

1 Intentional and incidental odour-colour binding in working memory

2  
3 Andrew J. Johnson<sup>1\*</sup> & Richard Allen<sup>2</sup>

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<sup>1</sup>Department of Psychology,  
Faculty of Science & Technology,  
Bournemouth University,  
Poole, UK

<sup>2</sup>School of Psychology,  
University of Leeds,  
Leeds,  
UK

\*Corresponding author

Address for Correspondence:

Department of Psychology

Bournemouth University

Poole House

Talbot Campus

Fern Barrow

Poole, UK

Tel: +0044 (0)1202 965977

Email\*: [andjohnson@bournemouth.ac.uk](mailto:andjohnson@bournemouth.ac.uk)

ORCID: [orcid.org/0000-0003-4138-9115](https://orcid.org/0000-0003-4138-9115)

Twitter: @Psychology\_Andy

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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.

## 1 Intentional and incidental odour-colour binding in working memory

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

15 The episodic buffer, a store within the multicomponent Working Memory Model  
16 (Baddeley & Hitch, 1974; Baddeley et al., 2021), has been implicated in the process of  
17 binding (e.g., Allen et al., 2006; Baddeley, 2000; Baddeley et al., 2011). This component was  
18 initially proposed by Baddeley (2000) to hold a limited number of chunks in a multi-  
19 dimensional code. If the representation of these conjunctions is not confined to a specific  
20 modality it logically follows that the buffer should hold cross-modal bindings. Support for  
21 this has indeed been shown with both visual-auditory (e.g., Allen et al., 2009; Gao et al.,  
22 2017; Guazzo et al., 2020; Jones et al., 2013; Wang et al., 2015, 2017), visual-spatial (e.g.,  
23 Cowan et al., 2006), and verbal-spatial (e.g., Campo et al., 2010; Darling et al., 2017; Elsley  
24 & Parmentier, 2009, 2015) bindings. However, there is very little existing research on how  
25 odours might be bound to other feature dimensions in working memory and how this might

1 interact with attention. The primary motivation of the study is to explore the functionality of  
2 odour-binding in working memory and begin exploring to what extent functionality might  
3 mirror that shown in more established domains such as visual binding. The following  
4 experiments are therefore one of the first to examine cross-modal binding in working  
5 memory from the perspective of incidental and intentional odour-colour binding. Our key  
6 questions concern (1) whether odours can be successfully bound to other stimuli in working  
7 memory and, if so, (2) to what extent does the pattern of performance reflect that shown for  
8 other modalities.

9         That cross-modal features can be bound to an olfactory stimulus is unclear, as the  
10 extent to which olfactory working memory exhibits functional similarities to that of other  
11 modalities is not well understood. Performance on the olfactory *n*-back task demonstrates that  
12 temporary maintenance of odorants can be performed at levels above chance (Dade et al.,  
13 2001; Jönsson et al., 2011; Moss et al., 2019), with reliance on verbal labelling/rehearsal  
14 being minimised via using hard-to-name odorants (Jönsson et al., 2011; Moss et al., 2019)  
15 and concurrent articulation (Moss et al., 2019). Short-term recognition of odorants is also  
16 above chance with serial position analysis providing some evidence of functional similarity  
17 with that of other modalities. Initial investigations into olfactory recognition and recall  
18 revealed a recency advantage, but no primacy (Annett & Lorimer 1995; White & Treisman,  
19 1997); although primacy has been reported following verbal elaboration (Annett & Lorimer  
20 1995; Miles & Jenkins, 2000). Recency is also reported for 2-alternative forced choice  
21 (2AFC) recognition of odorant sequences (Johnson & Miles, 2007; Miles & Hodder, 2005),  
22 consistent with that found with both verbal and visual stimuli (e.g., Avons, 1998; Phillips &  
23 Christie, 1977; Ward et al., 2005). Similarly, a recency advantage is found when the sequence  
24 is followed by a single yes/no recognition test odorant (Moss et al., 2018; a function also  
25 consistent with that found with visual stimuli, e.g., Hay et al., 2007; Johnson et al., 2014;

1 Kerr et al., 1999). These findings suggest mechanistic similarity in the short-term operation  
2 of olfactory recognition memory and that of other stimuli (although there is some preliminary  
3 evidence that order memory for odorants produces contradictory functions, Johnson et al.,  
4 2013; Johnson & Miles, 2009).

5 Evidence that olfactory short-term/working memory exhibits similarities to other  
6 modalities might lead one to predict olfactory cross-modal binding capabilities that mirror  
7 those reported for visual stimuli (e.g., Allen et al., 2009; Cowan et al., 2006). However, such  
8 a prediction is complicated by uncertainty as to how odorants are represented within the  
9 multicomponent Working Memory Model (WMM; Baddeley, 2000; Baddeley & Hitch,  
10 1974). Employing the classic working memory dual-task procedure, Andrade and Donaldson  
11 (2007) showed that performance on a primary olfactory recognition memory task was  
12 disrupted by a secondary olfactory recognition task but not by either a secondary verbal or  
13 visual recognition task. This was taken as evidence that short-term olfactory memory is  
14 supported by a specialised component in working memory, rather than reliant on verbal or  
15 visual recoding (via the phonological loop and visuo-spatial sketchpad, respectively; see also  
16 Zelano et al., 2009, for imaging evidence). Based on these findings, Andrade and Donaldson  
17 (2007) proposed the addition of an olfactory buffer within the WMM. Alternatively, the most  
18 recent iteration of the multicomponent model (Baddeley, 2012; Baddeley et al., 2021)  
19 speculatively identifies odour as having a direct route into the episodic buffer where it is  
20 accessible to conscious awareness and can be temporarily stored and maintained via  
21 attentional refreshing. If the Episodic Buffer is recruited to support temporary maintenance of  
22 olfactory stimuli, it is possible that the storage of feature bindings involving odorants may  
23 respond in a similar way to those observed in visual memory.

