Prioritizing feature bindings across space and modality in working memory

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Abstract

A growing body of evidence shows that selective attention can be strategically directed to prioritize items of higher 'value' in working memory. This work has typically been limited to tests of feature binding using simple 'unitized' colored shapes as memoranda. The current study explored whether value-directed prioritization can be effectively applied when feature pairings of color and shape are separated out, either into different spatial locations (Experiment 1) or across visual and auditory presentation modalities (Experiments 2a and 2b). Experiment 1 found an overall cost to working memory performance when features were spatially separated, relative to a unitized condition, while Experiments 2a and 2b found no such cost for cross-modal feature separation. Across these experiments, there was no evidence for interaction between binding condition and prioritization; participants were equally able to derive performance benefits from prioritizing high value items in the sequence, regardless of whether features were encountered as part of the same unitized object or separated in space or modality. The findings have implications for the relationship between working memory and attention, and suggest that value-directed prioritization can be effectively applied across different types of material.

Keywords: working memory, prioritization, binding, unitization, cross-modality

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Our ability to temporarily hold and process environmental input is served by working memory, a capacity-limited system that is integrally connected with broader cognition and closely related to attention (e.g. Baddeley et al., 2021; Cowan et al., 2021). This relationship means that what we attend to determines what we remember in working memory, and vice versa (e.g. Oberauer, 2019; Cowan et al., 2024); a useful feature given the constrained capacity of this system. The interaction between working memory and attention has been empirically demonstrated through experimental methods that promote the prioritization of certain items within a working memory task. For example, a visual cue might be presented before or after encoding that indicates which item is more likely to be tested (Griffin & Nobre, 2003; Souza & Oberauer, 2016). Alternatively, differential value or reward might be associated with memoranda from a sequence or array, with the aim of encouraging participants to strategically prioritize items of higher value (e.g. Hu et al., 2014). The present study focuses on this latter method, examining in three experiments whether value-directed strategic prioritization can be effectively applied to different classes of object.

In a typical value-directed prioritization paradigm (see Allen et al., 2024, for a review), notional point values are allocated to each item in a trial, with participants told they will collect these points if they correctly respond at test. Compared to an equal value condition with no variation in reward, this instruction typically results in improved memory for the higher value items, some costs to lower value items, and no overall change in performance. Thus, attentional focus can be flexibly shifted between items to ensure some are prioritized, but this does not mediate global capacity. Most work has been done in the visual domain, showing consistent findings across sequential and simultaneous presentation contexts and using a range of different response tasks such as cued recall, recognition, and precision-based continuous response (Allen et al., 2021; Allen & Ueno, 2018; Atkinson et al., 2018, 2019, 2022, 2024; Hitch et al., 2018; Hu et al., 2014, 2016, 2023). Importantly, the core findings have been replicated and extended to other domains, such as visually presented words (Sandry et al., 2014, 2020), auditory-verbal recall of digits (Atkinson et al., 2021), and sequences of tactile input (Roe et al., 2024), indicating the phenomenon to be modality-general rather than specific to any one task or input stream.

While there continues to be debate between proponents of leading theoretical models of working memory, most agree that attentional control is important in determining what is remembered and what is forgotten (Byrnes & Miller-Cotto, 2023), and that this principle applies in a general sense across different modalities and task contexts. In high-level working memory frameworks such as the multicomponent model of

Baddeley et al. (2021; Hitch et al., 2024) and Cowan's embedded processes approach (e.g. Cowan et al., 2021), strategic attentional control is achieved by the central executive, a set of processing resources responsible for a range of cognitive functions. Theorists agree that the concept of the executive is likely fractionable into several subcomponents (e.g. Baddeley, 2002; Miyake et al., 2000), though this has not yet been fully achieved or mapped out (Hitch et al., 2024). Strategic prioritization of some information over others may be one such component, and indeed Engle and colleagues (e.g. Draheim et al., 2022; Mashburn et al., 2021) regard attentional control as being the key predictive factor underlying the involvement of working memory in broader cognition. Models also generally agree on the importance of capturing how different kinds of information are held in working memory in active and accessible states. Within the multicomponent approach of Baddeley and colleagues (Baddeley, 2000; Baddeley et al., 2021; Hitch et al., 2024), this would be registered in distinct modality-specific stores and pulled together as a modality-general representation of the consciously accessible present in the episodic buffer (see also Barrouillet & Camos, 2014, for a similar structured description). The embedded processes approach (Cowan et al., 2021) does not explicitly differentiate between distinct stores but describes a focus of attention capable of holding different kinds of information in an active and accessible form (a concept which maps onto the episodic buffer).

These theoretical frameworks are therefore at least broadly able to capture how information is selectively and strategically prioritized, through active maintenance within the episodic buffer or focus of attention with support from the central executive (Allen et al., 2024; Hitch et al., 2020). Most work on prioritization in the visual domain has used tasks requiring binding of visual features such as shape and color when encountered as perceptually unitized objects, reflecting the emergence of this research from earlier exploration of how binding operates in working memory (Allen et al., 2006, 2012; Baddeley et al., 2011; Hitch et al., 2020). The question arises as to whether the same theoretical accounts can be extended to other forms of binding in which features are encountered separately, and perceptual binding as integrated and unitized objects is no longer as plausible. It is important to explore whether different forms of feature binding can indeed be enhanced through selective allocation of attention, to identify any possible boundary conditions and resulting constraints for theoretical interpretation.

Previous research has explored how different types of binding might vary in their behavioural properties, cognitive mechanisms, and neural underpinnings. This includes separation of to-be-remembered feature pairings in space, time, and presented modality (e.g. Allen et al., 2009; Ecker et al., 2013; Gao et al., 2017; Guazzo et al., 2020; Karlsen et al., 2010; Parra et al., 2015; Wang et al., 2015). For example, Karlsen et al. (2010) presented shape-color pairings in either unitized form (i.e. as single objects) or with the visual features spatially separated into vertically adjacent locations. Immediate recognition accuracy for feature binding was relatively lower when the features were spatially separated, indicating a unitization advantage, but this did not interact with concurrent task condition, suggesting a similar executive involvement in each case. Allen et al. (2009) contrasted visually unitized binding with a cross-modal condition in which feature pairings were simultaneously presented in visual and auditory modalities. Concurrent load again did not interact with binding condition, and in this case overall recognition accuracy was equivalent for visual and cross-modal combinations. These studies were interpreted as evidence that features encountered across space or modality can be bound together in working memory without placing any additional substantial costs on executive control, with resultant maintenance in the episodic buffer as part of the multicomponent model (Baddeley, 2000; Baddeley et al., 2021).

However, very few little is known about how selective prioritization might be applied to binding of features that are not visually unitized in the environment. Only one study that we know of has addressed this to date. Johnson and Allen (2023) examined memory for short sequences of color-odour bindings (using different odours encountered in colored boxes). Allocation of higher value to the first item in the sequence shifted the profile of performance across serial positions, indicating some attempt to prioritize, though there was no strong evidence that this enhanced accuracy for the high value item, compared to an equal value baseline. Thus, prioritization in this context appeared to be relatively ineffective.

This raises the important question of whether prioritization is challenging for any form of non-unitized binding, or if olfactory processing (as in the study by Johnson and Allen, 2023) represents a special case.

One possibility is that because the focus of attention is occupied in binding information across locations or modalities, it might not be available for prioritization of information at the same time, given that prioritization during working memory tasks is likely to be cognitively demanding (Atkinson et al., 2021; Hu et al., 2016). Alternatively, based on evidence from concurrent task studies indicating that initial binding into working memory does not come with increased attentional cost, even for spatially separated and cross-modal bindings (Allen et al., 2009; Karlsen et al., 2010), we might predict prioritization effects to be equivalent across different forms of binding task. Clearly, further research is needed to investigate this question. Outcomes will help identify boundary conditions in directed prioritization and generate new insights into processes of selective attention and prioritization, and feature binding within working memory.

We examined this question in three experiments. The first experiment remained focused within the visuospatial domain, comparing working memory for feature bindings when the constituent elements were encountered in a visually unitized form or were separated into distinct spatial locations, using a paradigm adapted from Karlsen et al. (2010). We followed this with two experiments examining working memory for binding of features that were separated across visual and auditory modalities (Allen et al., 2009). In each case, we examined whether impacts of prioritization varied when features were visually unitized or separated across space or modality.

