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Intentional and incidental odour-colour binding in working memory

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Abstract

The question of how features are bound together in working memory has become a topic of much research in recent years. However, this is typically focused on visual and/or auditory stimuli. The purpose of this study is to apply established feature binding procedures to investigate odour binding in working memory. Across three experiments, memory for intentionally and incidentally formed odour-colour pairings was tested. Experiment 1 showed that following explicit instruction to remember the odour-colour combinations, young adults can recall lists of 3-pairings at levels above that of chance and exhibit a recency advantage for the last pairing. In Experiment 2 participants were asked to prioritise the first pairing in the list or treat all pairings equally. We observed only limited evidence of prioritisation affecting the serial position function. Experiment 3 explored incidental odour-colour binding. Using a yes/no recognition procedure, accuracy did not differ for positive test probes presented in the same (bound) or different (unbound) colour to encoding. This study is one of the first to examine odour-colour binding in working memory and, taking the evidence together, suggests that odour-colour bindings can be formed in working memory; however, functionality may be limited compared to that of visual feature binding.

Intentional and incidental odour-colour binding in working memory

Binding is the process via which the component features of a stimulus or event are combined to form a unified representation in memory (e.g., Allen, 2015; Allen et al., 2006; Baddeley et al., 2011; Prabhakaran et al., 2000; Wheeler & Treisman, 2002). In visual working memory, surface-feature binding refers to the combination of visual features such as colour and shape (e.g., a green triangle) into temporary conjunctions. This process has been shown to be relatively automatic, as it survives secondary concurrent tasks such as backward counting and digit recall (Allen et al., 2006, 2009, 2012, 2014; Baddeley et al., 2011; see also Luck & Vogel, 1997, and Vogel et al., 2001; although for contrast see Brown & Brockmole, 2010, see also Delvenne & Bruyer, 2004, Olson & Jiang, 2002, and Wheeler & Treisman, 2002). However, these bound representations are thought to be fragile, with sequential presentation of the to-be-remembered bound representations selectively impairing earlier list items due to retroactive interference (Allen et al., 2006; Brown et al., 2017; Ueno et al., 2011; see Hitch et al., 2020 for a review).

The episodic buffer, a store within the multicomponent Working Memory Model (Baddeley & Hitch, 1974; Baddeley et al., 2021), has been implicated in the process of binding (e.g., Allen et al., 2006; Baddeley, 2000; Baddeley et al., 2011). This component was initially proposed by Baddeley (2000) to hold a limited number of chunks in a multi-dimensional code. If the representation of these conjunctions is not confined to a specific modality it logically follows that the buffer should hold cross-modal bindings. Support for this has indeed been shown with both visual-auditory (e.g., Allen et al., 2009; Gao et al., 2017; Guazzo et al., 2020; Jones et al., 2013; Wang et al., 2015, 2017), visual-spatial (e.g., Cowan et al., 2006), and verbal-spatial (e.g., Campo et al., 2010; Darling et al., 2017; Elsley & Parmentier, 2009, 2015) bindings. However, there is very little existing research on how odours might be bound to other feature dimensions in working memory and how this might interact with attention. The primary motivation of the study is to explore the functionality of odour-binding in working memory and begin exploring to what extent functionality might mirror that shown in more established domains such as visual binding. The following experiments are therefore one of the first to examine cross-modal binding in working memory from the perspective of incidental and intentional odour-colour binding. Our key questions concern (1) whether odours can be successfully bound to other stimuli in working memory and, if so, (2) to what extent does the pattern of performance reflect that shown for other modalities.

That cross-modal features can be bound to an olfactory stimulus is unclear, as the extent to which olfactory working memory exhibits functional similarities to that of other modalities is not well understood. Performance on the olfactory *n*-back task demonstrates that temporary maintenance of odorants can be performed at levels above chance (Dade et al., 2001; Jönsson et al., 2011; Moss et al., 2019), with reliance on verbal labelling/rehearsal being minimised via using hard-to-name odorants (Jönsson et al., 2011; Moss et al., 2019) and concurrent articulation (Moss et al., 2019). Short-term recognition of odorants is also above chance with serial position analysis providing some evidence of functional similarity with that of other modalities. Initial investigations into olfactory recognition and recall revealed a recency advantage, but no primacy (Annett & Lorimer 1995; White & Treisman, 1997); although primacy has been reported following verbal elaboration (Annett & Lorimer 1995; Miles & Jenkins, 2000). Recency is also reported for 2-alternative forced choice (2AFC) recognition of odorant sequences (Johnson & Miles, 2007; Miles & Hodder, 2005), consistent with that found with both verbal and visual stimuli (e.g., Avons, 1998; Phillips & Christie, 1977; Ward et al., 2005). Similarly, a recency advantage is found when the sequence is followed by a single yes/no recognition test odorant (Moss et al., 2018; a function also consistent with that found with visual stimuli, e.g., Hay et al., 2007; Johnson et al., 2014;

Kerr et al., 1999). These findings suggest mechanistic similarity in the short-term operation of olfactory recognition memory and that of other stimuli (although there is some preliminary evidence that order memory for odorants produces contradictory functions, Johnson et al., 2013; Johnson & Miles, 2009).

Evidence that olfactory short-term/working memory exhibits similarities to other modalities might lead one to predict olfactory cross-modal binding capabilities that mirror those reported for visual stimuli (e.g., Allen et al., 2009; Cowan et al., 2006). However, such a prediction is complicated by uncertainty as to how odorants are represented within the multicomponent Working Memory Model (WMM; Baddeley, 2000; Baddeley & Hitch, 1974). Employing the classic working memory dual-task procedure, Andrade and Donaldson (2007) showed that performance on a primary olfactory recognition memory task was disrupted by a secondary olfactory recognition task but not by either a secondary verbal or visual recognition task. This was taken as evidence that short-term olfactory memory is supported by a specialised component in working memory, rather than reliant on verbal or visual recoding (via the phonological loop and visuo-spatial sketchpad, respectively; see also Zelano et al., 2009, for imaging evidence). Based on these findings, Andrade and Donaldson (2007) proposed the addition of an olfactory buffer within the WMM. Alternatively, the most recent iteration of the multicomponent model (Baddeley, 2012; Baddeley et al., 2021) speculatively identifies odour as having a direct route into the episodic buffer where it is accessible to conscious awareness and can be temporarily stored and maintained via attentional refreshing. If the Episodic Buffer is recruited to support temporary maintenance of olfactory stimuli, it is possible that the storage of feature bindings involving odorants may respond in a similar way to those observed in visual memory.

This study describes three novel experiments that aimed to examine how binding between visual and olfactory features are maintained in working memory, using methodological approaches adopted from the literature on visual feature binding. We focus on odour-colour binding as there is good precedent that colour exhibits binding effects with features such as shape (e.g., Allen et al., 2006, 2009, 2012, 2014). Furthermore, attempting to pair olfactory stimuli with colour is prosaic given their co-occurrence in naturalistic environments. Thus we aim to maximise the opportunity of detecting binding effects with olfactory stimuli. Experiment 1 sought to establish the extent to which short sequences of colour-odour bindings can be encoded and retained in working memory for the purposes of an immediate cued recall task, and whether performance across the sequence exhibits the typical pattern of recency effect that is seen in visual feature binding (e.g., Allen et al., 2006, 2014). Here we test capability of working memory in storing odour-colour bound representations and explore whether the same fragility for representations seen in visual binding is evidenced via a recency effect. Experiment 2 then examined whether the observation from visual feature binding (e.g., Hu et al., 2014) that attention can be strategically allocated to one of the items in the sequence with observable changes in accuracy levels can be extended to this odour-colour binding task. Here we examine cross-domain functional capabilities in more detail by testing how attention can be selectively reallocated in the odour-colour binding task. Changes in the serial position function following reallocation of attention to a specific bound representation would replicate that shown with visual binding and support functional similarities between olfactory and visual binding. Finally, Experiment 3 explored whether evidence for incidental formation of colour-odour binding is observable in a change detection paradigm (e.g., Elsley & Parmentier, 2009). Here we examine the role of attention indirectly via testing whether odour-colour representations occur incidentally. If recall for an olfactory stimulus presented in a different coloured box to that encountered at learning (unbound) is impaired, it suggests that binding occurs incidentally consistent with that shown for verbal-spatial conjunctions (Elsley & Parmentier, 2009, 2015).