24 This study describes three novel experiments that aimed to examine how binding  
25 between visual and olfactory features are maintained in working memory, using

1 methodological approaches adopted from the literature on visual feature binding. We focus  
2 on odour-colour binding as there is good precedent that colour exhibits binding effects with  
3 features such as shape (e.g., Allen et al., 2006, 2009, 2012, 2014). Furthermore, attempting to  
4 pair olfactory stimuli with colour is prosaic given their co-occurrence in naturalistic  
5 environments. Thus we aim to maximise the opportunity of detecting binding effects with  
6 olfactory stimuli. Experiment 1 sought to establish the extent to which short sequences of  
7 colour-odour bindings can be encoded and retained in working memory for the purposes of  
8 an immediate cued recall task, and whether performance across the sequence exhibits the  
9 typical pattern of recency effect that is seen in visual feature binding (e.g., Allen et al., 2006,  
10 2014). Here we test capability of working memory in storing odour-colour bound  
11 representations and explore whether the same fragility for representations seen in visual  
12 binding is evidenced via a recency effect. Experiment 2 then examined whether the  
13 observation from visual feature binding (e.g., Hu et al., 2014) that attention can be  
14 strategically allocated to one of the items in the sequence with observable changes in  
15 accuracy levels can be extended to this odour-colour binding task. Here we examine cross-  
16 domain functional capabilities in more detail by testing how attention can be selectively  
17 reallocated in the odour-colour binding task. Changes in the serial position function following  
18 reallocation of attention to a specific bound representation would replicate that shown with  
19 visual binding and support functional similarities between olfactory and visual binding.  
20 Finally, Experiment 3 explored whether evidence for incidental formation of colour-odour  
21 binding is observable in a change detection paradigm (e.g., Elsley & Parmentier, 2009). Here  
22 we examine the role of attention indirectly via testing whether odour-colour representations  
23 occur incidentally. If recall for an olfactory stimulus presented in a different coloured box to  
24 that encountered at learning (unbound) is impaired, it suggests that binding occurs

1 incidentally consistent with that shown for verbal-spatial conjunctions (Elsley & Parmentier,  
2 2009, 2015).

### 3 Experiment 1

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



1 **Table 1**

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

3

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

4

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

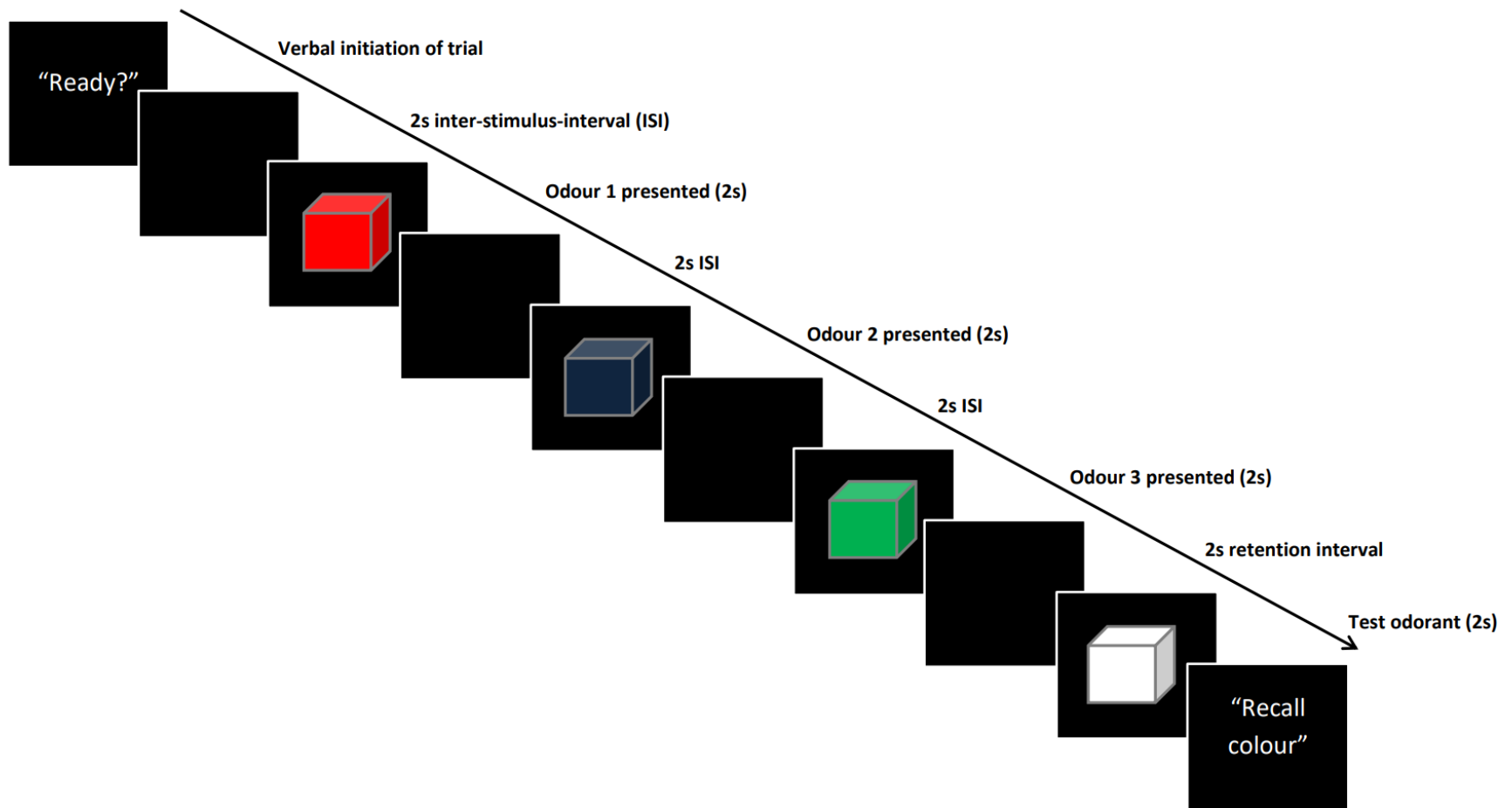
7 **Design**

8 Using an odour-cued colour recall task, a single-factor within-participants design was  
9 employed with the variable serial position (1-3). Specifically, in each trial we manipulated  
10 whether the test odorant was presented first, second, or third during the presentation phase.  
11 Across the 48-trial experiment, each serial position was probed an equal number of times (16)  
12 and each odorant was used as the test probe an equal number of times. Specifically, on the 12  
13 trials where each odorant was used as the test probe, that odorant was testing each serial  
14 position an equal number of times, i.e., on 4 occasions. During the presentation phase, odorants  
15 were sampled from a stimulus set of 16 odorants; the four odorants in red, blue, yellow, and  
16 green. Each odorant-colour combination was used an equal number of times across the  
17 presentation phase of the experiment (9) and each odorant-colour combination was the item for  
18 which participants were subsequently tested on an equal number of occasions (3). This served  
19 to balance the effect of certain odorants possessing pre-existing associations with specific