Experiment 1

The first experiment examined whether value-directed strategic prioritization effects would vary with unitization of visual features, asking whether prioritization is more effective for memoranda when constituent features are encountered as single objects rather than spatially distinct feature pairings. Spatial location is an important dimension in supporting binding of visual features (Rajsic & Wilson, 2014; Schneegans & Bays, 2017; Shepherdson et al. 2022; Treisman, 1982; Treisman & Gelade, 1980), and there is some evidence for different attentional requirements and neural underpinnings for feature binding when features are not visually unitized as single objects (e.g., Ecker et al., 2013; Parra et al., 2015). Memory for unitized and spatially separated features was directly compared in a series of experiments by Karlsen et al. (2010). Results indicated reduced recognition performance for binding when features were separated in space, compared to when they were visually unitized as single objects. However, the addition of demanding concurrent tasks indicated no evidence for an interaction between binding condition and attentional load. Thus, there is a performance cost to working memory binding from separating features in space, but this does not necessarily reflect any greater requirement for executive resource.

A similar paradigm to that used by Karlsen et al. (2010) was implemented in the present study, with each trial involving sequences of four feature pairings presented in either visually unitized (as single objects) or spatially separated (with shape and color as spatially proximate but separate stimuli) forms. Value-directed prioritization was implemented as in related studies (e.g., Allen et al., 2021; Atkinson et al., 2018, 2019, 2024), comparing a no-priority condition in which all items were of equal value with a priority condition in which the first item in the sequence was allocated higher value.

We predicted several effects to emerge in this experiment. Firstly, following prior work (see Allen et al., 2024 and Hitch et al., 2020 for reviews), we predicted a serial position effect, with improved accuracy for the later sequence items (i.e. a recency advantage).

Based on Karlsen et al. (2010), we predicted a main effect of binding type, with an advantage for spatially separated over unitized binding. Value-directed prioritization was not expected to emerge as a main effect, as prior work indicates that this manipulation does not enhance overall working memory capacity (Allen et al., 2024). It should instead emerge as an interaction with serial position, with increased accuracy for the first serial position in the prioritization condition (i.e. the targeted serial position). Finally, if the effectiveness or ease of prioritization does vary with binding type, these two factors should interact. Specifically, if prioritization of spatially separated feature bindings is more demanding and/or less effective, we might expect a relatively smaller boost to the high value first position, along with greater costs to lower value items in the same sequence.

Method

Participants

An initial estimated sample size calculation was carried out using G*Power 3.1 (Faul et al., 2009). The primary comparison in this study was between higher value and equal value conditions at the prioritized serial position (SP1). Based on the effect size of 0.8, power analysis indicated a required sample size of N = 23 to achieve .95 power with alpha of .05.

Thirty-one participants completed the experiment (aged 18-30 years; M = 20.32; SD = 2.34; 25 females, 5 males and 1 other) mostly in exchange for course credit. They were all native English speakers, and none reported a history of neurological disorders. The participants had normal or corrected-to-normal vision and no color blindness. Informed consent was acquired in accordance with the guidelines set by the University of Leeds's Psychology Ethics Committee (Ethics reference number: PSC-325).

Materials

Six colors (black, red, blue, green, yellow, and purple) and six shapes (circle, cross, diamond, star, flag, and triangle) were used as visual stimuli, as taken from Allen et al. (2006). A neutral formless shape (“a blob”) and shape outline of the same six shapes were utilised to display colors in spatially separated conditions and present as a test cue (Allen et al., 2009). Shapes and colors were not repeated within the same trial. All stimuli presented in the size of 3.3 x 3.3 cm on the white background.

Design and Procedure

A 2x2x4 repeated measures design was implemented in each experiment, with two types of binding type (unitized and spatially separated), two prioritization conditions (priority-SP1 and no-priority) and four probed serial positions (SP 1:4).

The Gorilla Experiment Builder (www.gorilla.sc) was used to collect data (Anwyl-Irvine et al., 2020) and the experiment was conducted in person. Participants needed to complete 4 blocks (one per condition) and each block included 40 test trials. Order of condition blocks was fully counterbalanced across participants. Each serial position was tested an equal number of times (10 times) in a random order within each block. There were two practice trials at the beginning of each block to familiarize participants with the condition.

At the beginning of all conditions, participants were informed of task details via written instructions. In the prioritization condition, they were told that the first stimulus would be paired with 10 points while the other three stimuli were worth 1 point. In the no-priority condition, participants were informed that all stimuli were paired with 5 points. Thus, in the no priority condition, none of the items were explicitly to be prioritized, whereas, in the priority-SP1 condition, the first stimulus was to be prioritized. Point values were notional and were not predictive of which item would be tested.

There were two different binding conditions. In the unitized condition, colors and shapes were presented as a single-colored shape (e.g., a circle outline with red infill). In the spatially separated condition, colors and shapes were presented simultaneously but visually separated as pairs of colored blobs and unfilled shapes (e.g., a red-colored blob and the outline of a circle). In this condition, colors and shapes were displayed as vertically adjacent, with colors always presented directly above the shapes, separated by 0.6cm (see Figure 1).

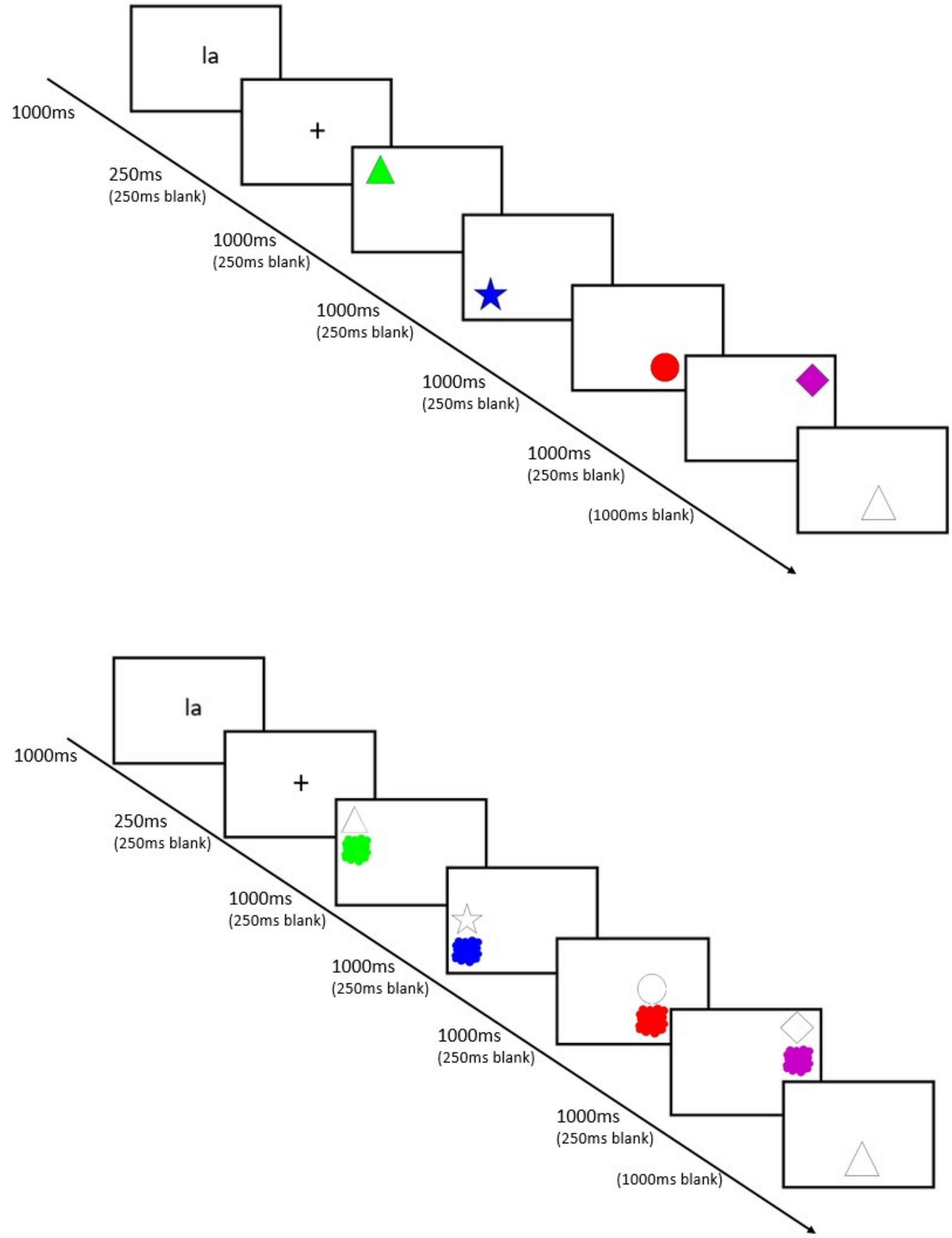


Figure 1. The experimental paradigm used in Experiment 1. The top panel shows an example of a unitized trial, whilst the bottom panel shows an example of a spatially separated trial. Figure not to scale.