Experiment 1

Experiment 1 examines intentional odour-colour binding in working memory. In this experiment participants were presented with sequences of three odorants in different coloured containers. At test, participants received one of the odorants from the preceding sequence but in a neutral-coloured container and were required to state the colour of the container in which the odorant was originally presented. The perception of olfactory stimuli necessitates the sequential presentation of the to-be-remembered pairings and this procedure broadly follows that described by Hu et al. (2014, see also Allen & Atkinson, 2021; Allen et al., 2014, 2021; Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2016), in which a series of shape-colour conjunctions are presented, with participants given a shape or a colour at test and asked to state the feature with which that item was originally combined. This task has revealed strong recency effects (see also Allen et al., 2006, Experiment 5, who reported lower accuracy for pre-recency conjunctions). The recency advantage for these conjunctions suggests that representations of bound features are relatively fragile and susceptible to retroactive interference. The final item in the sequence may also be more likely to be held in a readily accessible, privileged state within the episodic buffer (Hitch et al., 2020), analogous to the focus of attention within the embedded processes model (Cowan et al., 2021). If olfactory WM shares the characteristics of visual WM, we predict, firstly, above chance performance illustrating an ability to intentionally bind odour-colour pairings, and, secondly, a serial position function that exhibits a memory advantage for the last item (i.e., recency).

Method

Participants

Twenty-four Bournemouth University undergraduates (16 females and 8 males, mean age = 20.04, *SD* = 1.88) participated in exchange for course credit or an honorarium. Participants who self-reported olfactory impairments (e.g., symptoms of cold) and smoking (Katotomichelakis et al., 2007) were excluded. Ethical approval was obtained via the Bournemouth University Ethics Committee (approval code: 26043).

Materials

The odorants were selected from a corpus of 200 food and non-food related odorants, prepared by AromaPrime Ltd. (www.aromaprime.com), on the basis of normative scores reported by Moss et al. (2016). Each odorant comprised a liquid soaked in gauze contained within a 50 x 50 x 50-mm cube. One face of the cube had six perforations arranged in a circular array from which the odour could be inhaled. Four odorants were used (see Table 1) and were selected on the basis of receiving low verbalisability scores (see Moss et al., 2016). The verbalisability scores obtained from Moss et al. followed the rating of odorants from 0-3 according to the quality of the label, with a lower score indicative of a vague/affective label and a higher score indicative of a specific noun. In addition, the odorants in the present experiment were matched on familiarity, intensity, and hedonic strength.

Table 1

Table 1. *Normative ratings (Moss et al., 2016) for odours selected for Experiment 1.*

Odour	Verbalisability	Familiarity	Intensity	Hedonic Strength
Rum Barrel	1.26	3.10	5.18	1.56
Carbolic Soap	1.05	3.61	5.10	1.33
Patchouli	1.62	3.55	5.06	1.31
Mouse	1.53	3.36	5.06	1.50

Each odorant was presented in five different coloured cubes: red, yellow, green, blue, and white; with the latter obtained by wrapping a cube in white tape.

Design

Using an odour-cued colour recall task, a single-factor within-participants design was employed with the variable serial position (1-3). Specifically, in each trial we manipulated whether the test odorant was presented first, second, or third during the presentation phase. Across the 48-trial experiment, each serial position was probed an equal number of times (16) and each odorant was used as the test probe an equal number of times. Specifically, on the 12 trials where each odorant was used as the test probe, that odorant was testing each serial position an equal number of times, i.e., on 4 occasions. During the presentation phase, odorants were sampled from a stimulus set of 16 odorants; the four odorants in red, blue, yellow, and green. Each odorant-colour combination was used an equal number of times across the presentation phase of the experiment (9) and each odorant-colour combination was the item for which participants were subsequently tested on an equal number of occasions (3). This served to balance the effect of certain odorants possessing pre-existing associations with specific colours (see Demattè, et al., 2006; de Valk et al., 2017; Gilbert et al., 1996). Using these restrictions, an experimental protocol was developed for the 48 trials, with the order of these trials randomised for each participant. Within the skeleton template of the protocol, odorants were listed as letters (A, B, C, and D); the assignment of the 4-odorants to these different letters was fully counterbalanced across the 24 participants.

Procedure

The experiment was conducted in a quiet, well-ventilated room with a fan to circulate fresh air. Participants were tested individually and sat opposite the experimenter, separated by a wooden obfuscation screen. Figure 1 shows a visual depiction of a trial. Each trial was initiated via a verbal cue from the experimenter and then comprised the presentation of 3 different odorants each in a different coloured cube. Each odorant was individually held under the nose of the participant for 2s with a 2s inter-stimulus-interval. To present each stimulus, the experimenter removed the plastic lid from the top of the odorant to reveal the six perforations. The experimenter then held the odorant under the nose of the participant with the perforations directly underneath the nostrils. At test, participants received one of the previous 3 odorants, but this was presented in a neutral white coloured cube. The participant was required to verbally state the colour of the cube in which the test odorant was originally presented. Participants completed 48 trials, divided into 4 blocks of 12 trials, with a 2-3-minute rest period between blocks. The inter-trial interval was approximately 30s. The entire experiment lasted approximately 45 minutes.

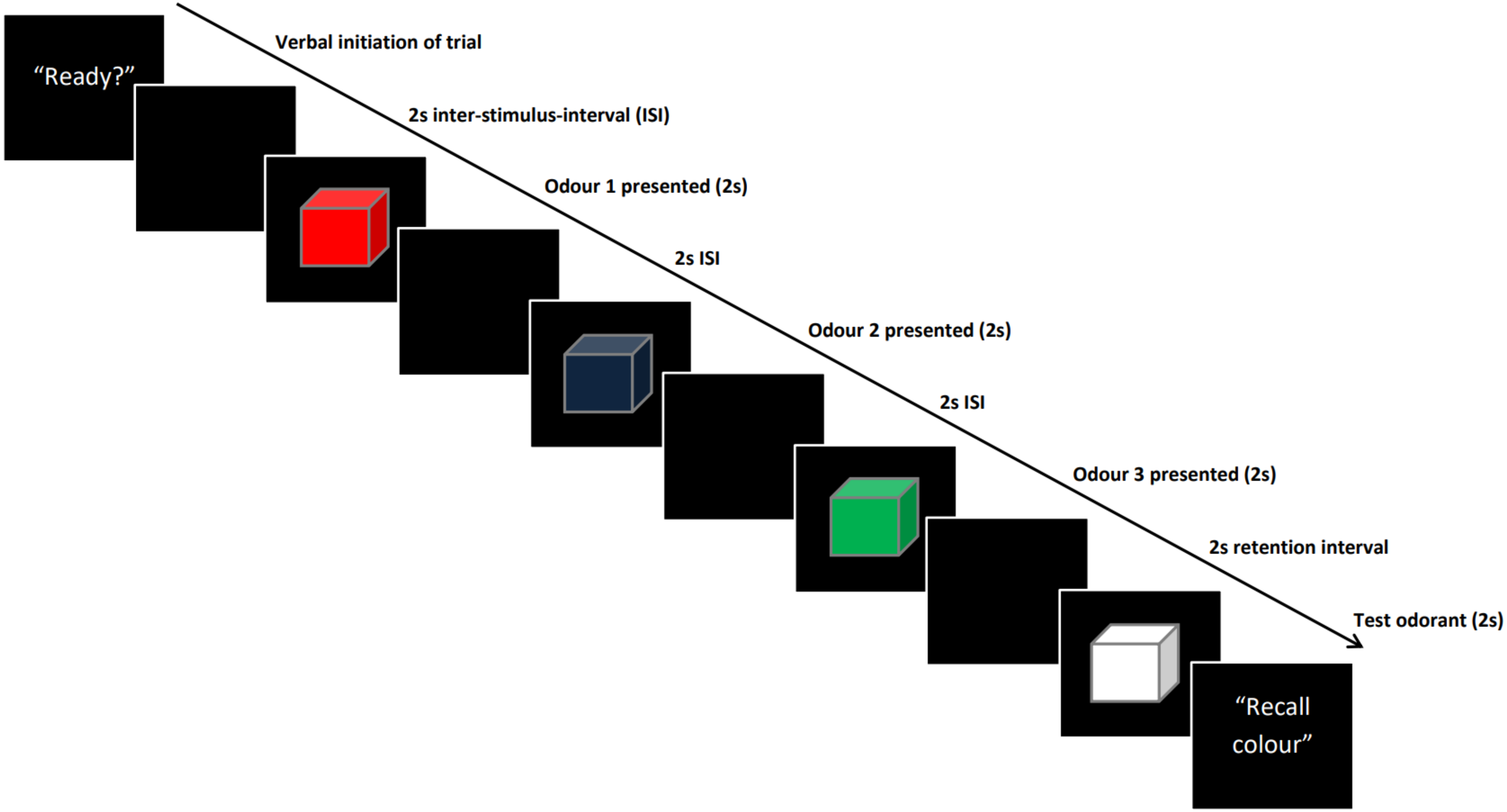

Figure 1. Schematic representation of a trial in Experiment 1. The test odorant (presented via the neutral white cube) is one of the odours from the preceding presentation phase. The participant is required to recall the colour of the odorant from which this test odour was initially presented. For example, if memory for serial position 1 was being tested, the test odorant would contain the same odour used in the red odorant. For a correct response, the participants must verbally respond "red".