1 colours (see Demattè, et al., 2006; de Valk et al., 2017; Gilbert et al., 1996). Using these  
2 restrictions, an experimental protocol was developed for the 48 trials, with the order of these  
3 trials randomised for each participant. Within the skeleton template of the protocol, odorants  
4 were listed as letters (A, B, C, and D); the assignment of the 4-odorants to these different letters  
5 was fully counterbalanced across the 24 participants.

## 6 **Procedure**

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



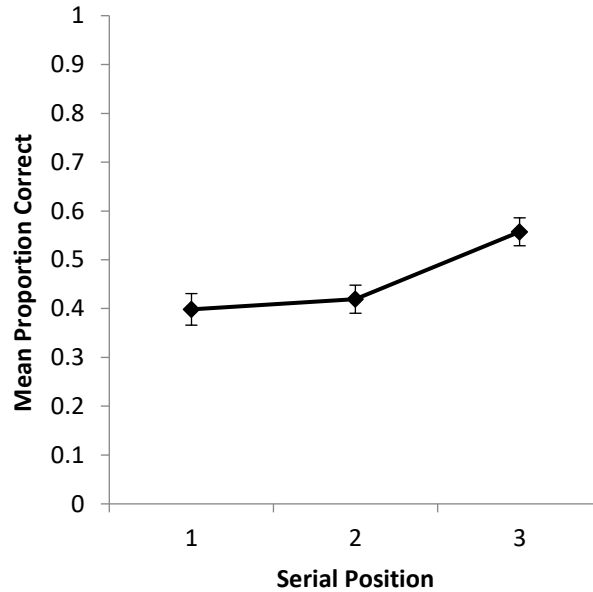
*Figure 1.* Schematic representation of a trial in Experiment 1. The test odorant (presented via the neutral white cube) is one of the odours from the preceding presentation phase. The participant is required to recall the colour of the odorant from which this test odour was initially presented. For 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".

## 1 **Data Analysis**

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

## 8 **Results**

9           Figure 2 displays the serial position function for the odorant-colour bindings. For each  
10 serial position, recall is assessed via the proportion of trials in which participants correctly  
11 recall the colour with which the test odorant was originally presented. Figure 1 shows that (1)  
12 participants can perform the task above that of chance (each trial uses 3 different colours,  
13 therefore chance = .33; however, given that 4 colours are used throughout the experiment,  
14 intrusion errors could result in a lower score of .25 following guessing), and (2) a recall  
15 advantage is evident for the last list item. A single-factor within-participants ANOVA was  
16 conducted and revealed a main effect of serial position,  $F(2, 46) = 8.236$ ,  $MSE = 0.022$ ,  $p <$   
17  $.001$ ,  $\eta_p^2 = .264$ ,  $BF_{10} = 131.202$ . Post-hoc Bonferroni-corrected ( $\alpha = .017$ ) t-tests revealed  
18 accuracy at serial position 3 was significant greater than both serial positions 1 ( $t(23) = 3.519$ ,  
19  $p = .002$ ,  $d = 0.718$ ,  $BF_{10} = 20.594$ ) and 2 ( $t(23) = 3.181$ ,  $p = .004$ ,  $d = 0.649$ ,  $BF_{10} = 10.193$ ).  
20 There was strong evidence in favour of a null difference between serial positions 1 and 2 ( $t(23)$   
21  $= 0.536$ ,  $p = .597$ ,  $BF_{10} = 0.245$ ).



1

2 *Figure 2.* Mean proportion accuracy for colour recall as a function of serial position.

3 Error bars denote the mean standard error.

4

## Discussion

5 Experiment 1 demonstrates that participants can perform an intentional odour-colour

6 binding task. Whilst performance was low (average proportion accuracy = .45), the serial

7 position function displayed the recency effect reported for the visual analogue of this task using

8 colour-shape binding (Allen et al., 2020; Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et

9 al., 2014, 2016). Thus, Experiment 1 suggests that working memory for odour-colour binding

10 may share common functional characteristics with those established for visual binding. The

11 recency effect is consistent with the proposed fragility of bound representations, where earlier

12 bound representations are disrupted by retroactive interference (e.g., Allen et al., 2006), while

13 the final sequence item remains relatively more intact and accessible within the focus of

14 attention (Hitch et al., 2020). Within the multicomponent model (Baddeley, 2012; Baddeley et

15 al., 2021), this focus of attention is described as a modality-general episodic buffer, a

16 component capable of holding intact object files, typically for the most recently encountered

1 stimulus (Hitch et al., 2020). Indeed, it has been speculatively suggested that olfactory  
2 information might be maintained within the episodic buffer (Baddeley, 2012; Baddeley et al.,  
3 2021).

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

1 colour bindings might suggest mechanistic differences between olfactory and visual binding in  
2 working memory.

