EVIDENCE FOR AN OLFACTORY STORE IN WORKING MEMORY?

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We tested the hypothesis that olfactory information can be temporarily retained in a modality-specific short-term memory system. The results of two experiments using short-term memory tasks supported this hypothesis. Experiment 1 showed an effect of concurrent odour memory on digit recall that was equivalent to the effect of concurrent visual memory and smaller than that of concurrent verbal memory. Experiment 2 showed a detrimental effect of concurrent odour memory on odour recognition, and no effect of concurrent verbal and visual memory tasks. Based on these findings, and on published evidence for rehearsal and imagery of olfactory information, we tentatively conclude that there is a subsystem in working memory dedicated to temporary maintenance of olfactory information.

Key words: olfaction, odor, selective interference, memory load

This paper contributes to a small body of evidence for a working memory subsystem dedicated to temporary storage of olfactory information. Baddeley (1992, p. 281) has argued that working memory enables us to integrate information from different sensory channels, including smell. Although his model of working memory (Baddeley, 2000, 1986; Baddeley & Hitch, 1974) contains only two modality-specific subsystems—the phonological loop for storing acoustic information and the visuo-spatial sketchpad for storing visual and spatial information—there is scope for adding additional subsystems if supported by empirical evidence. Working memory for olfactory, tactile or taste information has received very little research attention. We used a dual-task methodology to investigate whether short-term memory for odours is functionally independent of short-term memory for verbal and visuo-spatial information.

Most cognitive psychological research into human olfactory memory has focused on whether olfactory memory is intrinsically different from memory in other modalities and whether olfactory memory exists independently of memory for the verbal labels of odours. Olfactory information can be remembered over long periods, as illustrated by the effectiveness of olfactory cues for recalling autobiographical memories (e.g., Aggleton & Waskett, 1999; Chu & Downes, 2000; Herz & Schooler, 2002). Researchers have debated whether this long-term olfactory memory differs in its processing constraints from...
short-term olfactory memory, in the same way that long-term and short-term verbal memory have different characteristics. Early investigators held the view that olfactory memory was organised in a different way from that of verbal and visual memory, with no separate short-term memory (e.g., Engen & Ross, 1973). The ability to retain odours so well was attributed to the odour memory being less susceptible to interference or distortion after acquisition than verbal short-term memories (Engen, Kuisma, & Eimas, 1973; Engen & Ross, 1973).

More recent findings indicate a short-term memory for odours that is comparable to verbal memory in several ways. White, Hornung, Kurtz, Treisman, and Sheehe (1998) demonstrated olfactory substitution errors in which participants erroneously recalled stimuli that were similar in odour to the target stimuli. These were comparable to the acoustic substitution errors (e.g., P for V) that have been attributed to acoustic or phonological coding in verbal short-term memory (Conrad, 1964; Baddeley, 1986). They suggest that olfactory information is remembered over short intervals in the form of an olfactory code. Miles and Jenkins (2000) demonstrated olfactory suffix effects in olfactory memory, akin to those seen in verbal memory, even when participants had learned to identify and name the stimulus odours (see also Walk and Johns, 1984). In a review of the olfactory memory literature, White (1998) concluded that there is some evidence, in the form of differential capacity limits, differential coding, differential losses following brain damage, and serial position effects, to support a distinction between long-term and short-term memory for odours. A more recent review concluded that there was not sufficient evidence for two qualitatively different stores (Wilson & Stevenson, 2006). For example, challenging capacity by increasing set size affected performance on short-term and long-term odour memory tasks, although Wilson and Stevenson note that no-one has yet compared performance on these two tasks directly. Their review found a contribution of verbal coding of odours to performance on short-term and long-term memory tasks. There was a contribution of olfactory coding to short-term memory performance (as in White et al., 1998), but little evidence regarding a contribution of olfactory coding to long-term memory for odours.