Data Analysis

Analyses were conducted using JASP 0.9.1.0 (JASP Team, 2019). In addition to frequentist analysis, Bayes factors (BF) were reported (using default priors) as a continuous estimation of the strength of evidence for the data under the null and alternative hypothesis (e.g., Dienes & Mclatchie, 2018). When BF is >1 the evidence anecdotally supports the alternative hypothesis (with BF > 3 considered substantial evidence) and when BF is <1 the evidence anecdotally supports the null (with BF < 0.33 considered substantial evidence).

Results

Figure 2 displays the serial position function for the odorant-colour bindings. For each serial position, recall is assessed via the proportion of trials in which participants correctly recall the colour with which the test odorant was originally presented. Figure 1 shows that (1) participants can perform the task above that of chance (each trial uses 3 different colours, therefore chance = .33; however, given that 4 colours are used throughout the experiment, intrusion errors could result in a lower score of .25 following guessing), and (2) a recall advantage is evident for the last list item. A single-factor within-participants ANOVA was conducted and revealed a main effect of serial position, $F(2, 46) = 8.236$, $MSE = 0.022$, $p < .001$, $\eta_p^2 = .264$, $BF_{10} = 131.202$. Post-hoc Bonferroni-corrected ($\alpha = .017$) t-tests revealed accuracy at serial position 3 was significant greater than both serial positions 1 ($t(23) = 3.519$, $p = .002$, $d = 0.718$, $BF_{10} = 20.594$) and 2 ($t(23) = 3.181$, $p = .004$, $d = 0.649$, $BF_{10} = 10.193$). There was strong evidence in favour of a null difference between serial positions 1 and 2 ($t(23) = 0.536$, $p = .597$, $BF_{10} = 0.245$).

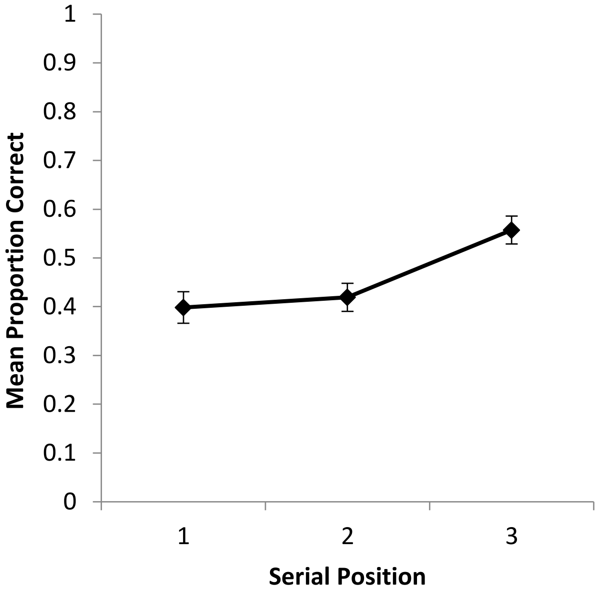

Figure 2. Mean proportion accuracy for colour recall as a function of serial position. Error bars denote the mean standard error.

Discussion

Experiment 1 demonstrates that participants can perform an intentional odour-colour binding task. Whilst performance was low (average proportion accuracy = .45), the serial position function displayed the recency effect reported for the visual analogue of this task using colour-shape binding (Allen et al., 2020; Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016). Thus, Experiment 1 suggests that working memory for odour-colour binding may share common functional characteristics with those established for visual binding. The recency effect is consistent with the proposed fragility of bound representations, where earlier bound representations are disrupted by retroactive interference (e.g., Allen et al., 2006), while the final sequence item remains relatively more intact and accessible within the focus of attention (Hitch et al., 2020). Within the multicomponent model (Baddeley, 2012; Baddeley et al., 2021), this focus of attention is described as a modality-general episodic buffer, a component capable of holding intact object files, typically for the most recently encountered stimulus (Hitch et al., 2020). Indeed, it has been speculatively suggested that olfactory information might be maintained within the episodic buffer (Baddeley, 2012; Baddeley et al., 2021).

However, it is worth emphasising that whilst odour-colour binding exhibited similarities with visual colour-shape binding, both in respect to being able to perform the task and showing a recency advantage, performance was substantially lower for the odour task. Specifically, in a similar procedure described for cued recall of 3-item colour-shape bindings Allen et al. (2014, Experiment 3) and Allen et al. (2020) reported accuracy levels > 60% despite the additional inclusion of concurrent articulation. There are three possible explanations for such relative low performance in the present experiment compared to colour-shape binding. First, olfactory memory tends to be poorer in general; this, in part, is due to the experimentally noisy nature of testing the chemical senses. For example, in a 4-item single yes/no recognition procedure, Moss et al. (2018) reported substantially higher recognition sensitivity for verbal and visual stimuli compared to odours. The second point of note is that the present study involves cross-modal pairings (visual and olfactory), compared to the same modality (visual) pairings in the aforementioned previous studies (e.g., Allen et al., 2006, 2020; Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016). It is possible that forming cross-modal binding incurs greater cost on cognitive resources due to combining information from modality-specific stores. Indeed, these costs may be greater for the present pairings due to temporal differences in the perception of olfactory and visual stimuli. It is, however, worth noting that Allen et al. (2009) reported equivalent overall accuracy and dual-task costs for cross-modal visual-verbal binding compared to memory for same modality (i.e., visual-visual) conjunctions (see also Guazzo et al., 2020). These findings suggest that cross-modal binding, per se, does not result in a dramatic drop in accuracy. Third, low performance levels for odour-colour bindings might suggest mechanistic differences between olfactory and visual binding in working memory.

The recency advantage for odour-colour pairings reported in Experiment 1 is consistent with that reported for colour-shape bound representations (e.g., Allen et al., 2006, 2020; Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016). This recency advantage is also consistent with other measures of olfactory working memory where recency has been shown for recognition (Johnson & Miles, 2007; Miles & Hodder, 2005, Moss et al., 2018; Reed, 2000; White & Treisman, 1997) and serial recall (Annett & Lorimer, 1995; Johnson et al., 2013; Miles & Jenkins, 2000). It is worth noting, however, that there exists limited evidence of a primacy benefit for olfactory memory (see Miles & Hodder, 2005, for failed replication of Reed, 2000; and the primacy reported by Miles & Jenkins, 2000, is attributable to the use of verbal labels, see also Annett & Lorimer, 1995) and this in part may be due to tasks characterised by primacy, such as immediate serial recall and serial order reconstruction, being unsuitable for olfactory stimuli. There is, however, some evidence of a primacy advantage using the currently employed cued recall task following explicit instruction to prioritise memory for the first conjunction in the list (Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016; although see null effect at serial position 1 reported by Allen et al., 2020). Indeed, participants can prioritise more valuable information in working memory resulting in improved recall for high value items across all serial positions (Allen et al., 2020; Allen & Atkinson, 2021; Atkinson et al., 2020; with prioritisation effects observed also in children and older adult samples, Allen et al., 2020; Atkinson et al., 2019). This memory facilitation for high value items is typically offset by memory decrements to the lower value items in the list. These findings show that attentional resources for these tasks are finite and that participants can strategically redistribute these resources to specific positions within the to-be-remembered sequence.