3         The recency advantage for odour-colour pairings reported in Experiment 1 is consistent  
4 with that reported for colour-shape bound representations (e.g., Allen et al., 2006, 2020;  
5 Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016). This recency advantage is also  
6 consistent with other measures of olfactory working memory where recency has been shown  
7 for recognition (Johnson & Miles, 2007; Miles & Hodder, 2005, Moss et al., 2018; Reed, 2000;  
8 White & Treisman, 1997) and serial recall (Annett & Lorimer, 1995; Johnson et al., 2013; Miles  
9 & Jenkins, 2000). It is worth noting, however, that there exists limited evidence of a primacy  
10 benefit for olfactory memory (see Miles & Hodder, 2005, for failed replication of Reed, 2000;  
11 and the primacy reported by Miles & Jenkins, 2000, is attributable to the use of verbal labels,  
12 see also Annett & Lorimer, 1995) and this in part may be due to tasks characterised by primacy,  
13 such as immediate serial recall and serial order reconstruction, being unsuitable for olfactory  
14 stimuli. There is, however, some evidence of a primacy advantage using the currently employed  
15 cued recall task following explicit instruction to prioritise memory for the first conjunction in  
16 the list (Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016; although see  
17 null effect at serial position 1 reported by Allen et al., 2020). Indeed, participants can prioritise  
18 more valuable information in working memory resulting in improved recall for high value  
19 items across all serial positions (Allen et al., 2020; Allen & Atkinson, 2021; Atkinson et al.,  
20 2020; with prioritisation effects observed also in children and older adult samples, Allen et al.,  
21 2020; Atkinson et al., 2019). This memory facilitation for high value items is typically offset  
22 by memory decrements to the lower value items in the list. These findings show that attentional  
23 resources for these tasks are finite and that participants can strategically redistribute these  
24 resources to specific positions within the to-be-remembered sequence.

1 Experiment 2 examines whether such working memory prioritisation effects can be  
2 found for memory of odour-colour pairings. This is of interest for two reasons. First, it is  
3 unknown whether the same strategic redistribution of resources shown with visual memory can  
4 be employed for olfactory working memory. Value-based prioritisation effects in visual and  
5 verbal working memory have been attributed to active maintenance of more valuable items in  
6 the focus of attention (Hitch et al., 2020; Hu et al., 2014), so it is informative to establish the  
7 extent to which binding involving olfactory information can be prioritised in the same way.  
8 Along similar lines, a candidate mechanism underlying prioritisation is that of attentional  
9 refreshing (e.g., Camos et al., 2018; Johnson et al., 2002), and this may offer one way in which  
10 olfactory information is actively maintained (Baddeley, 2012; Baddeley et al., 2021). Evidence  
11 regarding the presence or absence of such effects will therefore speak directly to the  
12 functionality for olfactory working memory. Second, detection of a reliable primacy effect for  
13 olfactory memory has proven elusive, and it is difficult to determine whether this is due to  
14 functional differences of olfactory memory or cross-modal task incongruency (Ward et al.,  
15 2005, argue that the serial position is task, rather than stimulus, dependent). By applying a  
16 methodology shown to produce primacy in visual memory to olfactory stimuli, we can test  
17 directly whether olfactory serial position functions qualitatively differ cross-modally with  
18 respect to primacy.

## 19 **Experiment 2**

20 To our knowledge, Experiment 2 is the first to examine working memory prioritisation  
21 effects in olfactory memory. Here we repeat the method described in Experiment 1 but  
22 include an additional block of 48-trials with a prioritisation condition (following the  
23 instructions outlined in Allen et al., 2020; Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu  
24 et al., 2014, 2016). Specifically, in the control block, participants were instructed to try and



1 remember all pairings equally, whereas in the prioritisation block, they were told that they  
2 would receive more points for correctly recalling the first pairing in the sequence.  
3 Participants were aware that these points were purely notional and that each item in the  
4 sequence was equally likely to be tested at cued recall. If working memory resources can be  
5 strategically reallocated for olfactory memory, we predicted that primacy should develop in  
6 the prioritisation condition, illustrated via a prioritisation condition by serial position  
7 interaction. This should emerge in the context of no overall main effect of prioritisation (Hu  
8 et al., 2014), indicating the reallocation of limited capacity resources according to item  
9 priority.

## 10 **Method**

### 11 **Participants**

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

### 17 **Materials**

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

20

21

1 **Table 2**

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

3

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

4

5 **Design**

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

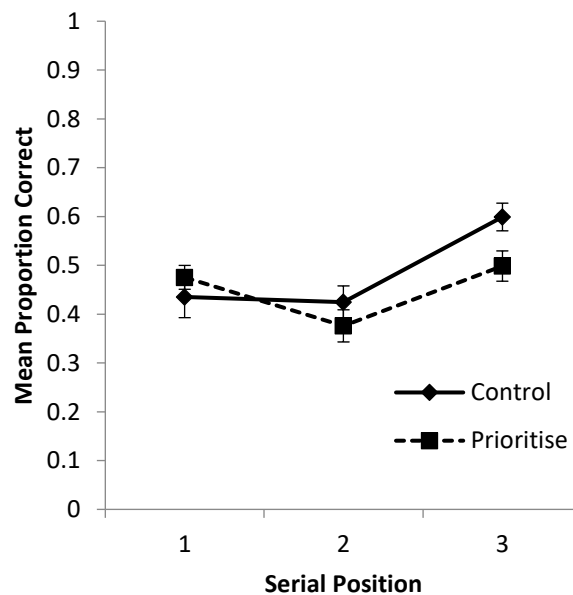
13 **Procedure**

14 The procedure followed that described for Experiment 1, with the exception that  
15 participants undertook two 48-trial sessions. The no-prioritisation condition was as described  
16 for Experiment 1. For the prioritisation condition, the procedure was based on that of Atkinson

1 et al. (2018; also, Allen et al., 2020). Thus, participants were told (via a PowerPoint  
2 presentation narrated by the experimenter) that they should: “Try extra hard to remember the  
3 first one. The first odour will be tested as often as the other odours, but you will get more points  
4 if you are asked about that odour and you get the answer right. If you are tested on the first  
5 odour and you get it right, you will get 4 points! If you are tested on any other odour and you  
6 get it right, you will get 1 point.” As in Experiment 1, the session was divided into four 12-trial  
7 sub-blocks and during that interval participants were reminded of the prioritisation instruction.