Figure 1 shows the experimental paradigm. To-be-remembered stimuli were presented in the four corner quadrants of the screen, pseudo-randomizing position with the constraint that each location was only occupied once per trial and a counterbalanced order. For example, the first shape color pairing was shown in the upper-right corner, the second in the lower-left corner, and so on. In each trial, only one item was presented within each quadrant.

Each trial began with the 1000ms presentation of the nonword "la" which participants were asked to repeat until the retrieval phase to disrupt verbal rehearsal. A fixation cross then appeared at the centre of the screen for 250ms, followed by a 250ms blank screen. Each of the four visual stimuli was presented on a white background in one of the four corner quadrants of the screen for 1000ms with an inter-stimulus interval of 250ms. A 1000ms blank screen delay followed the presentation of the four stimuli then the test cue was presented. The test cue, a shape outline, was pseudo-randomly selected from the four stimuli in the study array with the restriction that each SP was tested an equal number of times per participant. The test cue was presented below the screen centre so as not to spatially overlap with the target. Participants were asked to verbally recall the name of the color that was presented with that shape. The experimenter recorded their answers and then pressed the enter button to progress to the next trial. Reminders about the item values were presented to participants after every 20 trials. Participants were given feedback on their ongoing points score halfway through each block, and their total points score at the end of each block.

Data analysis

In this experiment, the outcome variable was proportional accuracy in recalling the correct color. The independent variables were binding type (unitized and spatially separated), prioritization (priority-SP1 and no priority), and SP (1-2-3-4). Thus, the data were subjected to 2 (binding types) x 2 (prioritization) x 4 (SP) repeated measures ANOVA. Results are initially reported in terms of SP function. Additional planned analysis was conducted at SP1 as the priority manipulations were aimed at this position. Data analysis was conducted using frequentist and Bayes Factor (BF) methods, using JASP (Version 0.16). Bayesian analysis considers the likelihood of the data under both the null and alternative hypotheses, compared via the Bayes Factor (*BF*). A *BF* between 1 and 3 is considered to reflect anecdotal evidence, between 3 and 10 indicates moderate evidence, and a *BF* of 10 or above is considered strong evidence (Jarosz & Wiley, 2014; Schönbrodt & Wagenmakers, 2018).

Results

The 2 (binding type) x 2 (prioritization) x 4 (SP) repeated measures ANOVA indicated no main effect of prioritization (Priority-SP1 M = 0.56, SE = 0.02; No priority M = 0.55, SE = 0.02; (F(1,30) = 0.79, p =.380, = 0.03, = 0.001; BF_{10} = 0.18). A main effect of serial position emerged (Greenhouse-Geisser corrected F(1.89, 56.96) = 33.42, p < .001, = 0.53, = 0.28; BF_{10} > 10,000). Pairwise comparisons (corrected using Bonferroni–

Holm) revealed significant differences between SP1 (M = 0.48, SE = 0.03) and SP3 (M = 0.61, SE = 0.03; p = .001), SP1 and SP4 (M = 0.73, SE = 0.03; p < .001), SP2 (M = 0.40, SE = 0.03) and SP3 (p < .001), SP2 and SP4 (P < 0.001), SP3 and SP4 (p = .002). A main effect of binding type emerged, with higher accuracy in the unitized (M = 0.58, SE = 0.02) than spatially separated (M = 0.53, SE = 0.02), (F(1,30) = 17.31, p <.001, = 0.37, = 0.02; BF_{10} = 11.67).

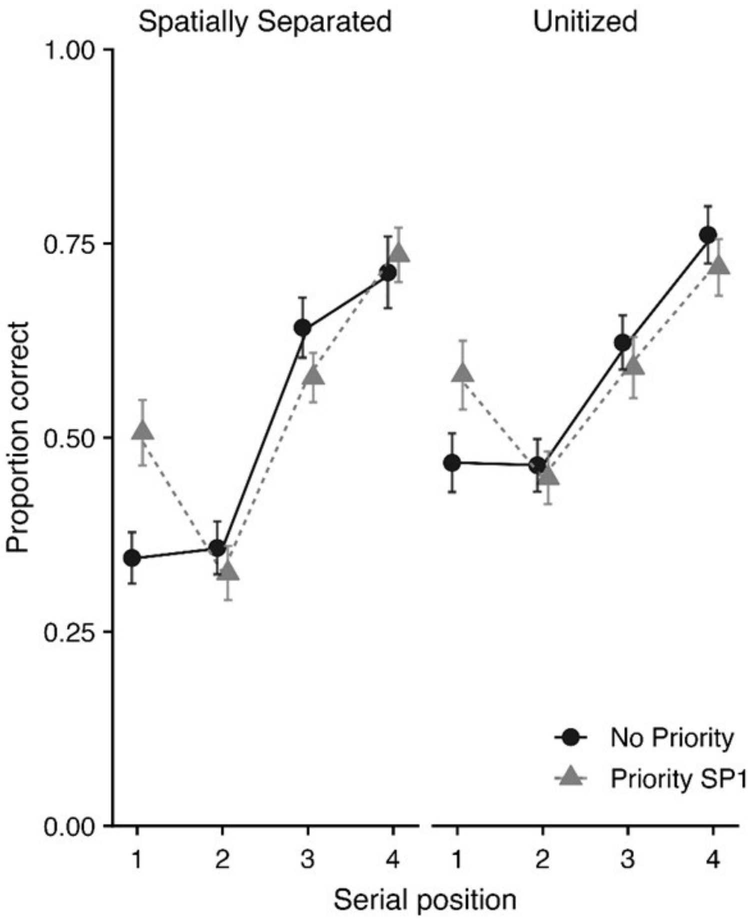


Figure 2. Mean proportion correct (with SE) for each binding type, prioritization, and SP condition in Experiment 1.

There was a significant interaction between SP and prioritization (Greenhouse-Geisser corrected F(2.47,73.97) = 5.95, p = .002, = 0.17, = 0.03; BF_{10} = 33.96) and between SP and binding type (Greenhouse-Geisser corrected F(2.82, 84.58) = 3.57, p = .019,   = 0.11, = 0.02; BF_{10}= 1.97), (see Figure 2). There was no significant interaction between binding type and prioritization (F(1, 30) = 0.26, p =.613, = 0.01, < .001; BF_{10}= 0.20); and no three-way interaction between SP, binding type and prioritization (F(3,90) = .66, p =.579, = 0.02, = 0.003 ; BF_{10}= 0.12).

To investigate the interaction between prioritization and SP, a series of paired sample t-tests were conducted (with Bonferroni-Holm correction applied). The mean proportion correct as a function of the prioritization and SP is displayed in Figure 3(A). A significant difference emerged only at SP1 (prioritized SP), with significantly higher accuracy in the priority-SP1 condition (M = 0.54, SE = 0.04), than no priority (M = 0.41, SE = 0.03), (t(30) = 3.91, p < .001, BF_{10} = 61.63, d = 0.70). No significant differences emerged between priority-SP1 and no priority conditions at SP2 (t(30) = -0.86, p = .396, BF_{10} = 0.27, d = -0.16), SP3 (t(30) = -1.43, p = .164, BF_{10} = 0.48, d = -0.26) or SP4 (t(30) = -0.27, p = .792, BF_{10} = 0.20, d = -0.05). To sum up, results showed that prioritizing the first item increased performance at SP1, but had no significant effect on performance at SP2, SP3 and SP4.

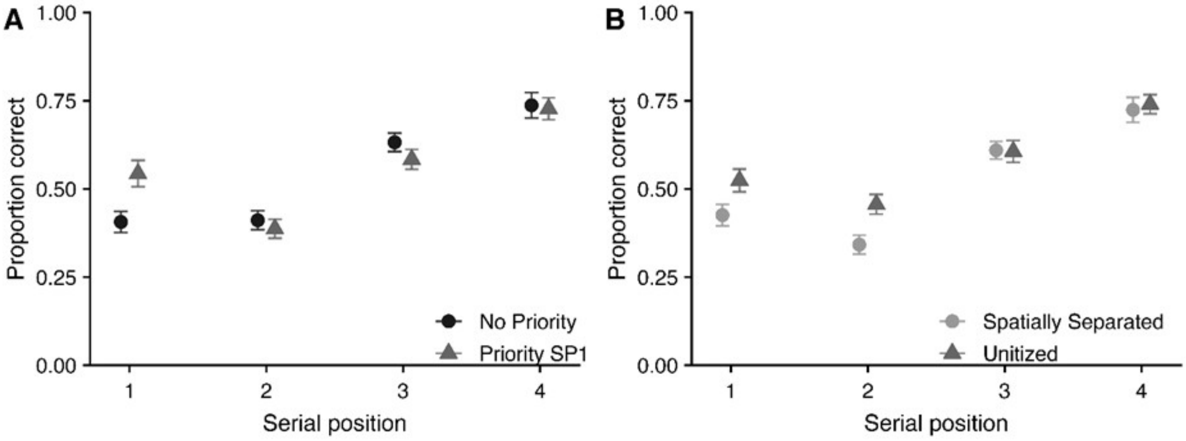


Figure 3. A) Mean accuracy (with SE) in Experiment 1 as a function of prioritization and SP, collapsed across binding type conditions; B) Mean accuracy (with SE) as a function of the binding type and SP, collapsed across prioritization conditions.