Experiment 2 examines whether such working memory prioritisation effects can be found for memory of odour-colour pairings. This is of interest for two reasons. First, it is unknown whether the same strategic redistribution of resources shown with visual memory can be employed for olfactory working memory. Value-based prioritisation effects in visual and verbal working memory have been attributed to active maintenance of more valuable items in the focus of attention (Hitch et al., 2020; Hu et al., 2014), so it is informative to establish the extent to which binding involving olfactory information can be prioritised in the same way. Along similar lines, a candidate mechanism underlying prioritisation is that of attentional refreshing (e.g., Camos et al., 2018; Johnson et al., 2002), and this may offer one way in which olfactory information is actively maintained (Baddeley, 2012; Baddeley et al., 2021). Evidence regarding the presence or absence of such effects will therefore speak directly to the functionality for olfactory working memory. Second, detection of a reliable primacy effect for olfactory memory has proven elusive, and it is difficult to determine whether this is due to functional differences of olfactory memory or cross-modal task incongruency (Ward et al., 2005, argue that the serial position is task, rather than stimulus, dependent). By applying a methodology shown to produce primacy in visual memory to olfactory stimuli, we can test directly whether olfactory serial position functions qualitatively differ cross-modally with respect to primacy.

Experiment 2

To our knowledge, Experiment 2 is the first to examine working memory prioritisation effects in olfactory memory. Here we repeat the method described in Experiment 1 but include an additional block of 48-trials with a prioritisation condition (following the instructions outlined in Allen et al., 2020; Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016). Specifically, in the control block, participants were instructed to try and remember all pairings equally, whereas in the prioritisation block, they were told that they would receive more points for correctly recalling the first pairing in the sequence. Participants were aware that these points were purely notional and that each item in the sequence was equally likely to be tested at cued recall. If working memory resources can be strategically reallocated for olfactory memory, we predicted that primacy should develop in the prioritisation condition, illustrated via a prioritisation condition by serial position interaction. This should emerge in the context of no overall main effect of prioritisation (Hu et al., 2014), indicating the reallocation of limited capacity resources according to item priority.

Method

Participants

Twenty-four Bournemouth University undergraduates (18 females, 5 males, and 1 non-binary; mean age = 21.46, *SD* = 3.54) participated in exchange for course credit or an honorarium. The same exclusion criteria were applied as described for Experiment 1. None had participated in Experiment 1.

Materials

The odorants were as described for Experiment 1, with the addition of a second list of low verbalisable odorants (see Table 2).

Table 2

Table 2. *Normative ratings (Moss et al., 2016) for odours selected for Experiment 2.*

Odour	List	Verbalisability	Familiarity	Intensity	Hedonic Strength
Rum Barrel	1	1.26	3.10	5.18	1.56
Carbolic Soap	1	1.05	3.61	5.10	1.33
Patchouli	1	1.62	3.55	5.06	1.31
Mouse	1	1.53	3.36	5.06	1.50
Sea Shore	2	1.53	2.96	5.20	1.84
Ginger	2	1.66	3.39	5.22	1.39
Burning Peat	2	1.67	3.81	5.38	1.54
Cardamom	2	1.54	4.08	5.08	1.52

Design

A (2x3) multi-factorial within-participants design was employed where the first factor concerned working memory prioritisation (no prioritisation versus prioritise the first odour-colour pairing in the list) and the second factor was serial position (1-3). Participants undertook two blocks of 48-trials separated by at least 24 hours. A different list of 4 odorants was used for each block, with the trial construction of each block following that described for Experiment 1. Each block included either the no prioritisation or the prioritisation trials, with the order of these blocks counterbalanced across participants.

Procedure

The procedure followed that described for Experiment 1, with the exception that participants undertook two 48-trial sessions. The no-prioritisation condition was as described for Experiment 1. For the prioritisation condition, the procedure was based on that of Atkinson et al. (2018; also, Allen et al., 2020). Thus, participants were told (via a PowerPoint presentation narrated by the experimenter) that they should: “Try extra hard to remember the first one. The first odour will be tested as often as the other odours, but you will get more points if you are asked about that odour and you get the answer right. If you are tested on the first odour and you get it right, you will get 4 points! If you are tested on any other odour and you get it right, you will get 1 point.” As in Experiment 1, the session was divided into four 12-trial sub-blocks and during that interval participants were reminded of the prioritisation instruction.

Results

Figure 3 displays the serial position function for the odorant-colour bindings in the no-prioritisation and prioritisation condition.

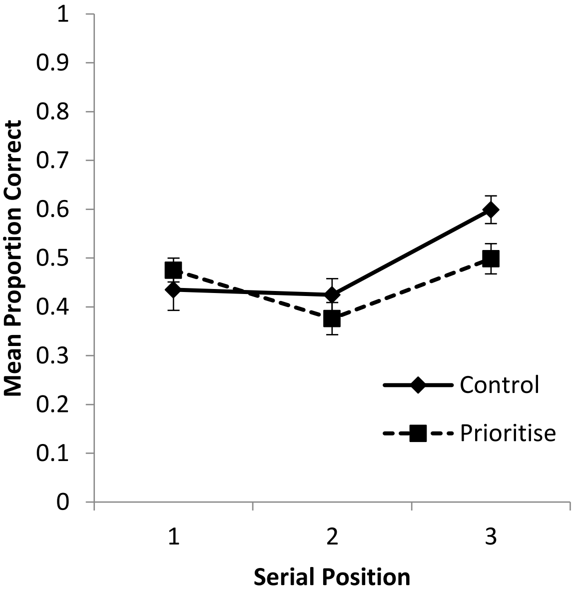

Figure 3. Mean proportion accuracy for colour recall for the control (no prioritisation) and prioritisation condition as a function of serial position. Error bars denote the mean standard error.

A multifactorial (2x3) within-participants ANOVA was conducted with the factors of prioritisation (no prioritisation and first-item prioritisation) and serial position (1-3). The main effect of prioritisation was non-significant, $F(1, 23) = 1.855$, $MSE = 0.025$, $p = .186$, $\eta_p^2 = .075$, $BF_{10} = 0.541$, whereas the main effect of serial position was significant, $F(2, 46) = 10.218$, $MSE = 0.026$, $p < .001$, $\eta_p^2 = .308$, $BF_{10} = 2523$. Importantly, the interaction between prioritisation and serial position was also significant, $F(2, 46) = 4.740$, $MSE = 0.013$, $p = .013$, $\eta_p^2 = .171$, $BF_{10} = 1.27$, although it should be noted that Bayesian support for the interaction was only weakly positive.

To explore the interaction in more detail, separate one-way ANOVAs were computed for serial position on the no prioritisation and prioritisation conditions. For the no prioritisation condition, the main effect of serial position was significant, $F(2, 46) = 12.250$, $MSE = 0.019$, $p < .001$, $\eta_p^2 = .348$, $BF_{10} = 600.818$. Post-hoc Bonferroni-corrected ($\alpha = .017$) t-tests revealed accuracy at serial position 3 was significant greater than both serial positions 1 ($t(23) = 3.539$, $p = .002$, $d = 0.722$, $BF_{10} = 21.504$) and 2 ($t(23) = 4.402$, $p < .001$, $d = 0.899$, $BF_{10} = 141.520$). There was strong evidence in favour of a null difference between serial positions 1 and 2 ($t(23) = 0.334$, $p = .741$, $BF_{10} = 0.226$). This analysis supports the presence of recency but no primacy, consistent with the trend reported for Experiment 1. For the prioritisation condition, the main effect of serial position was significant, $F(2, 46) = 4.944$, $MSE = 0.021$, $p = .011$, $\eta_p^2 = .177$, $BF_{10} = 8.259$. Post-hoc Bonferroni-corrected ($\alpha = .017$) t-tests revealed accuracy at serial position 2 was significantly lower than both serial positions 1 ($t(23) = -2.952$, $p = .007$, $d = 0.603$, $BF_{10} = 6.429$) and 3 ($t(23) = -2.740$, $p = .012$, $d = 0.559$, $BF_{10} = 4.253$). There was strong evidence in favour of a null difference between serial positions 1 and 3 ($t(23) = 0.515$, $p = .612$, $BF_{10} = 0.242$). This trend supports evidence of a bowed serial position function with both primacy and recency.

Discussion

Experiment 2 is the first experiment (to our knowledge) to examine working memory prioritisation effects in olfactory memory. Instruction to prioritise memory for the first odour-colour pairing in the sequence resulted in the shape of the function changing from recency to a more quadratic/bowed function with a small primacy and recency advantage. This shift followed a small increase in accuracy at position 1 and a reduction in accuracy for positions 2 and 3. Indeed, for the prioritisation condition, position 1 accuracy was statistically equivalent to that of the final sequence position, indicating some evidence for the strategic reallocation of attention between items in the sequence. It is, however, worth emphasizing that these prioritisation effects are smaller than those reported previously for shape-colour binding (Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2016), where primacy instruction typically led to a double digit percentage increase in accuracy for the prioritised item (even when performed under additional cognitive load, Hu et al., 2016; although it is worth noting that Allen et al., 2021, failed to find a prioritisation effect for serial position 1 with a 3-item load).