## 8 Results

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



11

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

1 A multifactorial (2x3) within-participants ANOVA was conducted with the factors of  
2 prioritisation (no prioritisation and first-item prioritisation) and serial position (1-3). The  
3 main effect of prioritisation was non-significant,  $F(1, 23) = 1.855$ ,  $MSE = 0.025$ ,  $p = .186$ ,  $\eta_p^2$   
4  $= .075$ ,  $BF_{10} = 0.541$ , whereas the main effect of serial position was significant,  $F(2, 46) =$   
5  $10.218$ ,  $MSE = 0.026$ ,  $p < .001$ ,  $\eta_p^2 = .308$ ,  $BF_{10} = 2523$ . Importantly, the interaction between  
6 prioritisation and serial position was also significant,  $F(2, 46) = 4.740$ ,  $MSE = 0.013$ ,  $p =$   
7  $.013$ ,  $\eta_p^2 = .171$ ,  $BF_{10} = 1.27$ , although it should be noted that Bayesian support for the  
8 interaction was only weakly positive.

9 To explore the interaction in more detail, separate one-way ANOVAs were computed  
10 for serial position on the no prioritisation and prioritisation conditions. For the no prioritisation  
11 condition, the main effect of serial position was significant,  $F(2, 46) = 12.250$ ,  $MSE = 0.019$ ,  $p$   
12  $< .001$ ,  $\eta_p^2 = .348$ ,  $BF_{10} = 600.818$ . Post-hoc Bonferroni-corrected ( $\alpha = .017$ ) t-tests revealed  
13 accuracy at serial position 3 was significant greater than both serial positions 1 ( $t(23) = 3.539$ ,  
14  $p = .002$ ,  $d = 0.722$ ,  $BF_{10} = 21.504$ ) and 2 ( $t(23) = 4.402$ ,  $p < .001$ ,  $d = 0.899$ ,  $BF_{10} = 141.520$ ).  
15 There was strong evidence in favour of a null difference between serial positions 1 and 2 ( $t(23)$   
16  $= 0.334$ ,  $p = .741$ ,  $BF_{10} = 0.226$ ). This analysis supports the presence of recency but no primacy,  
17 consistent with the trend reported for Experiment 1. For the prioritisation condition, the main  
18 effect of serial position was significant,  $F(2, 46) = 4.944$ ,  $MSE = 0.021$ ,  $p = .011$ ,  $\eta_p^2 = .177$ ,  
19  $BF_{10} = 8.259$ . Post-hoc Bonferroni-corrected ( $\alpha = .017$ ) t-tests revealed accuracy at serial  
20 position 2 was significantly lower than both serial positions 1 ( $t(23) = -2.952$ ,  $p = .007$ ,  $d =$   
21  $0.603$ ,  $BF_{10} = 6.429$ ) and 3 ( $t(23) = -2.740$ ,  $p = .012$ ,  $d = 0.559$ ,  $BF_{10} = 4.253$ ). There was  
22 strong evidence in favour of a null difference between serial positions 1 and 3 ( $t(23) = 0.515$ ,  
23  $p = .612$ ,  $BF_{10} = 0.242$ ). This trend supports evidence of a bowed serial position function with  
24 both primacy and recency.

## Discussion

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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

1 cross- compared to within-modality binding. Finally, it is possible that olfactory working  
2 memory has reduced functionality compared to that of visual working memory, i.e., there is  
3 less capability to strategically reallocate resources between components of the list and  
4 actively maintain early sequence items within the focus of attention using attentional  
5 refreshing.

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

### 15 Experiment 3

16 Experiments 1 and 2 have shown some evidence that memory for odour-colour pairings  
17 exhibit similarities to that of visual memory, namely an ability to store bound representations  
18 in working memory with a specific recall advantage for the last item in the sequence. We  
19 have shown in two experiments that participants can remember odour-colour pairings  
20 following explicit instruction and that this task produces a recency effect. Experiment 2 also  
21 demonstrated some weak evidence of qualitative changes in accuracy across serial position  
22 following instruction to prioritise the first pairing in the sequence, although the magnitude of  
23 these effects was reduced relatively to those typically seen in visual memory. Experiment 3  
24 aimed to further develop our understanding of olfactory binding by testing evidence for the

1 incidental formation of bound olfactory-based representations; here, we examine whether  
2 additional features (in this instance colour) are bound to olfactory stimuli without explicit  
3 task instruction in a working memory task.

4         There exists a large body of evidence demonstrating that olfactory stimuli are encoded  
5 incidentally alongside other to-be-remembered stimuli. Reinstatement of an odorant at test  
6 that was presented during encoding has been shown to facilitate long-term memory for verbal  
7 stimuli (Parker & Gellatly, 1997), faces (Hackländer & Bermeitinger, 2017), semantic  
8 information (Aggleton & Waskett, 1999), spatial information (Parker et al., 2001), and old  
9 autobiographical events (Larsson et al., 2014). In addition, fMRI studies have shown that  
10 when a visual stimulus is encoded alongside an odour, reinstatement of that visual stimulus  
11 can activate the olfactory cortex despite an absence of olfactory stimuli (Gottfried et al.,  
12 2004; Karunanayaka et al., 2015), thus indicating the incidental formation of a visual-  
13 olfactory engram. These studies demonstrate that long-term associations can be formed  
14 between to-be-remembered stimuli and incidentally presented odorants. Experiment 3  
15 explores associations between olfactory and visual stimuli where the incidental stimulus is  
16 the colour of the odorants.

17         Incidental feature binding is typically tested by presenting a set of features such as  
18 letters in different spatial locations (Campo et al., 2010; Elsley & Parmentier, 2009, 2015).  
19 Participants are instructed to remember one feature in the study (e.g., the letter). At test, they  
20 receive a single yes/recognition test for the letter, with the important comparison being  
21 recognition accuracy for positive test probes (requiring a “yes” response”) that were  
22 presented in the same spatial location as at learning (intact probes) or a different spatial  
23 location (recombined probes). Higher recognition accuracy and faster response latencies have  
24 been observed for intact test probes, compared to recombined probes (Elsley & Parmentier,

1 2009, 2015). This was taken as evidence of incidental letter-location binding, as disruption of  
2 these bindings at test negatively impacted on recognition (although there is some evidence of  
3 verbal-spatial incidental binding being asymmetric, Elsley & Parmentier, 2015).