Thus there is still debate about whether short-term memory for odours is qualitatively different from long-term memory for odours. There is also debate about the extent to which olfactory short-term memory depends upon verbal coding. Even if there is a separate short-term memory for olfactory information, verbal or visual recoding may be necessary for rehearsal or for conscious retrieval of odours from that store. The evidence on this point is equivocal. Murphy, Cain, Gilmore, and Skinner (1991) found that a verbal task, counting backwards, impaired short-term recognition of odours but Engen et al. (1973) found that it did not. Perkins and McLaughlin Cook (1990) found that a verbal shadowing task impaired odour recognition whereas a concurrent visual task did not. In contrast, Annett, McLaughlin Cook, and Leslie (1995) found that a concurrent visual task (playing a video game) impaired odour recognition as much as did a concurrent verbal shadowing task, but they attributed this finding to the greater difficulty of the visual task. A follow-up study (Annett & Leslie, 1996) confirmed that more difficult tasks impaired odour memory more than easier tasks, suggesting sensitivity of odour memory to general
resource or central executive loads. Thus there is some evidence that preventing verbal rehearsal impairs olfactory short-term memory. There is also some evidence that encouraging verbal rehearsal, by instructing participants to label odours, aids immediate (Walk & Johns, 1984) and delayed olfactory memory (Rabin & Cain, 1984).

Together, these findings suggest that performance on olfactory memory tests can be mediated by verbal labelling and verbal rehearsal processes. The question remains whether verbal recoding merely supplements olfactory short-term memory or whether it is an intrinsic part of it. We sought to answer this question by using dual task procedures to investigate the relative extents to which visual, verbal and olfactory short-term memory tasks compete for resources. Much of the evidence for Baddeley’s working memory model (Baddeley, 1986; Baddeley & Hitch, 1974) comes from studies that investigate the effects of concurrent, potentially interfering, tasks on the primary task of interest. For example, the finding that concurrent articulation impairs immediate recall of words (Murray, 1967), but not of spatial locations (Smyth, Pearson, & Pendleton, 1988), supports the hypothesis of separate limited-capacity verbal and visuo-spatial subsystems in working memory. If there is a separate olfactory sub-system in working memory, short-term odour memory tasks should disrupt verbal short-term memory very little, and no more so than visual tasks disrupt verbal memory, providing verbal labelling is prevented. We tested this prediction in Experiment 1. Conversely, short-term memory for odours should be disrupted substantially by concurrent olfactory tasks but only minimally by concurrent verbal or visual tasks. We tested this prediction in Experiment 2.

**EXPERIMENT 1**

Experiment 1 used serial recall of digits as an index of verbal short-term memory and compared the disruptive effects of concurrent verbal, visual and odour short-term memory tasks. We predicted that the visual and olfactory tasks would have similar effects on recall of digits and that these effects would be smaller than the effect of the concurrent verbal task. Verbal and visual short-term memory were assessed using conventional recall tasks. Olfactory memory was assessed by an odour recognition task rather than recall, to discourage verbal labelling of the odours.

**Method**

*Participants and Design*

We tested 24 psychology undergraduates from the University of Sheffield (16 female, 8 male). Their mean age was 19 years (range 18 to 22 years). Each participant was tested in every condition (single task, concurrent letter memory, concurrent visual memory, concurrent odour memory) with condition order being counterbalanced using a Latin square.

*Materials*

The stimuli and task parameters were selected following a pilot study to produce performance levels of around 80% correct on each memory test when there were no concurrent task demands. Stimuli for the primary, digit memory task comprised 34 lists of six digits, eight lists per condition plus two practice lists.
The digits were generated randomly but avoiding repeats. For the letter memory task, there were 10 lists of six consonants (8 trials plus 2 practice lists), selected pseudo-randomly from the alphabet but avoiding repeats, words and consecutive phonologically similar letters. Digits and letters were read aloud by the experimenter at a rate of one item per second, timed by a flashing metronome placed out of sight of the participant. For the visuo-spatial memory task, there were ten 16-square matrices (8 trials plus 2 practice) printed on card and presented for 5 seconds each. The squares had 1 cm sides and were arranged in a 4 × 4 array with a random eight squares shaded in each matrix (avoiding obvious patterns). Recall responses were marked on unshaded grids of the same dimensions. The odour memory task used a total of 12 commercially produced essential aromatherapy oils (bergamot, camomile, lavender, myrrh, eucalyptus, frankincense, tea tree, peppermint, pine, patchouli, rosemary, and lemon) with 10 drops of each oil diluted in 15 ml of sweet almond base oil and presented in small, opaque bottles, numbered from 1 to 12 for identification by the experimenter (capacity approximately 40 ml, aperture approximately 1 cm diameter). A random two odours were presented on each trial, with the only constraint being that no participant received the same target odour on two consecutive trials. Presentation time was around 6 to 10 seconds: participants were asked to inhale deeply from the first bottle, exhale, and then inhale deeply from the second bottle. The recognition probe was identical to one of the targets on five out of 8 trials. The 5 : 8 ratio was chosen to balance the conflicting requirements of collecting sufficient data on the position judgement task and avoiding positive response biases. A coin toss conducted when establishing the stimulus and test lists decided whether the first or second odour was probed on a particular trial. The non-target probes were selected randomly from the remaining odours. A further two sets of target and probe items were used for the practice trials.