The control (no prioritisation) condition replicated the serial position function reported for Experiment 1 in showing (i) that participants can intentionally form odour-colour bindings, albeit at relatively low performance levels, and (ii) that a recency advantage is found for memory of the last pairing in the sequence. That the prioritisation effects were weak in Experiment 2 may relate to the generally low performance levels on the task (relative to colour-shape conjunctions, e.g., Allen et al., 2021; Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2016). Another possibility is that prioritisation is generally less effective for cross-modal binding. Indeed, previous studies have focused on within-modality conjunctions, although as noted earlier Allen et al. (2009) reported no performance costs for cross- compared to within-modality binding. Finally, it is possible that olfactory working memory has reduced functionality compared to that of visual working memory, i.e., there is less capability to strategically reallocate resources between components of the list and actively maintain early sequence items within the focus of attention using attentional refreshing.

A secondary aim of Experiment 2 was to explore whether primacy effects could be found with olfactory memory using a task (i.e., recall of paired features with primacy prioritisation) that has been shown to produce primacy in other (i.e., visual) modalities (e.g., Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016). Whilst the olfactory working memory serial position function became more quadratic, the magnitude of primacy in the prioritisation condition was only slightly (4%) higher than the control (no prioritisation) condition. The development of primacy was not compelling and therefore, it remains for future work to resolve whether olfactory working memory (that is not reliant upon verbal recoding, Miles & Jenkins, 2000) can produce clear primacy effects.

Experiment 3

Experiments 1 and 2 have shown some evidence that memory for odour-colour pairings exhibit similarities to that of visual memory, namely an ability to store bound representations in working memory with a specific recall advantage for the last item in the sequence. We have shown in two experiments that participants can remember odour-colour pairings following explicit instruction and that this task produces a recency effect. Experiment 2 also demonstrated some weak evidence of qualitative changes in accuracy across serial position following instruction to prioritise the first pairing in the sequence, although the magnitude of these effects was reduced relatively to those typically seen in visual memory. Experiment 3 aimed to further develop our understanding of olfactory binding by testing evidence for the incidental formation of bound olfactory-based representations; here, we examine whether additional features (in this instance colour) are bound to olfactory stimuli without explicit task instruction in a working memory task.

There exists a large body of evidence demonstrating that olfactory stimuli are encoded incidentally alongside other to-be-remembered stimuli. Reinstatement of an odorant at test that was presented during encoding has been shown to facilitate long-term memory for verbal stimuli (Parker & Gellatly, 1997), faces (Hackländer & Bermeitinger, 2017), semantic information (Aggleton & Waskett, 1999), spatial information (Parker et al., 2001), and old autobiographical events (Larsson et al., 2014). In addition, fMRI studies have shown that when a visual stimulus is encoded alongside an odour, reinstatement of that visual stimulus can activate the olfactory cortex despite an absence of olfactory stimuli (Gottfried et al., 2004; Karunanayaka et al., 2015), thus indicating the incidental formation of a visual-olfactory engram. These studies demonstrate that long-term associations can be formed between to-be-remembered stimuli and incidentally presented odorants. Experiment 3 explores associations between olfactory and visual stimuli where the incidental stimulus is the colour of the odorants.

Incidental feature binding is typically tested by presenting a set of features such as letters in different spatial locations (Campo et al., 2010; Elsley & Parmentier, 2009, 2015). Participants are instructed to remember one feature in the study (e.g., the letter). At test, they receive a single yes/recognition test for the letter, with the important comparison being recognition accuracy for positive test probes (requiring a “yes” response”) that were presented in the same spatial location as at learning (intact probes) or a different spatial location (recombined probes). Higher recognition accuracy and faster response latencies have been observed for intact test probes, compared to recombined probes (Elsley & Parmentier, 2009, 2015). This was taken as evidence of incidental letter-location binding, as disruption of these bindings at test negatively impacted on recognition (although there is some evidence of verbal-spatial incidental binding being asymmetric, Elsley & Parmentier, 2015).

Experiment 3 employed a modified version of this incidental binding methodology. In the encoding phase, participants were presented with a sequence of odorants in different coloured cubes. At test, participants received a single test odorant and were required to state if that odorant was in the preceding sequence (a recognition task similar to that described in Moss et al., 2018). Participants only received instruction to remember the odours, with the key manipulation being whether the test probe was in the same (bound) or different (unbound) coloured cube as learning. Evidence of incidental binding would be shown via superior recognition for odorants re-presented in the same, compared to a different, coloured cube to that at learning. It is, however, worth noting that due to the nature of olfactory input, stimuli were presented sequentially in the encoding phase rather than simultaneously (as in Campo et al., 2010; Elsley & Parmentier, 2009, 2015). It is therefore possible that the sequential presentation of odour-colour pairings may be subjected to retroactive interference, evidenced via a recency effect (as shown with the intentional binding in Experiments 1-2). Indeed, an advantage of sequential presentation is that it enables us to test the (hitherto under explored) serial position effects for incidental binding. Single probe yes/no recognition for odorants has been shown to exhibit recency only (Moss et al., 2018; consistent with that shown for visual memory, e.g., Hay et al., 2007; Johnson et al., 2014; Kerr et al., 1999), therefore we predict a main effect of serial position. In addition, evidence for incidental binding would be expected to emerge via a main effect of the binding condition. However, if incidental binding is more pronounced for the recency component (as shown with intentional binding), we predict higher recognition accuracy for the last list item in the bound condition evidenced via a serial position by binding interaction.

Elsley and Parmentier (2009) used response latencies as an additional measure of binding. The present procedure does not lend itself to a sensitive measurement of response times. Instead, we employed the additional measure of recognition confidence ratings (as described by Moss et al., 2018). In that study, despite canonical recognition serial position effects, the confidence ratings produced a flat function. Evidence of incidental binding would therefore be shown via a main effect of binding condition (with confidence increasing across the serial positions for the bound condition), or, if incidental binding is confined/more pronounced for the last list item, the development of recency in the bound condition.

Method

Participants

Twenty-four Bournemouth University undergraduates (23 females and 1 male, mean age = 19.96, *SD* = 1.23) participated in exchange for course credit. The same exclusion criteria were applied as described for Experiment 1. None had participated in Experiment 1 or 2.

Materials

The odorants were sampled from the same stimulus set as described for Experiment 1 (see Table 3 for list of odorants). Each odorant was presented in four different coloured cubes (red, yellow, green, and blue).

Table 3

Table 3. *Normative ratings (Moss et al., 2016) for odours selected for Experiment 3*

Odour	Verbalisability	Familiarity	Intensity	Hedonic Strength
Carbolic Soap	1.05	3.61	5.10	1.33
Cardamom	1.54	4.08	5.08	1.52
Patchouli	1.62	3.55	5.06	1.31
Sea Shore	1.53	2.96	5.20	1.84

Design

Using a single probe yes/no recognition task, a multifactorial (2x3) within-participants design was employed testing the variables odour-colour incidental binding (bound and unbound) and serial position (1-3). Across the 48-trial experiment (see Figure 4 for a schematic of the experimental procedure), half of the trials used a test odorant that was presented in the preceding sequence. These 24 ‘hit’ trials (which required a “yes” response from participants) were subdivided into 12 bound and 12 unbound trials. In the bound trials, the test odorant was presented in the same colour cube as used when presented during the preceding 3-item sequence. In the unbound trials, the odorant is presented in a coloured cube not used in the preceding sequence. There were 24 ‘lure’ trials (requiring a “no” response) where the test odorant was not presented in the preceding 3-item sequence. For 12 of these trials the lure odorant was presented in a coloured cube not used in the preceding sequence, whereas for the remaining 12 trials, the lure odorant was presented in a colour used in the preceding colour (with this colour sampled from positions 1, 2, and 3 on an equal number of trials).