To investigate the interaction between binding type and SP, a series of paired sample t-tests were conducted (with Bonferroni-Holm correction applied). The mean proportion correct as a function of the binding type and SP is displayed in Figure 3B. Participants showed significantly better performance in the unitized binding condition at SP1 (M = 0.52, SE = 0.03), than spatially separated (M = 0.43, SE = 0.03), ($t(30) = 4.06$, $p < .001$, $BF_{10} = 88.54$, $d = 0.73$) and significantly better performance unitized binding condition at SP2 (M = 0.46, SE = 0.03) than spatially separated (M = 0.34, SE = 0.03), ($t(30) = 3.78$, $p < .001$, $BF_{10} = 44.68$, $d = 0.68$). No significant differences emerged between binding types at SP3 ($t(30) = -0.09$, $p = .931$, $BF_{10} = 0.19$, $d = -0.02$) or SP4 ($t(30) = 0.59$, $p = 0.562$, $BF_{10} = 0.23$, $d = 0.11$). To sum up, results showed that accuracy was higher for unitized binding relative to spatially separated bindings at SP1 and SP2, but there was no difference in performance at SP3 or SP4.

Further planned analysis was conducted at SP1 as the prioritization manipulation was targeted at this SP. To investigate the interaction between prioritization and binding type, a 2 (Prioritization) × 2 (Binding type) repeated-measures ANOVA was conducted. There was a significant main effect of prioritization ($F(1,30) = 15.27$, $p < .001$, = 0.34, = 0.09; $BF_{10} = 49.58$), with higher accuracy in the priority-SP1 (M = 0.54, SE = 0.04) than no priority condition (M = 0.41, SE = 0.03). There was also a main effect of binding type ($F(1,30) = 16.45$, $p < .001$, = 0.35, = 0.05; $BF_{10} = 10.85$); performance was higher in unitized (M = 0.52, SE = 0.03) than spatially separated binding (M = 0.43, SE = 0.03). There was no significant interaction between prioritization and binding type ($F(1,30) = 0.56$, $p = 0.462$, = 0.02, = 0.003; $BF_{10} = 0.40$), indicating that increased performance in the priority condition did not differ depending on the binding type.

Discussion

We replicated the previously observed unitization advantage in visual working memory (Karlsen et al., 2010), with improved recall for features presented as part of the same visual object rather than being separated in space. We also observed benefits of value-directed prioritization for higher value items compared to an equal value condition, in the context of no overall change in performance (e.g. Atkinson et al., 2018; Hitch et al., 2018; see Allen et al., 2024). There was also a clear recency advantage for later sequence items, even when attention was directed towards the first position (e.g. Hu et al., 2014). The novelty of the work lies in the interaction between these two factors, and here both the frequentist and Bayes factor results were clear in supporting a null effect; strategic prioritization was applied in an equally effective way regardless of whether the features were encountered as single unitary objects or separated in space.

Experiments 2a and 2b

The first experiment indicated that whilst spatial separation of visual features results in an overall reduction in performance, it does not lead to any measurable change in the effectiveness of strategic prioritization. Experiments 2a and 2b aimed to extend this exploration beyond the visuospatial domain, testing whether the same principle applies when to-be-remembered feature pairings are separated by encoding modality. This may be a particularly useful test of a modality-general working memory component such as the episodic buffer or focus of attention, as the different input streams would not be captured within the same specialised subsystem (Allen et al., 2009; Gao et al., 2017; Wang et al., 2015, 2017). Performance in the spatially separated condition in Experiment 1 might still be achieved externally to the episodic buffer. For example, it might be captured within the visuospatial sketchpad (using the Baddeley et al., 2021, multicomponent framework), based on separately stored visual features that share ordinal and timing signals along with proximate spatial location. In contrast, cross-modal binding can only be achieved within the episodic buffer (Baddeley et al., 2021), or the focus of attention within Cowan's embedded processes approach (e.g. Cowan et al., 2021). The same principle may apply to olfactory-color binding, which appears to be possible though with limited capacity and scope for prioritization (Johnson & Allen, 2023). Cross-modal binding may therefore be more demanding to actively prioritize during sequential encoding and retention, as processing of each new pairing that is encountered might detract from the active prioritization of an earlier item within the episodic buffer.

Experiments 2a and 2b used an adaptation of the paradigm implemented by Allen et al. (2009; see also Gao et al., 2017 and Guazzo et al., 2020), in which a visual feature (in this case, shape) is paired with an auditory feature (color name). Using single probe recognition, Allen et al. (2009) found that accuracy for cross-modal binding was in fact equivalent to that observed in unitized binding, thus showing no performance decline (or benefit) from presenting across, rather than within, modalities. This stood in contrast to reduced accuracy for spatially separated binding observed by Karlsen et al. (2010; see Experiment 1). Similarly to Karlsen et al., however, dual-task manipulations indicated no increased reliance on attentional control for cross-modal binding (Allen et al., 2009), suggesting that executive control resources are not particularly necessary during encoding and maintenance. In line with this, Arslan et al. (2024) have recently demonstrated that encoding of visual-auditory object binding can emerge in a relatively automatic, bottom-up manner. This would also fit with

Guazzo et al. (2020), who applied a cued recall task and found that cross-modal binding was no more affected than unitized binding by healthy ageing or Alzheimer's disease.

In this experiment, we predicted a prioritization by serial position interaction to again emerge as in Experiment 1 and previous studies, with enhanced recall for the higher value item (at SP1) but no overall main effect of priority condition. Based on previous findings (Allen et al. 2009; Guazzo et al., 2020), we also predicted no overall difference in accuracy between the two binding type conditions (unitized and cross-modal). Evidence of this would extend such observations from single probe recognition (Allen et al., 2009) to cued recall in the present paradigm. Finally, it is possible that feature bindings encountered in different modalities are more challenging to effectively prioritize (Johnson & Allen, 2023). If this is the case, cross-modal binding should show a reduced prioritization benefit relative to the unitized condition. Alternatively, given the null interaction in Experiment 1, and the absence of increased attentional load interference reported by Allen et al. (2009), prioritization might be just as effective cross-modally as within-modality. We tested these various predictions in two experiments (2a and 2b) that were identical apart from the exposure durations used during encoding.

Experiment 2a: Method

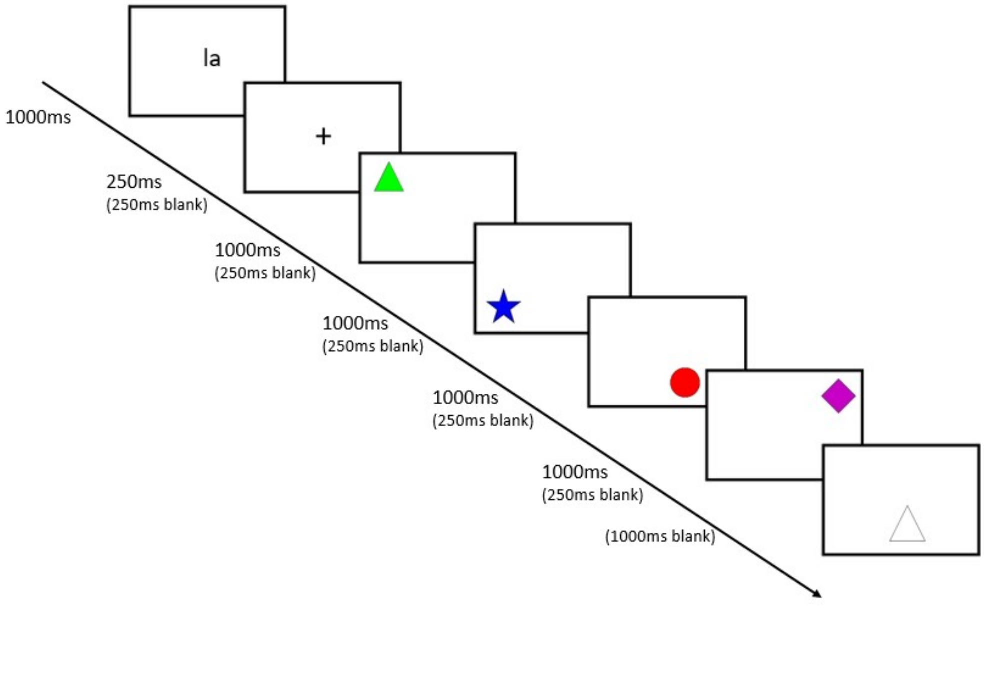
Participants

Thirty participants (aged 18-22 years; M = 19.23; SD = 1.04; 25 females and 5 males) took part in this experiment in exchange for course credit.