Procedure

All participants were tested individually, in a quiet, well-ventilated room. The full procedure lasted approximately 30 minutes.

The experimenter described the four memory tasks. For the digit recall and letter recall tasks, participants were told that a list of numbers or letters would be read aloud to them and they would be required to repeat them back in the same order. To explain the visuo-spatial memory task, the experimenter showed each participant a grid pattern and explained that they would be shown such a pattern for approximately 5 seconds and, at test, would be required to reproduce the pattern of shaded squares using the blank grid provided. To explain the olfactory memory task, participants were first asked to take some of the odours and smell each of them, taking a full inhalation and attending to the smell as best they could. They were then told that, in the memory test, two target odours would be presented one after the other, followed by a third, probe odour. Their task was to say whether they recognised the probe odour as being one of the two odours just presented and, if they did, to say whether it had been the first or second odour. Each participant was given two practice trials on each type of memory task. They were told that in most conditions they would be required to remember two types of stimuli at the same time.

The experimental conditions were blocked and separated by short breaks. There were eight trials in each condition, as follows:

Digit memory control trials: Participants attempted immediate verbal serial recall of a list of six digits, presented verbally at a rate of approximately one digit every second. The experimenter wrote down participants’ responses.

Digit-letter memory trials: The experimenter read aloud a list of six digits followed immediately by a list of six letters lasting 6 seconds. Participants attempted serial recall of the digits followed by the letters. The experimenter wrote down participants’ responses.

Digit-matrix memory trials: The experimenter read aloud the list of six digits and then presented a matrix for approximately 5 seconds. When the matrix was removed from sight, the participant attempted serial recall of the digits and then tried to reproduce the matrix.

Digit-odour memory trials: Participants were required to keep their eyes closed so the experimenter could manipulate the bottled odours unseen. They were reminded to inhale fully when each odour was presented. All twelve bottles of diluted essential oils were placed on the table in front of the experimenter at the start of this condition, with the lids unscrewed but resting on the bottles, to ensure efficient presentation of the odours. On each trial, the experimenter read aloud the list of six digits, then presented two target odours, sequentially, by placing each bottle just underneath the participant’s nostrils while they inhaled deeply. This took between 6 and 10 seconds. Next, the participant was asked to recall the list of digits, in their correct serial order. Then a third odour was presented, and the participant decided whether it had been one of the target odours and, if so, whether it had been the first or second odour in the target list. The experimenter wrote down participants’ responses.
Results

Each participant received a score for each memory task in each condition, being the number of correct responses out of a total of eight trials, expressed as a percentage. For the verbal and visual tasks, this score was the percentage of lists or matrices recalled perfectly. For the odour memory task, it was the number of correct recognition responses, that is, old items identified as old plus new items identified as new. Correct temporal position judgements (whether the recognised odour had been the first or second presented) were also recorded.

Table 1 shows mean digit recall performance in the four conditions. The digit recall scores were subjected to one-way repeated measures analysis of variance, which showed a highly significant effect of condition, $F(3, 69) = 107.08, p < .001$. Planned comparisons using paired samples t-tests with Bonferroni correction of alpha to 0.008 showed a significant difference between digit memory in the single task condition compared with each of the dual task conditions: concurrent letters, $t(23) = 17.72, p < 0.001$; concurrent matrices, $t(23) = 3.20, p = 0.004$; concurrent odours, $t(23) = 5.72, p < 0.001$. Digit memory in the digit-matrix memory and digit-odour memory conditions was significantly higher than in the digit-letter memory, $t(23) = 13.06, p < 0.001$, and $t(23) = 10.67, p < 0.001$, respectively. After Bonferroni correction, digit memory in the digit-odour condition did not differ significantly from digit memory in the digit-matrix condition, $t(23) = 2.23, p = 0.04$. These results seem robust across individuals: every participant obtained their lowest score in the digit-letter memory condition.