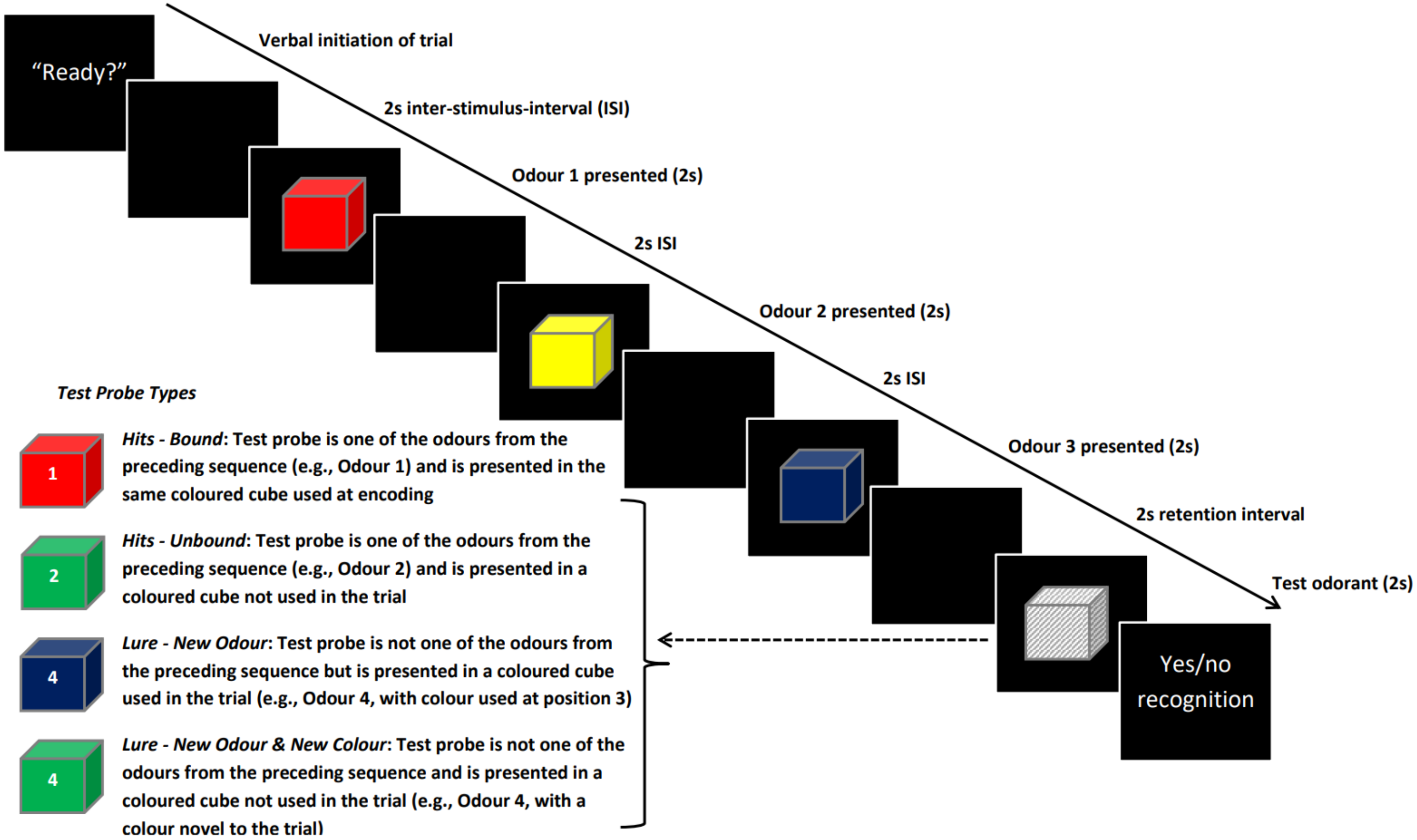

Figure 4. Schematic representation of a trial in Experiment 3. The participant is required to state whether the test odour was presented in the preceding trial (yes/no recognition). There are 4 types of test odorants: 1. *Hits - bound* (where the test odour was presented in the preceding sequence in the same coloured odorant); 2. *Hits - unbound* (where the test odour was presented in the preceding sequence but in a coloured cube not used in the trial); 3. *Lures – new odour* (where the test odour was not presented in the preceding sequence but is presented in a coloured cube used in this trial); and 4. *Lures –new odour and new colour* (where the test odour was not presented in the preceding sequence and is presented in a coloured cube not used in this trial).

For the hit trials, each serial position was probed an equal number of times (8), with this equally distributed across the bound and unbound trials. During the presentation phase, odorants were sampled from a stimulus set of 16 odorants: the four odorants in red, blue, yellow, and green. Each odorant-colour combination was used an equal number of times across the presentation phase of the experiment (9). Using these restrictions, an experimental protocol was developed for the 48 trials, with the order of these trials randomised for each participant. Within the skeleton template of the protocol, odorants were listed as letters (A, B, C, and D); the assignment of the 4-odorants to these different letters was fully counterbalanced across the 24 participants.

Three dependent variables were recorded. Recognition accuracy was recorded as proportion of hits (correct recognition for a positive test odorant) and false alarms (incorrect test odorant recognition for a lure). In addition, confidence ratings were recorded for all responses ranging from 1 (guess) to 5 (certain) (see Moss et al., 2018).

Procedure

The procedure was as described for Experiment 1 with the exception that participants were instructed only to remember the odorants presented in the preceding sequence. At test, participants received a single odorant and were required to state whether the odour was included in the preceding sequence. Participants provided a verbal “yes” or “no” response followed by a verbally articulated confidence rating for their response (1-5). Participants completed 48 trials, divided into 4 blocks of 12 trials, with a 2-3-minute rest period between blocks. The entire experiment lasted approximately 45 minutes.

Results

Figure 5a displays the serial position functions for hits in the bound and unbound conditions. A multifactorial (2x3) within-participants ANOVA was conducted on the hits with the factors incidental binding (bound and unbound) and serial position (1-3). The main effect of incidental binding was non-significant, $F(1, 23) = 0.043$, $MSE = 0.091$, $p = .838$, $\eta_p^2 = .002$, $BF_{10} = 0.179$, whereas the main effect of serial position was significant, $F(2, 46) = 3.893$, $MSE = 0.045$, $p = .027$, $\eta_p^2 = .145$, though only weakly positive in Bayesian analysis ($BF_{10} = 1.80$). Post hoc (Bonferroni-corrected, $\alpha = .017$) t-tests revealed that serial position 3 was significantly greater than serial position 1 ($t(23) = 2.632$, $p = .015$, $d = 0.537$, $BF_{10} = 3.368$). The advantage for serial position 3 over position 2 was not significant after Bonferroni correction ($t(23) = 2.209$, $p = .037$, $d = 0.451$, $BF_{10} = 1.637$). There was strong evidence in favour of a null difference between serial positions 1 and 2 ($t(23) = 0.249$, $p = .806$, $d = 0.051$, $BF_{10} = 0.221$). The interaction between incidental binding and serial position was non-significant, $F(2, 46) = 0.870$, $MSE = 0.031$, $p = .426$, $\eta_p^2 = .036$, $BF_{10} = 0.203$.

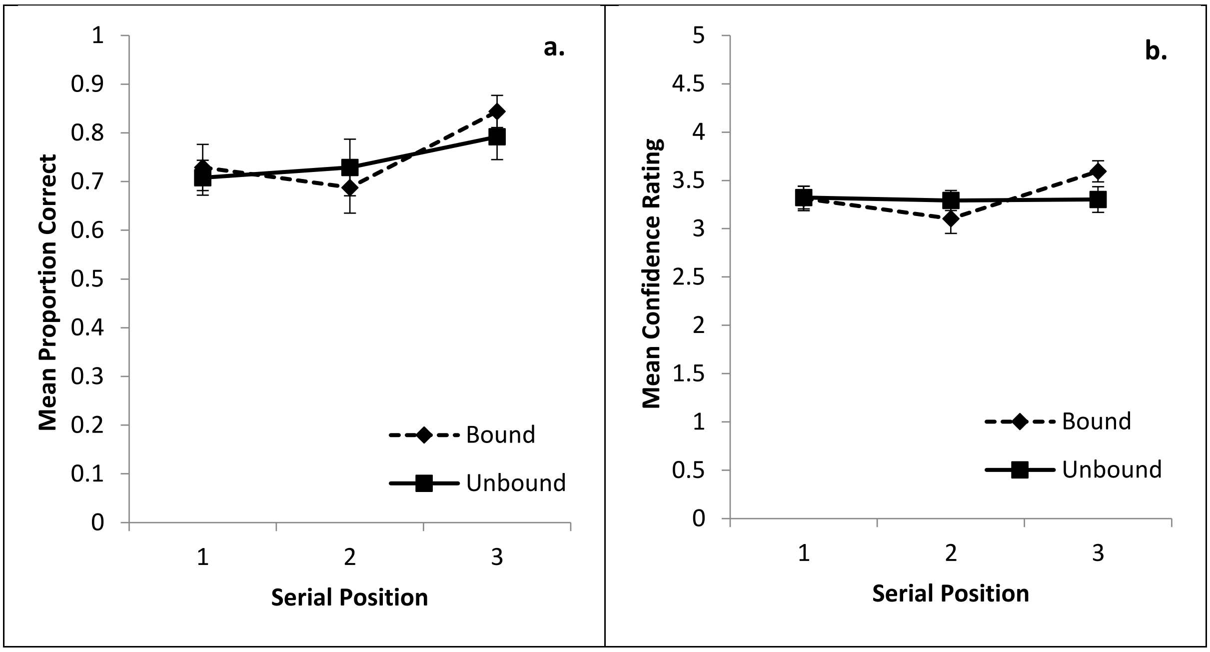

Figure 5 (a-b). Mean recognition proportion correct (a) and confidence rating (b) for the bound and unbound condition as a function of serial position. Error bars denote the mean standard error.