They were all native English speakers, and none reported a history of neurological disorders. The participants had normal or corrected-to-normal vision and no color blindness. Informed consent was acquired in accordance with the guidelines set by the University of Leeds's Psychology Ethics Committee (Ethics reference number: PSYC-608).

Design and Procedure

The method was closely based on Experiment 1, with the same material set, design, and trial procedure. The only exception was that participants completed cross-modal binding conditions instead of spatially separated binding. In cross-modal binding, each shape was presented visually in pairing with an auditory color name (see Figure 4).



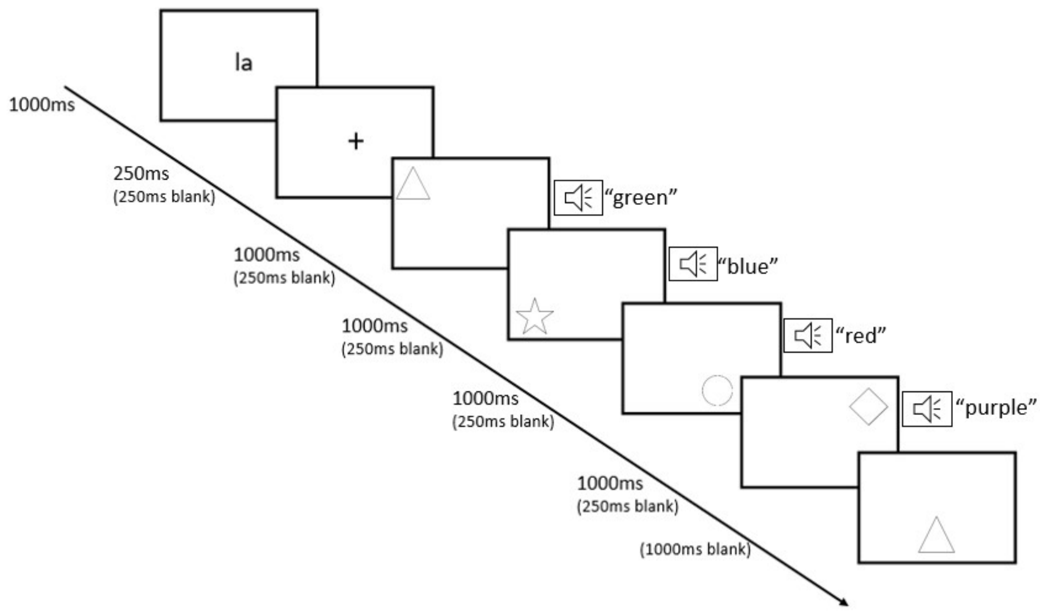


Figure 4: Illustration of the paradigm used in Experiment 2a.

The procedure was the same as in Experiment 1 for unitized conditions. In the cross-modal conditions, each shape was paired with an auditory color name (see Figure 4). Four paired visual and audio stimuli in each trial were serially presented, after which the visual test probe followed. The test probe was always a shape and provided in the visual modality, and as in Experiment 1 participants needed to verbally recall the name of color that was paired with the shape.

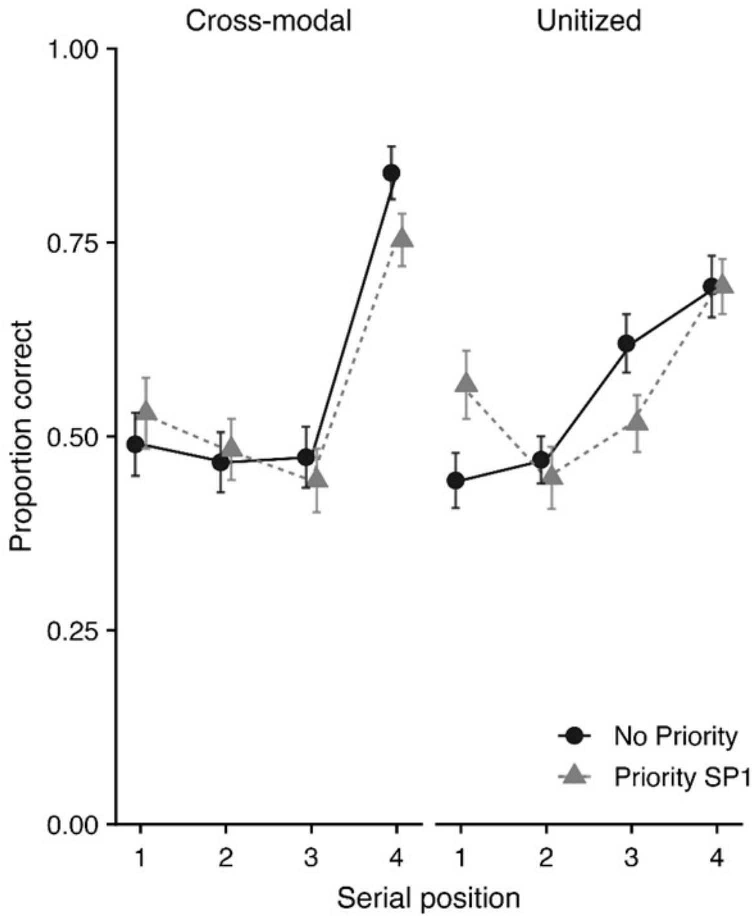
As with Experiment 1, a 2x2x4 repeated measures design was implemented in each experiment, with two types of binding type condition (unitized and cross-modal binding) and prioritization condition (priority and no-priority) and probed serial position (SP 1:4).

Results

The 2 (binding type) x 2(prioritization) x 4 (SP) repeated measures ANOVA indicated no main effect of prioritization (Priority-SP1 $M = 0.55$, SE = 0.02; No priority $M = 0.56$, SE = 0.02; ($F(1,29) = 0.21$, $p = .651$, = 0.007, < 0.001; $BF_{10} = 0.11$) and no main effect of binding type (Unitized $M = 0.56$, SE = 0.02; Cross-modal $M = 0.56$, SE = 0.02; $F(1,29) = 0.06$, $p = .817$, = 0.002, < 0.001; $BF_{10} = 0.11$).

A main effect of SP emerged (Greenhouse-Geisser corrected $F(2.06, 59.65) = 23.63$, $p < .001$, = 0.45, = 0.22; $BF_{10} > 1000$). Pairwise comparisons (corrected using Bonferroni-Holm) revealed significant differences between SP1 ($M = 0.51$, SE = 0.03) and SP4 ($M = 0.75$, SE = 0.02; $p < 0.01$), SP2 ($M = 0.47$, SE = 0.03) and SP4 ($p < 0.001$), and SP3 ($M = 0.51$, SE = 0.03) and SP4 ($p < .001$).

There was a significant interaction between SP and prioritization (Greenhouse- Geisser corrected $F(2.08, 60.35) = 3.47$, $p = .035$, = 0.11, = 0.02; $BF_{10} = 2.34$, albeit with weak Bayes Factor support), and between SP and binding (Greenhouse- Geisser corrected $F(2.81, 81.55) = 8.40$, $p < .001$, = 0.22, = 0.03; $BF_{10} > 10{,}000$), (see Figure 5). There was no significant interaction between binding type and prioritization ($F(1, 29)$ =



0.26, $p = .612$, = 0.01, < .001; $BF_{10} = 0.20$); or for the three-way interaction between SP, binding type and prioritization (Greenhouse-Geisser corrected $F(2.79, 80.91) = 2.37$, $p = .081$, = 0.08, = 0.01 ; BF_{10} = 1.65).

Figure 5. Mean proportion correct (with SE) for each binding (cross-modal and unitized) and priority condition in Experiment 2a. Data are presented by serial position.

