar prior work. This may not be a mere methodological difference given earlier seminal work showing that increasing the number of features to encode and maintain does not impair change detection (e.g., Luck & Vogel, 1997). The current paradigm of continuous reproduction of randomly probed features will thus be useful to future work in that it may better reveal the increased demand of additional features in visual WM. Furthermore, adapting the paradigm so that its overall difficulty does not overwhelm participants will be important, for example, by calibrating the presented set size of the arrays to each individual participant’s ability level (e.g., Loaiza & Souza, 2019).

A further caveat to the pattern of results is that binding errors were relatively low across conditions of both experiments. Furthermore, binding errors tended to occur more frequently in the intrinsic-extrinsic baseline condition than the other baseline conditions in both experiments. This may suggest that locations as targets yield more binding errors than shape and color in baseline conditions, which will require further investigation. It is important to note that this pattern does not impact the current analyses or conclusions given that the critical comparisons for the research questions were conducted by comparing the effect of disrupting or guiding attention to the relevant baseline within each probe-target combination. Furthermore, the general low rate of binding errors makes it difficult to determine whether there were no true effects of our conditions on binding errors or simply a reduced opportunity to observe any effects, such that binding errors may have been too low overall to be sensitive to disruption or retro-cue effects.

Notwithstanding, the pattern of results for target memory makes it unlikely that recalling intrinsic versus extrinsic features varies depending on attentional disruption or retro-cues as we had predicted. Although disrupting central attention hampered target recall of the extrinsic feature in Experiment 1, we observed retro-cue effects in Experiment 2 that did not consistently distinguish between extrinsic and intrinsic features. Extrinsic retro-cues most effectively enhanced target memory compared to other cues, consistent with recent work (Arnicane & Souza, 2021), but in one case intrinsic retro-cues also enhanced target memory of extrinsic features. Thus, we interpret these results to suggest that manipulating attention does not differently impact intrinsic and extrinsic feature binding, calling into question whether a distinction should be made between them. However, further work is required to replicate this pattern of results in other paradigms to determine whether there truly are no distinctions between intrinsic and extrinsic feature binding.

Open Practices Statement

The power analysis, accepted stage 1 registered reports, experiment materials, anonymized raw data, and analysis scripts for the experiments are available on the Open Science Framework (OSF): https://osf.io/jr3eh/

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