Figure 5b displays the serial position functions for response confidence rating (1-5) in the bound and unbound conditions. The same multifactorial (2x3) within-participants ANOVA was conducted on the confidence ratings. The main effect of incidental binding was non-significant, $F(1, 23) = 0.203$, $MSE = 0.173$, $p = .838$, $\eta_p^2 = .002$, $BF_{10} = 0.191$, as was the main effect of serial position, $F(2, 46) = 3.013$, $MSE = 0.249$, $p = .059$, $\eta_p^2 = .116$, $BF_{10} = 1.279$. The interaction between incidental binding and serial position was significant, $F(2, 46) = 3.846$, $MSE = 0.704$, $p = .029$, $\eta_p^2 = .143$, $BF_{10} = 1.585$. This interaction was examined further by comparing confidence at each serial position for the bound and unbound condition (using Bonferroni-corrected t-test, $\alpha = 0.017$). Substantial evidence in favour of a null difference at serial position 1 was observed, $t(23) = 0.085$, $p = .933$, $d = 0.017$, $BF_{10} = 0.215$. The difference between bound and unbound at serial position 2 was non-significant, $t(23) = 1.619$, $p = .119$, $d = 0.330$, $BF_{10} = 0.670$. At serial position 3, the higher confidence rating for the bound condition did not reach significance after correction, $t(23) = 2.274$, $p = .033$, $d = 0.464$, $BF_{10} = 1.827$.

Although the interaction was statistically significant, Bayes Factors for both the interaction and the comparison at serial position 3 suggest that evidence for this effect is relatively weak (albeit positive).

Despite being informed that the odorant colour was task-irrelevant, it is possible that participants used the colours as a cue to recall. For example, in a positive-probe trial in which the test odorant was in a different colour at learning and test (the unbound condition), participants may erroneously reject the test odorant because the colour was absent at learning. Such a strategy would artificially inflate the performance advantage for the bound condition. To test this strategy, we analysed the false alarm rates following lure trials. If presence of a colour at encoding is being used to inform responses, there should be a greater proportion of false alarms for trials where the test odorant was not presented at learning but the colour was, compared to trials where both the test odorant and the colour were absent at learning. However, there was substantial evidence for a null difference between these types of false alarms (mean proportion of false alarms for the test colour repeated and test colour novel conditions = .43 and .42, respectively), $t(23) = 0.222$, $p = .826$, $d = 0.045$, $\mathrm{BF}_{10} = 0.220$. Similarly, there was a non-significant difference in confidence ratings between these conditions, $t(23) = 1.123$, $p = .273$, $d = 0.229$, $\mathrm{BF}_{10} = 0.377$.

Discussion

Experiment 3 provides one of the first examinations of incidental odour-colour binding in working memory. Using a single probe yes/no recognition procedure, we replicated the recency effect shown previously with olfactory stimuli (Moss et al., 2018), and for odour-colour binding in the first two experiments in the present study. However, we show no evidence of incidental odour-colour binding in respect to recognition accuracy, with neither a main effect of binding condition nor a binding by serial position interaction. The recognition confidence ratings revealed some tentative evidence in support of incidental binding, with an interaction between binding condition and serial position (although Bayesian evidence was weak). Consistent with Moss et al. (2018), confidence ratings for the unbound condition exhibited a flat function, whereas there was some evidence of a development of recency for the bound condition. However, such evidence should be treated with caution given that the post-hoc comparisons at serial position 3 did not reach the threshold for statistical significance and Bayesian evidence was weak. Notwithstanding the aforementioned caution, a shift to recency is consistent with the fragility of incidental binding (consistent with the intentional binding effects of Experiments 1 and 2) and is consistent with the detrimental effect of retroactive interference on memory for the bindings.

The absence of evidence for incidental binding when using recognition accuracy is inconsistent with previous studies that have examined incidental verbal-spatial binding (Campo et al., 2010; Elsley & Parmentier, 2009, 2015). These studies presented the to-be-remembered stimuli simultaneously as a single array and it is therefore possible that degradation of bindings over serial presentation may mask such an effect (although Elsley & Parmentier, 2015, reported some evidence of incidental binding after a 15s retention interval). That said, given the fragility of bound representations (see Allen et al., 2006), one might still predict evidence for incidental binding for the last odour-colour pairing in the sequence as this pairing may be automatically retained in the focus of attention (Allen et al., 2014; Hu et al., 2016). To directly test this speculative point, we conducted a post-hoc exploratory analysis at serial position 3. Specifically, we compared whether recognition for the last odorant in the sequence was superior when it was re-presented in the same colour cube used at encoding (bound) compared to when re-presented in a different coloured cube (unbound). The analysis found support for a null difference in hits between the bound (= .844) and unbound (= .792) conditions, $Z = 58.50$, $p = .336$, $r_{rb} = -0.610$, $BF_{10} = 0.367$. Thus, we see no support for incidental binding even in the most recently encoded pairing where there is least opportunity for the bindings to degrade.

The absence of evidence for incidental binding between odours and colours contradicts the incidental binding effects shown with verbal-spatial pairings (Campo et al., 2010; Elsley & Parmentier, 2009, 2015). An overarching goal of this research is to explore whether universal processes are applied to the problem of binding irrespective of the stimulus types employed, and one interpretation of the current finding is that olfactory working memory has different functionality to that of visual working memory. However, it remains plausible that the absence of incidental odour-colour binding effects may be a result of methodological differences and/or features of the stimuli. For example, in general, accuracy levels are substantially lower for olfactory compared to visual recognition, and given this increased task difficulty, it is possible that less cognitive resources are available for incidental binding to occur. It is also worth noting that evidence for verbal-spatial incidental binding is not universally reported. Specifically, there is evidence of incidental verbal-spatial binding operating asymmetrically, such that when memorizing locations, letters are not automatically bound (Campo et al., 2010; Elsley & Parmentier, 2015). Such asymmetry could be tested directly through replicating the present methodology with participants instructed to memorize the colour rather than the odorant.

The present findings appear inconsistent with other studies showing that olfactory stimuli are automatically and incidentally associated in memory with stimuli from other modalities (e.g., context-dependent memory studies involving olfaction, Aggleton & Waskett, 1999; Cann & Ross, 1989; Hackländer & Bermeitinger, 2017; Schab, 1990). However, it is worth noting that studies showing an association between odorants and other modality stimuli typically present the aromas ambiently, with participants receiving no instruction to remember the odours. At recall, it is assessed whether the odours have been implicitly associated by testing whether re-presentation of the ambient odour can cue retrieval of the other modality to-be-remembered information. In the present study, the odorants are the to-be-remembered stimuli and it is unclear to what extent these associative effects are found when the non-olfactory stimuli function as the memory cue and the odorant as the focus of memory.

General Discussion

The present set of experiments are one of the first to examine odour-colour binding in working memory using procedures typically employed with visual and verbal memory. Consistent with our prediction that olfactory WM would produce binding effects similar to that of visual WM, Experiment 1 demonstrated that individuals are capable of intentionally maintaining odour-colour bindings in working memory at a level above that of chance and in doing so exhibit a recency effect. This recency effect was replicated in Experiment 2 but with only limited evidence for prioritisation effects (i.e., limited strategic reallocation of resources to the first pairing in the sequence). This limited development of primacy was far less than the predicted strong prioritisation effects shown with visual binding (Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2016). Experiment 3 examined evidence for the incidental formation of odour-colour binding and found no evidence for this using recognition accuracy, along with some weak evidence for incidental binding for the last pairing in the list when analysing confidence ratings. This is inconsistent with the predicted superior recognition for the odorants re-presented in the same coloured cube as that used at encoding and fails to support incidental odour-colour binding in working memory.