Mean scores on the secondary memory tasks were 10.9% (s.d. 13.45) for letter recall, 59.4% (s.d. 22.8) for matrix recall, and 79.2% (s.d. 13.3) for odour recognition. Matrix recall was significantly higher than letter recall, $t(23) = 10.99, p < 0.001$, and lower than odour recognition, $t(23) = 3.19, p = 0.004$. These scores confirm that the poor digit memory performance in the digit-letter memory condition was not due to participants remembering the letters well at the expense of the digits. Participants correctly identified the serial position of 68.4% (s.d. 28.4) of recognised odours (significantly above chance performance of 50%, $t(23) = 3.17, p < .005$).

Table 1. Memory performance in single and dual task conditions in Experiment 1, expressed as percentage correct (±standard deviation).

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<td></td>
<td>Letter recall</td>
<td>Matrix recall</td>
<td>Odour recognition</td>
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<tr>
<td>Digit recall</td>
<td>82.81 (16.82)</td>
<td>23.96 (18.40)</td>
<td>72.40 (18.05)</td>
<td>64.06 (20.95)</td>
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<tr>
<td>Secondary task performance</td>
<td>10.94 (13.45)</td>
<td>59.38 (22.80)</td>
<td>79.17 (13.63)</td>
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Concurrent letter memory had a large, detrimental effect on digit recall, demonstrating the sensitivity of the digit memory task to disruption by another verbal memory task. Concurrent olfactory memory and visual memory tasks had smaller but still significant detrimental effects on digit recall. There are several possible interpretations of these small effects of olfactory and visual memory on digit recall. Digit recall may be sensitive to a general attentional or central executive load imposed by the concurrent tasks. Alternatively, the effects may reflect the longer retention interval in the concurrent task conditions (approximately 6 sec) compared with the single task condition where digit recall was immediate. The effect of olfactory memory on digit span was slightly but not significantly greater than the effect of visual memory, which is already thought to depend on a modality-specific, non-verbal working memory store (Baddeley, 1986). It is possible that odour memory performance involved some, modest verbal mediation and therefore had modest effects on digit recall. If these results do reflect verbal mediation rather than a general attentional load in olfactory memory, then we would expect a concurrent verbal memory task to disrupt odour memory more than would a concurrent visual memory task. Experiment 2 tested this prediction. However, it is also possible that participants verbally recoded some of the visual stimuli, leading to the observed small effect of the visual task on digit span.

The present experiment used odour recognition to discourage the verbal labelling of odours that would have been essential for an odour recall task. It is conceivable that the use of a recognition test for odour memory and a recall test for visual memory led to the effect of odour memory being underestimated. Note that performance on the odour recognition task is higher than performance on the visual recall task. If we had used a visual recognition rather than recall task, perhaps it would have had a smaller effect on digit recall than the odour recognition task had. Such a finding would suggest that odour short-term memory does impose a selective load on the phonological loop. Another interpretation of our results is that the odour memory and visual memory tasks had similar effects on verbal recall because participants used the visuo-spatial sketchpad to retain the odours. Experiment 2 aimed to rule out these explanations.

**EXPERIMENT 2**

Experiment 2 used a recognition procedure for all the memory tasks to equate the general demands imposed by each task. Retention interval was also equated across tasks. We compared the effects of concurrent odour, visual and verbal memory tasks on odour memory, to test whether verbal and visual concurrent tasks have similar effects on odour memory. If odour recognition depends on a short-term memory store that is neither verbal nor visual, then verbal and visual memory tasks should interfere equally with odour memory, and do so considerably less than a concurrent odour memory task. Single task conditions were included for all modalities, to look more closely at the mutually disruptive
effects of performing two memory tasks concurrently.

**Method**

**Participants and design**
A total of 24 students from the University of Sheffield took part (nine male, 15 female, age range 18 to 27 years, mean age 21 years). Each participant received £4 for taking part or took part to fulfil a course requirement to participate in research. Every participant was tested in each of six conditions, with condition order being counterbalanced using a Latin square. There were three single task conditions (odour, digit and matrix recognition) and three dual task conditions (odour-digit, odour-matrix and odour-odour recognition). Each condition comprised 10 trials.

**Materials**
Materials were selected following pilot testing to ensure performance levels of around 80% correct on each memory test when there were no concurrent task demands.

Verbal recognition was tested with 20 study lists of seven digits, with ten lists used in the single task condition and ten in the dual task condition. No list of digits contained two identical digits. For the recognition test stimuli, half the lists remained the same and half, selected randomly, were changed by switching the positions of two adjacent digits. However, because of an error in typing the final stimulus set, the first 12 participants actually received four ‘old’ lists and six ‘new’ lists in the test phase for the single task condition. The test phase of the dual task condition contained five old and five new lists as intended. Two additional lists were used as practice items.