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





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

2

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

3

#### 4 **Design**

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

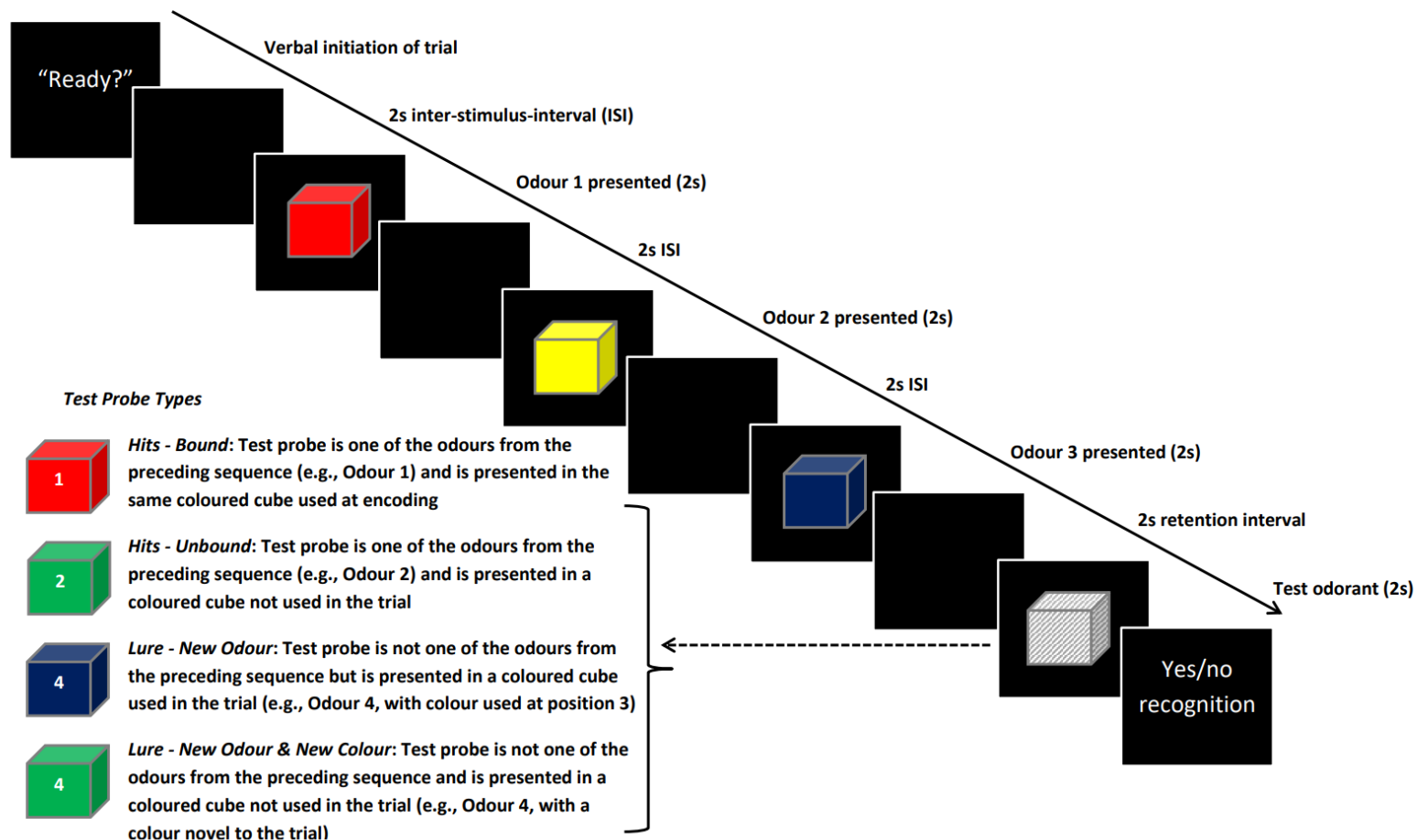


Figure 4. Schematic representation of a trial in Experiment 3. The participant is required to state whether the test odour was presented in the preceding trial (yes/no recognition). There are 4 types of test odorants: 1. *Hits - bound* (where the test odour was presented in the preceding sequence in 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).

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

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

#### 14 **Procedure**

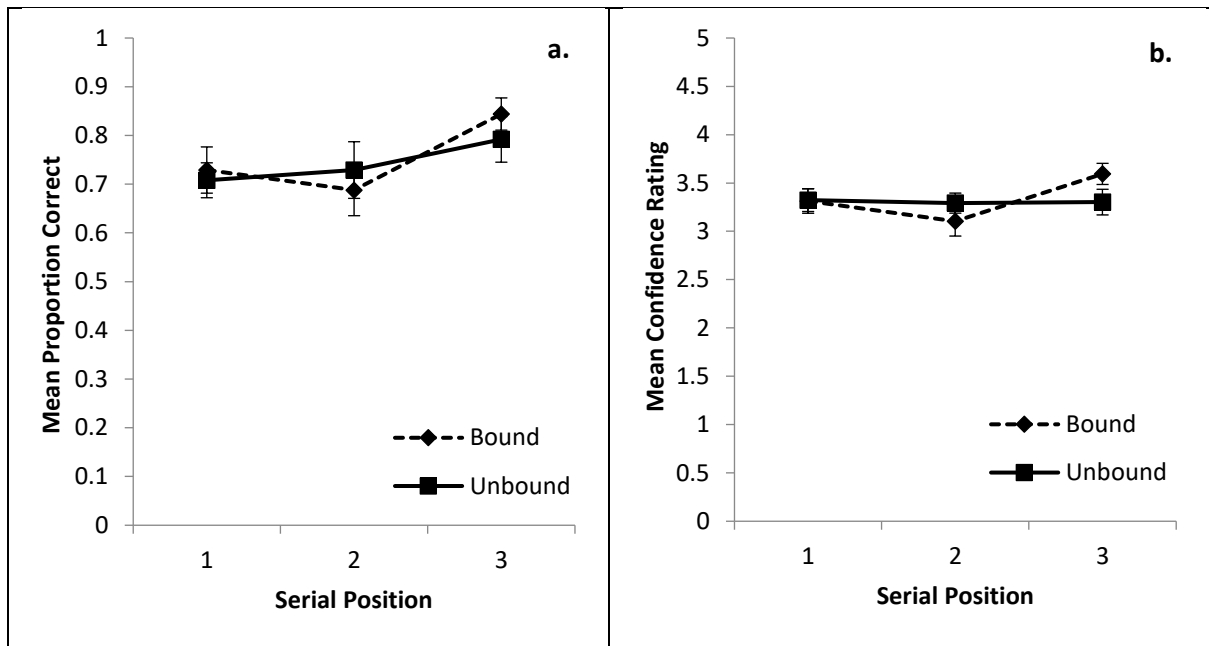
15           The procedure was as described for Experiment 1 with the exception that participants  
16 were instructed only to remember the odorants presented in the preceding sequence. At test,  
17 participants received a single odorant and were required to state whether the odour was  
18 included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