To investigate the interaction between prioritization and SP, a series of paired sample t-tests were conducted (with Bonferroni-Holm correction applied). The mean proportion correct as a function of the prioritization and SP is displayed in Figure 6A. No significant differences emerged following correction (p > .05 in all cases; SP1, $t(29) = 2.01$, $BF_{10} = 1.12$, $d = 0.37$; SP2, $t(29) = 0.11$, $BF_{10} = 0.20$, $d = 0.02$; SP3, $t(29) = 2.65$, $BF_{10} = 3.62$, $d = 0.48$; SP4, $t(29) = 1.09$, $BF_{10} = 0.33$, $d = 0.20$). To sum up, although some numerical differences were found, there were no significant effects of prioritizing the first item on any serial position.

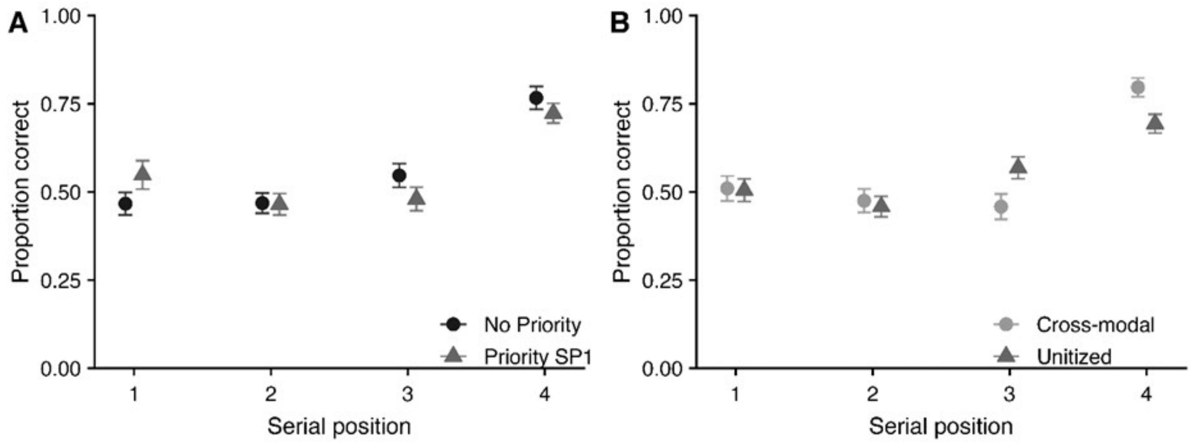


Figure 6. A) Mean accuracy (with SE) in Experiment 2a as a function of prioritization and SP, collapsed across binding conditions; B) Mean accuracy (with SE) as a function of the binding type and SP, collapsed across priority conditions. Data are presented by serial position.

To investigate the interaction between binding type and SP, a series of paired sample t-tests were also conducted, with Bonferroni-Holm correction. Mean proportion correct as a function of binding type and SP is displayed in Figure 6B. Performance was significantly better in the unitized binding condition at SP3 (M = 0.57, SE = 0.03) compared to cross-modal binding (M = 0.46, SE = 0.04) ($t(29) = 4.25$, $p < .001$, $BF_{10} >$ 10,000, $d = 0.78$), but at SP4 performance was significantly better for cross-modal (M = 0.80, SE = 0.03) than unitized binding (M = 0.69, SE = 0.03), ($t(29) = 3.77$, $p < .001$, $BF_{10} >$10,000, $d = 0.69$). No significant differences emerged between binding types at SP1 ($t(29) = 0.17$, $p = .870$, $BF_{10} = 0.20$, $d = 0.03$) or SP2 ($t(29) = 0.44$, $p = .664$, $BF_{10} = 0.21$, $d = 0.08$). To sum up, accuracy was higher for unitized bindings relative to cross-modal bindings at SP3 and vice versa at the SP4, but there was no difference in performance at SP1 or SP2.

Finally, a planned 2 (Prioritization) × 2 (Binding type) repeated-measures ANOVA was conducted focusing on serial position 1. There was a marginal non-significant effect of priority, with anecdotal Bayesian support ($F(1,29) = 4.02$, $p = .054$, = 0.12, = 0.03; $BF_{10} = 1.28$), characterised by a higher accuracy in the priority-SP1 (M = 0.55, SE = 0.04) than no priority condition (M = 0.47, SE = 0.04). There was no effect of binding type ($F(1,29) = 0.03$, $p = .870$, < .001, < .001; $BF_{10} = 0.26$) and no significant interaction between prioritization condition and binding type ($F(1,29) = 2.32$, $p = .138$, = 0.07, = 0.01; $BF_{10} = 0.86$), indicating that the numerical but non-significant increase in performance in the priority condition was equivalent across the two binding type conditions.

Discussion

Experiment 2a replicated previous observations that cross-modal binding is as accurate as visually unitized binding, supported by both frequentist and BF analyses (Allen et al., 2009; Guazzo et al., 2020). This differs from the reduced accuracy observed in spatially separated binding (Experiment 1, and Karlsen et al., 2010), and indicates that not all forms of feature separation are equivalent. We also found no clear evidence that prioritization varied with binding type, either overall or when focusing on the first serial position. However, the predicted evidence for prioritization was only marginally non-significant and anecdotally supported, both in the overall prioritization x SP interaction and the main effect of prioritization condition at SP1. It is also notable that the prioritization effect appeared to be numerically smaller in the cross-modal condition, although there was no evidence for a prioritization x binding type interaction. Experiment 2b was therefore conducted to follow up on this and establish a clearer set of findings on which to develop interpretation.

Experiment 2b

One factor that might be important to consider is the timing profile of the task that was implemented in Experiment 2a. The 1000ms exposure duration per item was taken from the visuospatial paradigm used in Experiment 1. However, the audio component of each cross-modal pairing in Experiment 2a was somewhat shorter than this duration, varying between around 450-600ms per stimulus. This means that there was a timing asynchrony between the visual and audio components in this cross-modal condition, which may have affected performance and could undermine direct comparison between the two binding conditions. Experiment 2b therefore reduced this asynchrony by limiting exposure duration per feature pairing to 600ms, implemented for both unitized and cross-modal conditions. This is comparable to exposure times used in a range of previous studies examining prioritization of unitized feature pairings (e.g. 500ms per item in Atkinson et al., 2018, 2019, and Hu et al., 2023). Using these adjusted presentation timings, we again examined whether value-directed prioritization effects would emerge to a similar or different extent for visually unitized and cross-modal binding conditions.

Method

Participants

Thirty-one participants (aged 18-21 years; M = 19.13; SD = 0.72; 27 females and 4 males) took part in this experiment in exchange for course credit. They were all native English speakers, and none reported a history of neurological disorders. The participants had normal or corrected-to-normal vision and no color blindness. Informed consent was acquired in accordance with the guidelines set by the University of Leeds's Psychology Ethics Committee (Ethics reference number: PSYC-608).

Design and Procedure

The method was closely based on Experiment 2a, with the same material set, design, and trial procedure. The only exception is that stimulus presentation time was 600ms per item rather than 1000ms.

Results

Figure 7 showed that the 2 (binding type) x 2 (prioritization) x 4 (SP) repeated measures ANOVA indicated no main effect of prioritization (Priority-SP1 $M = 0.57$, SE = 0.02; No priority $M = 0.56$, SE = 0.02; ($F(1,30) = 0.75$, $p = .394$, = 0.02, = 0.002; $BF_{10} = 0.15$) and no main effect of binding type (Unitized $M = 0.57$, SE = 0.02; Cross-modal $M = 0.56$, SE = 0.02; $F(1,30) = 0.26$, $p = .615$,   = 0.01, < .001; $BF_{10} = 0.11$). A main effect of SP emerged ($F(3,90) = 34.07$, $p < .001$, = 0.53, = 0.25; $BF_{10} > 1000$). Pairwise comparisons (corrected using Bonferroni-Holm) revealed significant differences between SP1 ($M = 0.51$, SE = 0.03) and SP4 ($M = 0.75$, SE = 0.02; $p < .001$), SP2 ($M = 0.46$, SE = 0.02) and SP4 ($p < .001$), and SP3 ($M = 0.54$, SE = 0.02) and SP4 ($p < .001$).