Visual recognition was tested with ten 24-square matrices, with a random half of the squares shaded in each matrix, avoiding obvious patterns. For the recognition test, a random five matrices were altered by moving the location of one square, the remaining five stayed the same. For the second visual memory condition attempted by each participant, the same matrices were turned though 90 degrees to create ten new matrices and their associated recognition probes. Another two matrices were used as practice items.

Odour recognition was tested with the same stimuli as in Experiment 1, with 40 pairs of odours (ten per condition) selected randomly from the full set of 12 odours. In each condition, a random five recognition trials used an odour from the presented pair and five used a new odour selected randomly from the remaining ten odours. Whether the ‘old’ probes were the first or second odour in the study pair was selected randomly. Two further odour pairs and recognition probes served as practice items.

Stimulus presentation was timed with a metronome and lasted 7 s. The digits were presented at the rate of one digit per second, the matrices were shown for 7 s each, and the odours were presented for 2 s each with a 3 s interval between stimuli.

**Procedure**
Participants were tested individually in a quiet, well-ventilated study room. The full procedure lasted approximately 50 minutes. All stimuli were kept out of view from the participant until presentation. Participants were briefed about all the memory tasks. They practised each memory test, in single task conditions, just before the first experimental condition in which that test appeared. The six conditions, described below, were attempted in counterbalanced order. Each contained ten trials. After completing each condition, participants had a short break before resuming the experiment. The experimenter recorded participants’ responses of ‘same’ or ‘different’ on each trial.

**Single task conditions.** On each of ten digit memory trials, a list of seven digits was presented verbally at a rate of one digit per second. Following presentation there was a 7 s silent retention interval and then the test list of digits was presented, at the same pace. Participants responded ‘same’ or ‘different’ following the test presentation. For each of ten matrix memory trials, a 24-square matrix was presented for 7 s, followed by a silent 7 s retention interval. Then the test matrix was shown and participants responded ‘same’ or ‘different’. For each of ten odour memory trials, one odour was presented for 2 s, participants inhaled deeply, exhaled during a 3 s inter-stimulus interval, then inhaled a second odour, which was also presented for 2 s. After a 7 s silent retention interval, a probe odour was presented. Participants were required to respond ‘same’ or ‘different’ and if their response was ‘same’ they were asked to state whether the odour was the first or the second that they had smelled in the presentation phase.
Dual task conditions. The component tasks in the dual task conditions were identical to the tasks in the single task conditions. They were combined as follows: For each of ten trials in the odour-digit memory condition, participants were given two odours to smell, sequentially, immediately followed by a verbally presented list of seven digits. There was no retention interval after the digits, hence the total presentation time was the same as that in the single task conditions, i.e. 14 s. Odour recognition was tested first, followed by digit list recognition. For each of ten trials in the odour-matrix memory condition, participants received two odours followed by a 24-square matrix, followed by the test odour and then the test matrix. For each of ten trials in the odour-odour memory condition, two odours were presented and followed immediately by two further, odours. Neither of the odours in the second pair was the same as either of the odours in the first pair. In the test phase, participants received one target odour, and decided whether it was one of the odours in the first pair, then received a second target odour and decided whether they recognised it from the second pair. The test odours that were different from their presentation pair were never one of the odours from the other presentation pair. Whenever participants recognised an odour, they decided whether it had been the first or second odour in the pair.

Results

Memory scores are expressed as the percentage of correct responses (i.e., old items identified as old plus new items identified as new) on the recognition task in each condition. Table 2 shows odour memory in the single task odour recognition condition and the three dual task conditions, and performance on the odour, digit and matrix memory secondary tasks. The primary task odour recognition scores were subjected to one-way repeated measures analysis of variance which showed a significant effect of condition, $F(2, 46) = 14.50, p < .001$. Paired samples t-tests showed that performance on the primary odour recognition task was worse with a secondary odour memory task than with a secondary digit memory task, $t(23) = 4.89, p < 0.001$, or matrix memory task, $t(23) = 4.21, p < 0.001$. Performance on the primary odour memory task did not differ between the digit and matrix secondary task conditions, $t(23) = 0.44, p = 0.66$.