22

23

## 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,  $F(2, 46) = 0.870$ ,  $MSE = 0.031$ ,  $p = .426$ ,  $\eta_p^2 = .036$ ,  $BF_{10} = 0.203$ .



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

4            Figure 5b displays the serial position functions for response confidence rating (1-5) in  
 5 the bound and unbound conditions. The same multifactorial (2x3) within-participants ANOVA  
 6 was conducted on the confidence ratings. The main effect of incidental binding was non-  
 7 significant,  $F(1, 23) = 0.203$ ,  $MSE = 0.173$ ,  $p = .838$ ,  $\eta_p^2 = .002$ ,  $BF_{10} = 0.191$ , as was the main  
 8 effect of serial position,  $F(2, 46) = 3.013$ ,  $MSE = 0.249$ ,  $p = .059$ ,  $\eta_p^2 = .116$ ,  $BF_{10} = 1.279$ . The  
 9 interaction between incidental binding and serial position was significant,  $F(2, 46) = 3.846$ ,  
 10  $MSE = 0.704$ ,  $p = .029$ ,  $\eta_p^2 = .143$ ,  $BF_{10} = 1.585$ . This interaction was examined further by  
 11 comparing confidence at each serial position for the bound and unbound condition (using  
 12 Bonferroni-corrected t-test,  $\alpha = 0.017$ ). Substantial evidence in favour of a null difference at  
 13 serial position 1 was observed,  $t(23) = 0.085$ ,  $p = .933$ ,  $d = 0.017$ ,  $BF_{10} = 0.215$ . The difference  
 14 between bound and unbound at serial position 2 was non-significant,  $t(23) = 1.619$ ,  $p = .119$ ,  $d$   
 15  $= 0.330$ ,  $BF_{10} = 0.670$ . At serial position 3, the higher confidence rating for the bound condition  
 16 did not reach significance after correction,  $t(23) = 2.274$ ,  $p = .033$ ,  $d = 0.464$ ,  $BF_{10} = 1.827$ .

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

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

## 18 Discussion

19 Experiment 3 provides one of the first examinations of incidental odour-colour  
20 binding in working memory. Using a single probe yes/no recognition procedure, we  
21 replicated the recency effect shown previously with olfactory stimuli (Moss et al., 2018), and  
22 for odour-colour binding in the first two experiments in the present study. However, we show  
23 no evidence of incidental odour-colour binding in respect to recognition accuracy, with  
24 neither a main effect of binding condition nor a binding by serial position interaction. The

1 recognition confidence ratings revealed some tentative evidence in support of incidental  
2 binding, with an interaction between binding condition and serial position (although Bayesian  
3 evidence was weak). Consistent with Moss et al. (2018), confidence ratings for the unbound  
4 condition exhibited a flat function, whereas there was some evidence of a development of  
5 recency for the bound condition. However, such evidence should be treated with caution  
6 given that the post-hoc comparisons at serial position 3 did not reach the threshold for  
7 statistical significance and Bayesian evidence was weak. Notwithstanding the aforementioned  
8 caution, a shift to recency is consistent with the fragility of incidental binding (consistent  
9 with the intentional binding effects of Experiments 1 and 2) and is consistent with the  
10 detrimental effect of retroactive interference on memory for the bindings.

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



1 support for incidental binding even in the most recently encoded pairing where there is least  
2 opportunity for the bindings to degrade.

3         The absence of evidence for incidental binding between odours and colours  
4 contradicts the incidental binding effects shown with verbal-spatial pairings (Campo et al.,  
5 2010; Elsley & Parmentier, 2009, 2015). An overarching goal of this research is to explore  
6 whether universal processes are applied to the problem of binding irrespective of the stimulus  
7 types employed, and one interpretation of the current finding is that olfactory working  
8 memory has different functionality to that of visual working memory. However, it remains  
9 plausible that the absence of incidental odour-colour binding effects may be a result of  
10 methodological differences and/or features of the stimuli. For example, in general, accuracy  
11 levels are substantially lower for olfactory compared to visual recognition, and given this  
12 increased task difficulty, it is possible that less cognitive resources are available for incidental  
13 binding to occur. It is also worth noting that evidence for verbal-spatial incidental binding is  
14 not universally reported. Specifically, there is evidence of incidental verbal-spatial binding  
15 operating asymmetrically, such that when memorizing locations, letters are not automatically  
16 bound (Campo et al., 2010; Elsley & Parmentier, 2015). Such asymmetry could be tested  
17 directly through replicating the present methodology with participants instructed to memorize  
18 the colour rather than the odorant.

19         The present findings appear inconsistent with other studies showing that olfactory  
20 stimuli are automatically and incidentally associated in memory with stimuli from other  
21 modalities (e.g., context-dependent memory studies involving olfaction, Aggleton & Waskett,  
22 1999; Cann & Ross, 1989; Hackländer & Bermeitinger, 2017; Schab, 1990). However, it is  
23 worth noting that studies showing an association between odorants and other modality stimuli  
24 typically present the aromas ambiently, with participants receiving no instruction to

1 remember the odours. At recall, it is assessed whether the odours have been implicitly  
2 associated by testing whether re-presentation of the ambient odour can cue retrieval of the  
3 other modality to-be-remembered information. In the present study, the odorants are the to-  
4 be-remembered stimuli and it is unclear to what extent these associative effects are found  
5 when the non-olfactory stimuli function as the memory cue and the odorant as the focus of  
6 memory.