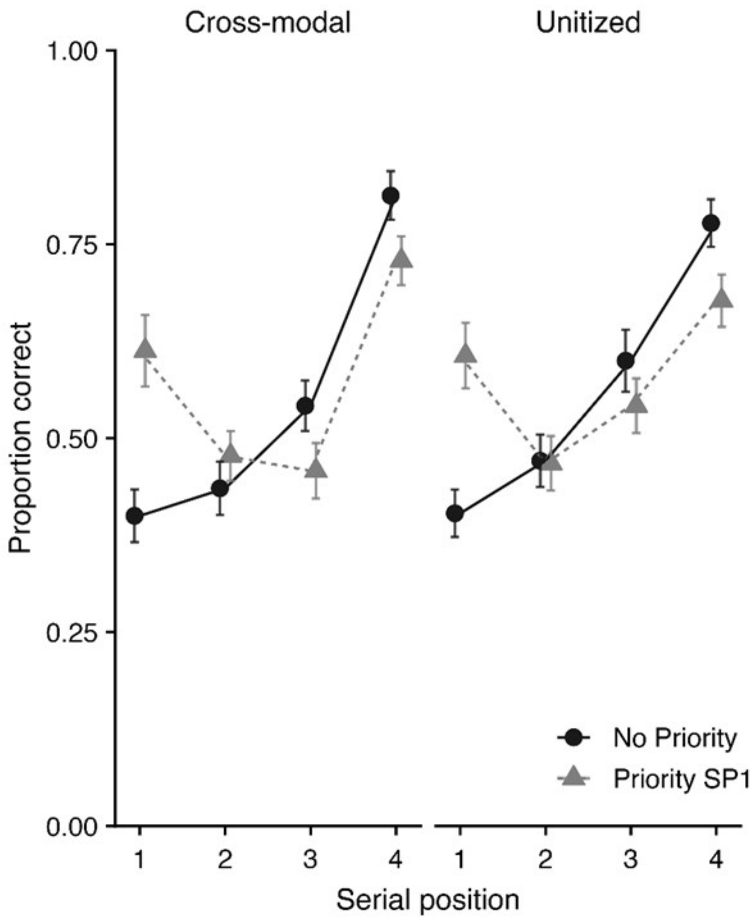


Figure 7. Mean proportion correct (with SE) for each binding type (cross-modal and unitized), prioritization, and SP in Experiment 2b.

There was a significant interaction between SP and prioritization (F(3,90) = 19.75, p < .001, = 0.40, = 0.09; BF_{10} > 10000), and a marginal interaction between SP and binding type (Greenhouse-Geisser corrected F(2.53, 67.59) = 2.97, P = .052, = 0.09, = 0.01; BF_{10} = 0.55). There was no significant interaction between binding type and prioritization (F(1, 30) = 0.15, p =.699 , = 0.01, < .001; BF_{10}= 0.33); or for the three-way interaction between SP, binding type and prioritization (F(3,90) = 0.27, p =.850 , = 0.01, = 0.001; BF_{10}= 5.74).

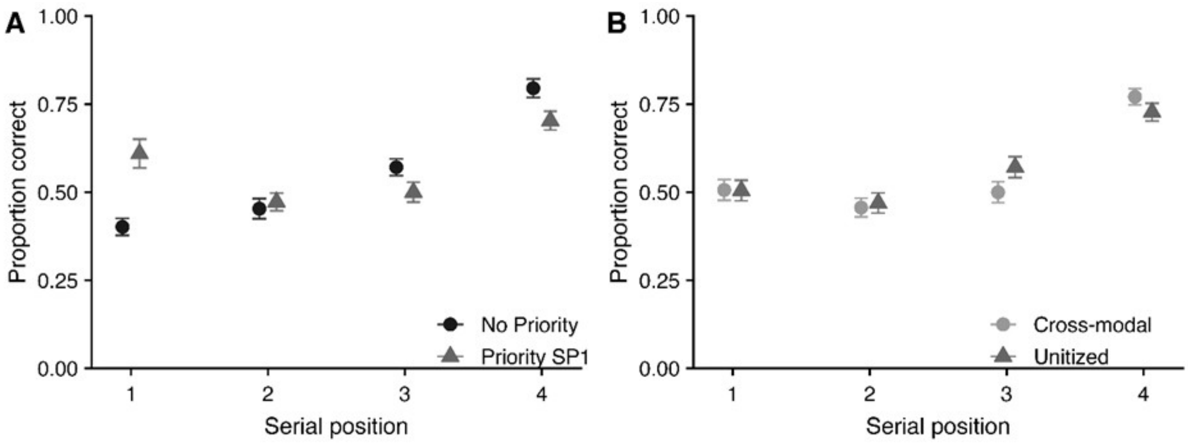


Figure 8. A) Mean accuracy (with SE) in Experiment 2b as a function of priority and SP, collapsed across the binding type conditions; B) Mean accuracy (with SE) as a function of the binding type and SP, collapsed across the prioritization conditions.

To investigate the key interaction between prioritization and SP, a series of paired sample t-tests were conducted, corrected using Bonferroni-Holm. The mean proportion correct as a function of prioritization and SP is displayed in Figure 8A. A significant difference emerged at SP1 (prioritized SP), with significantly higher accuracy in the priority-SP1 condition in SP1 (M = 0.61, SE = 0.04) than no priority (M = 0.40, SE = 0.02), ($t(30) = 4.88$, $p < .001$, $BF_{10} > 10{,}000$, $d = 0.88$). In contrast, performance was significantly better in the no priority condition at SP3 (M = 0.57, SE = 0.02) than priority-SP1 (M = 0.50, SE = 0.03), ($t(30) = 2.62$, $p < .05$, $BF_{10} = 3.40$, $d = -0.47$). Moreover, at SP4, performance was significantly better in the no priority condition (M = 0.80, SE= 0.03) than priority-SP1 (M = 0.70, SE = 0.03), ($t(30) = -3.01$, $p < .01$, $BF_{10} = 8.92$, $d = 0.55$). No difference emerged between priority-SP1 and no priority conditions at SP2 ($t(30) = 0.69$, $p = .495$, $BF_{10} = 0.24$, $d = 0.12$). To sum up, the results showed that prioritizing the first item increased performance at SP1, decreased performance at SP3 and SP4, and had no significant effect on performance at SP2.

Mean proportion correct as a function of binding type and SP is displayed in Figure 8B. To investigate the interaction between these factors, a series of (Bonferroni-Holm corrected) paired sample t-tests were conducted. There were no significant differences at SP1 ($t(30)= 0.06$, $p = .955$, $BF_{10} = 0.19$, $d = 0.01$); or SP2 ($t(30)= 0.43$, $p = .673$, $BF_{10} = 0.21$, $d = 0.08$); or SP3 ($t(30)= 1.81$, $p = .081$, $BF_{10} = 0.81$, $d = 0.33$). At SP4, there was marginally better performance in cross-modal binding (M = 0.77, SE = 0.02) than unitized (M = 0.73, SE = 0.03), ($t(30) = 2.02$, $p >$

.05, BF_{10} = 1.13, d = 0.36, with weak Bayes Factor support). To sum up, accuracy was slightly higher for cross-modal binding relative to unitized binding at SP4, but there was no evidence of differences in performance at the other SPs.

Finally, a planned 2 (Prioritization) × 2 (Binding type) repeated-measures ANOVA was conducted, targeted at SP1. There was a main effect of prioritization (F(1,30) = 23.82, p < .001, = 0.44, = 0.19; BF_{10} > 10000), with higher accuracy in the priority-SP1 condition (M = 0.61, SE = 0.03) relative to the no priority condition (M = 0.40, SE = 0.03). There was no main effect of binding type (F(1,30) = 0.003, p = .955, < .001, < .001; BF_{10} = 0.24), or no interaction between prioritization and binding type (F(1,30) = 0.03, p = .862, = 0.001, < .001; BF_{10}= 0.27).

Discussion

The results of Experiment 2b indicate clear value-directed prioritization effects, that did not differ in size between visually unitized and cross-modal conditions. Thus, participants can effectively allocate selective attention to feature pairings when they are separated across visual and auditory modalities. These findings emerged following changes in presentation duration from Experiment 2a to 2b, to ensure appropriate timing synchrony between feature pairings in the cross-modal condition[1]. More broadly, overall accuracy was again equivalent in the two binding conditions as in Experiment 2a and previous work (Allen et al., 2009; Guazzo et al., 2020), with BF analysis providing evidence of no effect of binding type. We also replicated (albeit with relatively weak evidence) the small advantage for cross-modal binding (over unitized) at the final sequence position that was found in Experiment 2a.

General Discussion

The present study aimed to establish to what extent strategically directed selective attention can be applied to feature binding in working memory when features are visually unitized or separated over space or modality. The first experiment replicated Karlsen et al. (2010) in that separating out visual features into distinct locations had a negative impact on working memory for the associations between these features. However, this did not impinge on an individual's ability to strategically prioritize one of these feature pairings. Experiments 2a and 2b then replicated the absence of difference between unitized and cross-modal binding accuracy as observed by Allen et al. (2009; see also Guazzo et al., 2020), with Bayesian support in both experiments indicating no effect. Here too we found that strategic prioritization was equally effective when features were separated across visual and auditory modalities (though these effects were clearer when a shorter, more synchronous audio-visual presentation duration was implemented). Thus, selective prioritization is not limited to unitized binding and can be effectively applied within sequences of feature pairings that are separated in space or modality. Directed prioritization served to enhance memory for high value items but did not improve overall performance, providing further support for a limited resource that can be flexibly and strategically shifted around within a working memory task without changing global capacity (Allen et al., 2024; Atkinson et al., 2018; Hitch et al., 2018).