In the present study olfactory working memory has demonstrated some of the binding effects reported with the more extensively examined domain of visual memory. Participants can intentionally maintain an odour bound to a colour in working memory, a capability shown repeatedly when a feature (such as shape) is bound to a colour (e.g., Allen et al., 2006, 2012; Brown & Brockmole, 2010; see Hitch et al., 2020 for a review). Furthermore, memory for odour-colour pairings also exhibits the recency advantage shown with shape-colour pairings (Allen et al., 2006, 2014, 2021; Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016), supporting the proposition that binding of such information is fragile in working memory due to a vulnerability to retroactive interference (e.g., Allen et al., 2006). One might argue that these findings suggest functional similarity between olfactory working memory and that of visual memory, although the relatively low performance levels across Experiments 1 and 2 indicate that such binding functionality may be limited. That olfactory working memory may operate analogously to other modalities is consistent with recognition serial position function data (Johnson & Miles, 2009; Miles & Hodder, 2005; Moss et al., 2018; although see also Reed, 2000), Hebb repetition effects (Johnson et al., 2013), and preliminary studies examining the *n*-back task (Dade et al., 2001; Jönsson et al., 2011; Moss et al., 2019). One possible explanation for these similarities is that the same processes/mechanisms are being employed irrespective of stimulus type. That is, that the working memory processes are task, rather than stimulus, specific (although see Hurlstone et al., 2014, for a detailed review of this debate).

Although intentional memory for odour-colour bindings was above chance at all serial positions in Experiments 1 and 2, accuracy levels were nevertheless relatively low compared to those found for visual shape-colour binding using similar cued recall tasks and 3-item sequences (indeed the working memory capacity for integrated conjunctions has been previously reported to be around 4, Luck & Vogel, 1997; Vogel et al., 2001). Applying Cowan's *k* estimate of working memory capacity (Atkinson, Baddeley, et al., 2018; Chen & Cowan, 2013) indicates a mean capacity estimate of .83 (SE = .07) for Experiment 1 and .87

(.07) for Experiment 2 (averaging across the priority conditions). This compares to capacity estimates in visual shape-colour binding of 1.78 items in Allen et al. (2014, Experiment 3) and 1.88 in Allen et al. (2020, Experiment 2). Thus, the capacity estimate for odour-colour binding in the current paradigm falls (on average) below one item. Participants can sometimes retain one binding between odour and colour in working memory, and the clear recency effects observed in Experiments 1 and 2 indicate this is more likely to be the final pairing in the sequence. However, holding more than one odour-colour binding in mind appears to be achieved only very infrequently. This may reflect very strict capacity limitations for such disparate feature pairings, and/or possible general attentional costs required in encoding and maintaining the association between such features. Another related possibility is that odour-colour bindings are more susceptible to general experimental interference than other modalities. Whilst our previous work suggests that recognition for hard-to-name odours is in fact less susceptible to proactive interference than visual and verbal stimuli (Moss et al., 2018), future work should examine whether working memory capacity for odour-colour bindings are improved when different odours are used for each trial.

Experiment 2 furthermore indicates some possible limitations to the functionality of olfactory working memory, with rather limited evidence for working memory prioritisation effects. Whilst the prioritisation instruction to allocate greater value to remembering the first pairing in the list induced a more quadratic function, the increase in the magnitude of primacy following this manipulation was small relative to the strong prioritisation effects found with visual memory (Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016). The limited prioritisation effects may be explicable via the relatively low performance levels for the task and the apparent capacity limits that exist for this form of feature binding. It has been suggested that prioritisation effects are dependent on the availability of executive attentional resources in working memory (Hitch et al., 2020; with prioritisation reduced under increased cognitive load, Hu et al., 2016). If these resources are depleted due to general task difficulty, it follows that the reallocation of resources to other serial positions will be limited. Moreover, it is worth noting that the accentuation of primacy following prioritisation instruction is not universally reported (Allen et al., 2020). It would be worthwhile for future work to systematically explore whether prioritisation might be more effectively applied across an increased range of sequence lengths (e.g., 2-4 items) and serial positions.

An important distinction between the prioritisation procedure in Experiment 2 and that of previous feature binding prioritisation studies (Allen et al., 2021; Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016) is that the present study employed cross-modal binding. It is not known to what extent prioritisation effects interact with cross-modal binding. Whilst Allen et al. (2009) reported no attentional cost of forming cross-modal (i.e., auditory verbal-visual) bindings (see also Guazzo et al., 2020), other studies have shown asymmetry in cross-modal binding effects (Campo et al., 2010; Elsley & Parmentier, 2015). Distinctions have also been drawn between intrinsic and extrinsic (Ecker et al., 2013), and conjunctive and relational (Parra et al., 2015) binding, postulating the involvement of different mechanisms and brain regions in each case. Under these categories, while the type of shape-colour memory task (for features drawn from unitary objects) typically explored in visual working memory would reflect intrinsic or conjunctive binding, the present task requiring memory for odour-colour pairings would require a form of extrinsic or relational binding. It should be empirically testable whether prioritisation effects are in general weaker for different forms of binding (i.e., cross-modal, extrinsic, or relational) or whether such limitations are confined to olfactory memory.

Experiment 3 found very limited evidence for incidental binding effects. We predicted that test probe odorants re-presented in the same coloured cube as at learning (bound) would be recalled better than odorants in a different coloured box (unbound). These effects were found with verbal-spatial pairings (Campo et al., 2010; Elsley & Parmentier, 2009, 2015) and were argued to reflect automatic binding of features in working memory. Whilst there was some weak confidence rating evidence for incidental binding of the last pairing in the sequence, the effects were far less pronounced than that reported for verbal-spatial pairings. Whilst further work is required to test evidence for asymmetry in incidental olfactory binding (as shown with verbal-spatial pairings, Campo et al., 2010; Elsley & Parmentier, 2015), our data suggests that odour-colour binding may not occur incidentally. Specifically, participants can form and retain (albeit in a highly capacity-limited way) odour-colour associations following explicit task instructions (Experiments 1 and 2) but there is very limited evidence for these bindings being stored in memory without such instruction (Experiment 3). Finally, it is worth noting that while odour recognition memory in this experiment was clearly above chance, the *k* capacity estimate (Chen & Cowan, 2013) fell at just under 1 item (mean = .98, SE = .13), again indicating (as in Experiments 1 and 2) a very limited capacity for this form of stimulus in working memory.

From a theoretical perspective, the present findings raise questions about the storage of olfactory representations within working memory. The above chance but relatively low accuracy levels for intentional odour-colour binding memory in Experiments 1 and 2 could be incorporated within working memory frameworks that posit a modality-general focus of attention or episodic buffer (e.g., Baddeley et al., 2021; Cowan et al., 2021). For example, within the multicomponent working memory framework, odour-colour binding retention has been attributed to the episodic buffer; the current findings indicate this to be generally limited to the retention of one binding at a time, most likely to be the most recently encountered feature pairing (see Hitch et al., 2020). Experiment 2 provides some indication that the particular binding being retained in this focus of attention is open to strategic influences, but with little evidence that this directly benefits the prioritised high value item. It may be that cross-modal binding in general, or odour-colour binding in particular, is difficult to actively maintain via attentional refreshing. Finally, Experiment 3 indicates that odour-colour binding does need to be intentional and does not develop incidentally and automatically. Whilst the initial encoding and retention of visual feature bindings have been argued to emerge relatively automatically through processing in specialised subsystems (e.g., Allen et al., 2006, 2012), odour-colour associative memory may be extremely limited in capacity and require executive control resources for encoding and ongoing maintenance. Future work should directly test this. It would also be useful to systematically explore the mechanistic overlap between intentional and incidental binding more generally.

In summary, these experiments provide mixed evidence with respect to the functionality of olfactory working memory. We show that participants can form intentional odour-colour binding in memory (albeit at relatively low levels of accuracy) and that performance on this task exhibits a recency advantage (as demonstrated with visual memory, Allen et al., 2021, 2014; Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016). However, we observed weak evidence of primacy prioritisation and very little evidence for incidental bindings. This is one of the first investigations of odour binding in working memory and further work is needed to establish to what extent the present findings reflect methodological limitations (e.g., overall low performance levels), capacity issues (e.g., overloading the episodic buffer), and stimulus-specific effects (i.e., that the functionality of olfactory memory qualitatively differs to that of other stimuli).

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