Performance on the odour memory task when performed alone was higher than when combined with an odour memory secondary task, $t(23) = .93, p = 0.001$. Performance on the secondary odour task was also lower than on the primary odour memory task, $t(23) = 2.60, p = 0.02$. This is the only significant result from the seven t-tests reported here that does not survive Bonferroni correction of alpha to 0.007. Digit memory or matrix memory secondary tasks did not reduce odour memory performance relative to the

Table 2. Mean recognition performance, expressed as percentage of correctly answered trials, in single and dual task conditions in Experiment 2 (±standard deviations).

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<tr>
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<th>Secondary memory tasks</th>
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<th>Primary memory task (Olfactory memory)</th>
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<tr>
<td></td>
<td>Verbal memory</td>
<td>Visual memory</td>
<td>Olfactory memory</td>
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<tr>
<td>Single task</td>
<td>74.58</td>
<td>85.00</td>
<td>78.33</td>
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<td></td>
<td>(19.11)</td>
<td>(12.16)</td>
<td>(14.03)</td>
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<tr>
<td>Dual task</td>
<td>67.50</td>
<td>87.50</td>
<td>67.92</td>
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<td></td>
<td>(18.24)</td>
<td>(10.32)</td>
<td>(15.32)</td>
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Combining the digit memory or matrix memory task with odour memory did not impair performance relative to performing them alone. Digit memory dropped by a mean of 7.1 percentage points, $t(23) = 1.53, p = 0.14$, and matrix memory rose by 2.5 percentage points, $t(23) = 0.83, p = 0.42$. Thus the null effects of digit memory and matrix memory on odour memory cannot be attributed to performance trade-offs, i.e., preserved odour memory with impaired digit or matrix memory.

Performance was not perfectly matched across the odour, digit and matrix memory tasks when the tasks were completed alone. Performance on the matrix memory task was higher than on the digit memory task, $t(23) = 2.37, p = 0.03$, but not the odour memory task, $t(23) = 1.81, p = 0.08$. Performance on the digit and odour memory tasks did not differ, $t(23) = 0.88, p = 0.39$. The significant difference between scores on the matrix and digit tasks does not survive Bonferroni correction of alpha to 0.017.

In each odour memory task, participants judged the serial position of each correctly recognised old item. Scores on this position judgement task were 80.3% (s.d. 22.0) in the single task condition, 79.9% (s.d. 14.1) in the odour-digit condition, 78.6% (s.d. 19.4) in the odour-visual condition, and 86.9% (s.d. 19.7) on the primary task of the odour-odour condition. These means all exceeded chance performance of 50% (all $p$ values < 0.001), fell short of ceiling performance of 100% (all $p$ values < 0.005), and did not differ significantly across conditions, $F(2, 46) = 0.92, p = 0.43$. Participants correctly judged a mean of 63.1% (s.d. 23.3) of the positions of hits on the secondary odour memory task in the odour-odour condition. This score exceeds chance, $t(23) = 2.76, p = 0.01$, and is lower than performance in the single task odour memory condition, $t(23) = 2.65, p = 0.01$.

**Discussion**

Experiment 2 showed a significant effect of concurrent odour memory on the primary odour memory task, and a smaller effect of the primary odour task on the secondary odour task (non-significant after Bonferroni correction). The effect of a secondary odour memory task was selective: visual memory or verbal memory tasks were combined with the odour memory task with no impairment to either task. Participants did not appear to use visuo-spatial processes to retain the odour information, although single task performance suggested that the visual memory task was somewhat easier than the verbal and odour memory tasks so its effect may have been underestimated. Nonetheless, there is no debate in the literature about a visual contribution to odour memory, only about a verbal contribution. The present results show that short-term olfactory memory can be effected without verbal support, consistent with the hypothesis of a short-term olfactory memory that, like short-term verbal or visual memory, is the function of modality-specific memory processes.

Performance on the secondary digit and matrix memory tasks was unaffected by the primary odour memory task, suggesting that participants did not remember the odours by verbally or visually recoding them. Recall of the serial position of correctly recognised odours in the primary odour memory task was unaffected by secondary task condition,
though position recall was poorer when odour memory was performed as a secondary task than as a single task.