The interplay between strategic control and automatic capture that plays out in the current paradigm can be broadly captured within high-level working frameworks such as the multicomponent model (Baddeley et al., 2021; Hitch et al., 2024) and the embedded processes approach (Cowan et al., 2021). Within these frameworks, the content of the episodic buffer or focus of attention is assumed to shift from one item to the next as they are encountered via sequential presentation, in a relatively automatic way (Allen et al., 2024). When a higher value stimulus pairing is encountered, participants can strategically direct their attention to it to ensure it remains active and accessible within this state. As described in Allen et al. (2024), this is likely to take place during encoding of the pairing and during maintenance via a mechanism such as attentional refreshing (Atkinson et al., 2022; Barrouillet et al., 2004; Camos et al., 2018; Johnson, 1992; Hitch et al., 2020; Raye et al., 2002; Sandry et al., 2020).

The current pattern of findings fit with the absence of interactions between binding type and concurrent task that have previously been observed (Allen et al., 2009; Karlsen et al., 2010; see Baddeley et al., 2011). Those studies suggest equivalent executive control involvement across unitized, spatially separated, and cross-modality binding. Therefore, as strategic selective prioritization of an item from within a to-be-remembered sequence may itself have an executive control component (Atkinson et al., 2021; Hu et al., 2016), it then follows that this should be no more demanding for the different forms of binding currently under examination. An object-based attentional resource might also be important in actively maintaining visually unitized, spatially separated, and cross-modal bindings in working memory (Gao et al., 2017; Shen et al., 2015), though this yet to be explored in the context of directed prioritization.

The current findings also indicate that the limited benefits of value-directed prioritization observed by Johnson and Allen (2023) in olfactory-color binding may be associated with that specific combination of modalities, and particularly the requirement to handle olfactory information, rather than being more broadly indicative of any form of non-unitized binding. Spatially separated and cross-modal binding would each be classed as forms of relational (e.g. Parra et al., 2015) or extrinsic (Ecker et al., 2013) binding, with the unitized task capturing conjunctive or intrinsic binding in these respective taxonomies. For visually encountered features (either unitized or spatially separated), the multicomponent framework of Baddeley et al. (2021; Hitch et al., 2024) would capture this within the same working memory component (i.e. the visuospatial sketchpad). The critical difference between binding conditions in Experiment 1 lies in the availability of a shared spatial code. Feature integration theory highlights spatial location as key in feature binding (Treisman, 1982; Treisman & Gelade, 1980). Spatial coding is important in visual unitization, and spatial location plays a role in binding object features together (Rajsic & Wilson, 2014; Schneegans & Bays, 2017; Shepherdson et al. 2022). The spatial separation of features in

Experiment 1 (and Karlsen et al., 2010) means that this shared spatial location is lacking, preventing unitization. Common contextual timing signals based on position and/or time (Burgess & Hitch, 1992, 1999; Brown et al., 2000; Farrell, 2008) would still be available and potentially contribute to feature binding (Schneegans et al., 2023), and participants might also be able to generate a holistic representation of the shape-color pairing. However, the spatial separation and lack of unitization may result in less effective and more error-prone feature binding, which would explain overall reduced performance in this condition.

The observation of effective prioritization of items in the context of these lower overall accuracy levels indicates that ease or effectiveness of strategic prioritization does not necessarily improve with the broader accuracy or ease of the task (though it can become more important under greater working memory load, e.g. Atkinson et al., 2019). This stimulus-based observation is analogous to group difference observations in Allen et al. (2021), who found that older adults were relatively less accurate on a visual working memory task compared to a younger group, but just as able to prioritize high value items from the sequence. In Experiment 1 of the current series, selective attentional prioritization neither minimized nor exacerbated the difference between binding conditions. This would again indicate that the difference between unitized and spatially separated bindings likely emerges at a perceptual level rather than as an attentional impact (in line with Karlsen et al., 2010).

For cross-modal binding, visual and auditory features are encountered and processed separately. Under the multicomponent approach (Baddeley et al., 2021), this requires separate specialised components (visuospatial sketchpad and phonological loop) for initial registration. This information from different modalities would become simultaneously available in conscious awareness within the episodic buffer or focus of attention. Prioritization would then be applied within this modality-general format, as is assumed to be the case with any form of single or multimodal stimulus. Note that this description does not critically rest on accepting any one preferred working memory framework; most leading approaches assume activation of distinct capacities for visual and auditory information, with their association or combination captured in modality-general conscious awareness (e.g. Baddeley et al., 2021; Cowan et al., 2021; Barrouillet & Camos, 2021).

Contextual timing signals (e.g. Farrell, 2008) may also be particularly important in supporting binding between visual and auditory input. As participants were exposed to visual and auditory stimuli simultaneously in our experiments, this might help give rise to relatively automatic binding, which would also make prioritization more straightforward. In keeping with this, the prioritization effect for cross-modal binding was more reliably observed in Experiment 2b, when visual and auditory presentation timings were better matched, compared to Experiment 2a. The role of contextual timing signals was not a focus of the current study, and clear conclusions cannot be drawn as any direct comparison of encoding time between Experiments 2a and 2b is confounded by retention time; shorter exposure means that earlier items (including the first in the sequence) did not need to be retained for as long. This may reduce impacts of decay and interference, and help the participant actively maintain the first item during subsequent presentation and through to the test. It would be productive for future work to systematically examine how both exposure and maintenance duration impact on binding memory, and what is being selectively attended or deprioritized in this context.

Finally, the current findings offer intriguing possibilities regarding the nature of feature binding and the capacity of the focus of attention. If feature pairings that are separated in space or modality are stored as distinct (but linked) forms, their effective prioritization suggests a multi-item capacity for information in this state, at least for input that is sufficiently dissimilar and simultaneously encountered. This is in line with other evidence (e.g. Allen & Ueno 2018, Hitch et al. 2018, Souza & Oberauer 2016; Ueno & Allen, submitted) suggesting that 'more than one item, but probably less than four' (Cowan et al., 2024, p.190) can be concurrently prioritized in working memory. Alternatively, the notion of a single-chunk capacity can still be retained if we see both unitized and separated features as being held in this chunked form. Of course, a third possibility allows for both chunking of unitized and separated features, and a capacity for more than one item chunk to be concurrently prioritized within the focus of attention. The current experiments cannot clearly differentiate between these alternatives, and further exploration of chunking and capacity limits within working memory is clearly going to be useful.

Our aim in this study was to examine whether value-directed strategic prioritization can be effectively applied to working memory binding when the constituent features are separated either visually in space (Experiment 1) or across visual and auditory modalities (Experiment 2a and 2b). Firstly, we observed that spatial separation produced reduced binding accuracy relative to visually unitized objects, while cross-modal binding did not differ from the latter case, in each case replicating and extending prior findings. Furthermore, prioritization did not vary with binding condition; participants showed improved cued recall accuracy for higher value items when the features were visually unitized or separated, or when presented in different modalities. Thus, strategic direction of selective attention in working memory tasks is effective across different kinds of material and can be applied to distinct feature pairings that are not initially encountered as single objects.

Declarations

Funding: This work was supported by Republic of Turkey.

Conflicts of interest: The authors report no conflicts of interest.

Ethics approval: Ethical approved was granted by the School of Psychology Ethics Committee at the University of Leeds.

Consent to participate: All participants gave informed consent.

Consent for publication: All information is anonymized, with none of the participants being identifiable.

Availability of data and materials: All data and research materials are available at (https://osf.io/6yu84/?view_only=614c90ba6a14408c97d1b8ce29dce753).

Code availability: Not applicable.

Authors' contributions: Hatice Cinar: Conceptualisation, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, visualization, writing – original draft, writing – review and editing. **Amy Atkinson:** Conceptualisation, methodology, software, supervision, writing – review and editing. **Amanda Waterman:** Conceptualisation, methodology, supervision, writing – review and editing. **Richard Allen:** Conceptualisation, data curation, formal analysis, methodology, project administration, resources, software, supervision, visualization, writing – original draft, writing – review and editing.

Open Practices Statement: This study's design and its analysis were not pre-registered.

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