## 7 **General Discussion**

8 The present set of experiments are one of the first to examine odour-colour binding in  
9 working memory using procedures typically employed with visual and verbal memory.  
10 Consistent with our prediction that olfactory WM would produce binding effects similar to  
11 that of visual WM, Experiment 1 demonstrated that individuals are capable of intentionally  
12 maintaining odour-colour bindings in working memory at a level above that of chance and in  
13 doing so exhibit a recency effect. This recency effect was replicated in Experiment 2 but with  
14 only limited evidence for prioritisation effects (i.e., limited strategic reallocation of resources  
15 to the first pairing in the sequence). This limited development of primacy was far less than  
16 the predicted strong prioritisation effects shown with visual binding (Atkinson, Berry, et al.,  
17 2018; Hitch et al., 2018; Hu et al., 2016). Experiment 3 examined evidence for the incidental  
18 formation of odour-colour binding and found no evidence for this using recognition accuracy,  
19 along with some weak evidence for incidental binding for the last pairing in the list when  
20 analysing confidence ratings. This is inconsistent with the predicted superior recognition for  
21 the odorants re-presented in the same coloured cube as that used at encoding and fails to  
22 support incidental odour-colour binding in working memory.

23 In the present study olfactory working memory has demonstrated some of the binding  
24 effects reported with the more extensively examined domain of visual memory. Participants

1 can intentionally maintain an odour bound to a colour in working memory, a capability  
2 shown repeatedly when a feature (such as shape) is bound to a colour (e.g., Allen et al., 2006,  
3 2012; Brown & Brockmole, 2010; see Hitch et al., 2020 for a review). Furthermore, memory  
4 for odour-colour pairings also exhibits the recency advantage shown with shape-colour  
5 pairings (Allen et al., 2006, 2014, 2021; Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu  
6 et al., 2014, 2016), supporting the proposition that binding of such information is fragile in  
7 working memory due to a vulnerability to retroactive interference (e.g., Allen et al., 2006).  
8 One might argue that these findings suggest functional similarity between olfactory working  
9 memory and that of visual memory, although the relatively low performance levels across  
10 Experiments 1 and 2 indicate that such binding functionality may be limited. That olfactory  
11 working memory may operate analogously to other modalities is consistent with recognition  
12 serial position function data (Johnson & Miles, 2009; Miles & Hodder, 2005; Moss et al.,  
13 2018; although see also Reed, 2000), Hebb repetition effects (Johnson et al., 2013), and  
14 preliminary studies examining the *n*-back task (Dade et al., 2001; Jönsson et al., 2011; Moss  
15 et al., 2019). One possible explanation for these similarities is that the same  
16 processes/mechanisms are being employed irrespective of stimulus type. That is, that the  
17 working memory processes are task, rather than stimulus, specific (although see Hurlstone et  
18 al., 2014, for a detailed review of this debate).

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

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

16 Experiment 2 furthermore indicates some possible limitations to the functionality of  
17 olfactory working memory, with rather limited evidence for working memory prioritisation  
18 effects. Whilst the prioritisation instruction to allocate greater value to remembering the first  
19 pairing in the list induced a more quadratic function, the increase in the magnitude of primacy  
20 following this manipulation was small relative to the strong prioritisation effects found with  
21 visual memory (Atkinson, Berry, et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016). The  
22 limited prioritisation effects may be explicable via the relatively low performance levels for  
23 the task and the apparent capacity limits that exist for this form of feature binding. It has been  
24 suggested that prioritisation effects are dependent on the availability of executive attentional  
25 resources in working memory (Hitch et al., 2020; with prioritisation reduced under increased

1 cognitive load, Hu et al., 2016). If these resources are depleted due to general task difficulty,  
2 it follows that the reallocation of resources to other serial positions will be limited. Moreover,  
3 it is worth noting that the accentuation of primacy following prioritisation instruction is not  
4 universally reported (Allen et al., 2020). It would be worthwhile for future work to  
5 systematically explore whether prioritisation might be more effectively applied across an  
6 increased range of sequence lengths (e.g., 2-4 items) and serial positions.

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

23 Experiment 3 found very limited evidence for incidental binding effects. We predicted  
24 that test probe odorants re-presented in the same coloured cube as at learning (bound) would

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

16 From a theoretical perspective, the present findings raise questions about the storage  
17 of olfactory representations within working memory. The above chance but relatively low  
18 accuracy levels for intentional odour-colour binding memory in Experiments 1 and 2 could be  
19 incorporated within working memory frameworks that posit a modality-general focus of  
20 attention or episodic buffer (e.g., Baddeley et al., 2021; Cowan et al., 2021). For example,  
21 within the multicomponent working memory framework, odour-colour binding retention has  
22 been attributed to the episodic buffer; the current findings indicate this to be generally limited  
23 to the retention of one binding at a time, most likely to be the most recently encountered  
24 feature pairing (see Hitch et al., 2020). Experiment 2 provides some indication that the  
25 particular binding being retained in this focus of attention is open to strategic influences, but

1 with little evidence that this directly benefits the prioritised high value item. It may be that  
2 cross-modal binding in general, or odour-colour binding in particular, is difficult to actively  
3 maintain via attentional refreshing. Finally, Experiment 3 indicates that odour-colour binding  
4 does need to be intentional and does not develop incidentally and automatically. Whilst the  
5 initial encoding and retention of visual feature bindings have been argued to emerge  
6 relatively automatically through processing in specialised subsystems (e.g., Allen et al., 2006,  
7 2012), odour-colour associative memory may be extremely limited in capacity and require  
8 executive control resources for encoding and ongoing maintenance. Future work should  
9 directly test this. It would also be useful to systematically explore the mechanistic overlap  
10 between intentional and incidental binding more generally.

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

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