GENERAL DISCUSSION

Results from two experiments are consistent with the hypothesis that short-term olfactory memory is the function of a specialised subsystem in memory, rather than being dependent on verbal recoding. Experiment 1 showed a substantial effect of concurrent verbal memory on a primary verbal memory task, but a smaller effect of concurrent odour memory that did not differ significantly from the effect of a concurrent visual memory task, suggesting that it imposed a general resource load rather than loading selectively on verbal memory processes. This finding suggests that olfactory short-term memory does not require verbal labelling or rehearsal processes, as these processes would have interfered selectively with performance of the primary verbal memory task. Experiment 2 showed that short-term recognition of odours was selectively impaired by a concurrent odour memory task. Concurrent visual or verbal memory tasks had no effect on odour memory, indicating that they did not impose a general resource load on the odour memory task, or that the odour memory task was not sensitive to general resource demands.

The absence of non-selective effects of visual and verbal secondary tasks in Experiment 2 contrasts with the results of Experiment 1, where visual and odour memory tasks did have a nonspecific effect on verbal memory. One possible explanation of the difference may be that, because of a design flaw in Experiment 1, the visual and odour memory tasks may have impaired digit recall simply because they necessitated a brief delay before digit recall, whereas recall was immediate in the single task condition. Retention interval was equated across conditions in Experiment 2. Another possible explanation of Experiment 1’s results was that participants used verbal recoding strategies for the odour memory task, and perhaps also for the visual memory task, leading to small interference effects on the primary digit recall task. The mutual null effects of odour memory and digit memory in Experiment 2 help to rule out this explanation.

So, the effects of the concurrent visual or odour memory tasks on verbal memory in Experiment 1 may be due to the dual task conditions imposing a delay before recall that was not present in the single task verbal memory condition. They may also be attributable to a general resource load. If this is the case, then the absence of general dual task effects in Experiment 2 may be due to the use of recognition procedures rather than recall. Recognition is considered to be less resource-limited and less sensitive to interference than recall (Craik & McDowd, 1987). The use of recognition rather than recall in Experiment 2 may also explain the fact that the competing odour memory tasks had rather modest effects on each other whereas the effect of concurrent letter memory on digit recall was catastrophic: performance on the primary digit recall task in Experiment 1 dropped by 58.9 percentage points when combined with the letter recall task, whereas performance on the primary odour recognition task in Experiment 2 dropped by 14.6 percentage points when combined with another odour recognition task.
Digit recall in Experiment 1 may have been susceptible to general resource loads because it emphasises retention of order as well as item information. Retaining the correct items is relatively easy (six from a set of nine) but retaining the items in the correct serial order is crucial for correct performance. For the odour memory task in Experiment 2, retaining the correct items is relatively difficult (two from a set of 12) and remembering their order is relatively unimportant. Two results from Experiment 2 contradict this explanation. First, recall of item order (i.e. whether a recognised item was first or second in the study list) on the primary odour memory task was unaffected by the resource loads imposed by the secondary memory tasks. Second, performance on the digit recognition task was unaffected by being combined with the odour memory task, even though the digit task strongly emphasised retention of order information because the distractor items at test contained the correct items but in the wrong order. It would appear that the small effects of concurrent visual memory and odour memory tasks on digit recall in Experiment 1 were either due to the increased retention intervals in those conditions or to the greater sensitivity of recall rather than recognition to general resource loads.

The findings from this study suggest that odours can be stored temporarily in memory in an olfactory code that does not require verbal or visual processing. The findings are consistent with the hypothesis that there is a modality-specific short-term memory system for olfactory information (White, 1998). This hypothesis is also supported by White et al.’s (1998) demonstration of olfactory substitution errors in short-term free recall. Similar effects have not been demonstrated in long-term olfactory memory. This conclusion, of a modality-specific short-term store for odours, does not conflict with findings in the literature that verbal processing can contribute to olfactory memory (Annett et al., 1995; Murphy et al., 1991; Perkins & McLaughlin Cook, 1990; Rabin & Cain, 1984; Walk & Johns, 1984; but see Engen et al., 1973). We suggest that verbal labels aid memory for odours by providing an additional memory code, in the same way that visual imagery can aid memory for words (e.g., Paivio, 1986). Our findings suggest that odours can be retained in an olfactory code without verbal support.

We have not shown that people can rehearse or manipulate olfactory information, merely that they can store it. The concept of working memory, rather than simply short-term memory, embodies the idea that temporarily stored information can be rehearsed and manipulated in the service of complex cognitive tasks. In Baddeley’s working memory model (Baddeley, 1986), the phonological loop and visuo-spatial sketchpad serve rehearsal and manipulation functions as well as simply storing verbal and visuo-spatial information respectively. The extent to which rehearsal and manipulation are modality-specific functions rather than the function of a general central executive remains under debate (see Andrade, 2001, p. 284–285 for discussion). Nonetheless, to argue for an olfactory subsystem in working memory, rather than merely a capability for retaining odours over short intervals, we need evidence for rehearsal or manipulation of odour information. Studies of primacy effects potentially provide relevant evidence, because primacy effects in verbal memory have been attributed to greater rehearsal of early list items than later items (e.g., Tan & Ward, 2000). However, most researchers failed to find primacy effects in olfactory memory (Annett & Lorimer, 1995; White and Treisman,
Reed (2000) did find primacy effects, but Miles and Hodder (2005) failed to replicate his findings.

Some evidence for olfactory rehearsal comes from a recent brain imaging study (Dade, Zatorre, Evans, & Jones-Gotman, 2001). Dade et al used a two-back task, in which participants decide if the current stimulus is the same as or different from the stimulus they received two trials ago. The task is considered to require item maintenance and also manipulation, because of the requirement to update working memory continually. Dade et al used positron emission tomography to compare activation of prefrontal cortex during performance of two versions of the two-back task, one with faces as stimuli and one with odours as stimuli. Both versions of the task activated the same regions of prefrontal cortex. Although the authors concede that there may be modality-specific populations of neurones within the prefrontal cortex, their study did not reveal any differences in extent or site of activation between the two working memory tasks. They therefore suggest that, although olfactory and visual information may be stored in different brain areas, they are manipulated by common executive processes located in prefrontal cortex.

Mental imagery functions have been ascribed to the phonological loop and visuo-spatial sketchpad. For example, Baddeley and Andrade (2000) argued that vividness of imagery was determined in part by retention and manipulation of sensory information in the relevant slave system. Evidence for olfactory imagery would be consistent with the notion of an olfactory slave system in working memory. In a review of the olfactory imagery literature, Stevenson and Case (2005) concluded that people can imagine odours, but that they often find it hard to do so without practice. Djordjevic, Zatorre, Petrides, and Jones-Gotman (2004) demonstrated perceptual effects of olfactory imagery similar to those of visual imagery on visual perception (Segal & Fusella, 1971). Participants detected rose or lemon odours at individually-determined threshold intensities. Imagining a rose odour impaired detection of lemon, and vice versa. Imaging the appearance of a rose (or lemon) did not impair odour detection. Levy, Henkin, Lin, Hutter, and Schellinger (1999) showed that imagining an odour was associated with activation in the same brain regions as perceiving an odour, for participants with normal olfaction and for those with acquired loss of odour perception (anosmia). People with congenital anosmia (and therefore no olfactory memories) could not imagine odours and did not show this pattern of activation.

Thus there is evidence in the literature that people can actively process olfactory information as well as store it. It is too early to say what the specific mechanisms of that active processing might consist in. The study by Dade et al. (2001) suggests that olfactory rehearsal may involve generic attentional or executive processes rather than a modality-specific ‘re-smelling’ rehearsal loop’. However, the olfactory imagery study by Levy et al. (1999) points to the involvement of olfactory perceptual areas in odour imagery, consistent with modality-specific manipulation processes.

We only tested short-term retention of odour information. Evidence for modality-specific short-term stores in working memory comes from demonstrations of differential effects of manipulations on short-term and long-term memory (e.g., Baddeley, 1966a, 1966b; Hitch, Brandimonte, & Walker, 1996; but see Russo & Grammatopoulou, 2003).
and from neuropsychological dissociations between damage to short-term and long-term memory (e.g., Hanley, Young, & Pearson, 1991; Warrington & Shallice, 1969). There have not yet been convincing neuropsychological dissociations between short-term and long-term memory for odours (Wilson & Stevenson, 2006). However, our study provides tentative evidence for a functional dissociation. Our finding, of selective interference with short-term memory for odours, contrasts with the results of a study by Zucco (2003). Zucco tested recognition of lists of 15 odours, pictures or sounds after filled retention intervals lasting approximately two and a half minutes. During the retention intervals, participants rated the pleasantness of olfactory, visual or acoustic stimuli. Memory for the visual and acoustic stimuli was impaired by rating stimuli in the same modality during the retention interval. Long-term memory for the olfactory stimuli was unaffected by the presence or nature of the retention interval task. In other words, only short-term memory for odours is subject to modality-specific interference. We conclude that olfactory information can be temporarily stored, without verbal or visual re-coding, in a dedicated olfactory subsystem of working memory.

REFERENCES


