Memory and executive function impairments after frontal or posterior cortex lesions

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Free recall and recognition, memory for temporal order, spatial memory and prospective memory were assessed in patients with frontal lobe lesions, patients with posterior cortex lesions and control subjects. Both patient groups showed equivalent memory deficits relative to control subjects on a range of free recall and recognition tasks, on memory for temporal order and on a prospective memory task. The patient groups also performed equivalently on the spatial memory task although only patients with frontal lobe lesions were significantly impaired. However, the patients with frontal lobe lesions showed an increased false alarm rate and made more intrusion errors relative not only to the control subjects, but also to the patients with poster or cortex lesions. These memory problems are discussed in relation to deficits in executive function and basic memory processes.

Keywords: Frontal lesions, memory, executive function, false memory

1. Introduction

It is well known that damage to the frontal association neocortex can cause a variety of memory impairments (see [28] for a review). However, three things are less well known. First, although it is widely believed that these memory problems result from several functional deficits, caused by lesions to the frontal cortex, the evidence for this is still rather weak. Second, it is poorly understood what these functions are. Third, little is known about the extent to which the memory deficits are specific to frontal lobe lesions. This paper reports a study that is primarily aimed at the third of these issues concerned with the nature of the memory deficits caused by frontal lobe lesions.

It has been argued by Bachevalier and Mishkin [3] that, in monkeys, ventromedial frontal cortex (orbitofrontal and anterior cingulate) lesions produce amnesia because they found that such lesions disrupted object recognition memory. In contrast, dorsolateral prefrontal cortex lesions did not have this effect. The human evidence on this issue is inconclusive partly because it is very rare to encounter damage that is selective, but extensively disrupts anterior cingulate and orbitofrontal cortices (see [11,31] for reviews). Even if ventromedial frontal cortex lesions do cause amnesia in humans, the memory deficits produced by lesions to other frontal cortex regions (such as the dorsolateral frontal cortex) overlap with, but also typically differ from those shown by amnesics. It is widely believed that this more common pattern of memory deficits is secondary to the disruption of executive or planning abilities that such lesions cause (for example, see [7, 14,26–28,44,47,48]. For example, both encoding and retrieval can present relatively novel problems which require strategic organization to arrive at an optimal solution. If planning ability is impaired, then encoding will be inefficient and memory poor. Similarly, if retrieval is rendered inefficient by poor planning so that search and monitoring operations are sub-optimal, then memory will be poor. These deficits will be most striking in situations where the encoding and retrieval procedures are both intentional and likely to be least routinized.

There is considerable evidence supporting this hypothesis. Frontal lobe lesions typically disrupt free recall more than recognition [28] although the reverse pattern of deficit has occasionally been reported [12]. This pattern of impairment probably occurs because free recall is more dependent on forming links between items at encoding, which is likely to be a less routinized procedure, and/or more dependent on the less routinized retrieval procedures involved in finding links between remembered items. Gershberg and Shimamura [14] have provided support for this interpretation

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by showing that strategy instruction at either study or test particularly helped patients with frontal lesions.

One of the best established deficits associated with frontal lobe damage is a disruption of memory for temporal order, regardless of whether this is tested by recall or recognition [23,25,32]. In contrast, it is less clear whether frontal cortex lesions cause deficits in spatial memory as neither Smith and Milner [46] nor Kesner et al. [23] found an effect on long-term spatial memory in patients with focal lesions of this region. This is puzzling for two reasons. First, frontal cortex lesions do disrupt memory for the source of remembered information (for example, see [21]) and it seems likely that included in the source information is the knowledge of the spatial location of the source. Second, as with the free recall problems that result from frontal lobe damage, a plausible account of the origin of the problems with temporal order memory is that this kind of memory is particularly dependent on organized encoding and retrieval of associative information. This view is supported by evidence that the deficit can be overcome if subjects have to perform actions with common objects that are presented in a specific temporal order, i.e., if they are directed to engage in appropriate encoding operations [25]. Also, Mangels [27] has suggested that the temporal ordering of semantically organized word lists is only impaired in patients with dorsolateral frontal cortex lesions after intentional encoding instructions. As a deficit is not found after incidental encoding instructions, this strongly suggests that the problem arises primarily because patients do not organize their encoding in an appropriate strategic fashion. As spatial memory presumably depends on similar organized encoding and retrieval procedures, it is surprising that previous studies have shown it to be largely spared.

There is also a strong association between frontal lobe lesions and confabulation (for example, see [34]). Confabulation arises when free recall particularly of personal information leads to an abnormal number of false memories, which the patient thinks are true memories [22]. A plausible explanation of this deficit is that patients engage in a suboptimal search and use inferior checking procedures. They may also mix components of several events inappropriately together because of their poor temporal memory and source amnesia. In other words, confabulation is probably a result of poor organizational abilities at retrieval as well as poor context memory.

Confabulation is very similar to two other kinds of memory deficit that have been reported in patients with frontal cortex lesions so all three deficits may be caused by the same processing impairment. The first deficit is a tendency to produce an abnormal number of false alarms both in recognition and recall. Patients are frequently confident that these false alarms are true memories [12,39]. The patient with an extensive right frontal cortex lesion, described by Schacter et al. [39], believed that with a high proportion of these false memories he had recollected details of their original encoding. The authors interpreted this deficit as an impairment in the search process in which the patient did not feel the necessity of carrying out anything more extensive than a superficial search. The interpretation is compatible with positron emission tomography studies which indicate that the right frontal cortex is consistently active during episodic retrieval [30,41].

The second memory deficit, similar to confabulation, that has been reported in patients with frontal cortex lesions is an abnormal sensitivity to various kinds of interference. They are abnormally susceptible to proactive interference in A–B, A–C learning paradigms. Frontal patients were impaired at learning the second list and showed an abnormal number of prior list intrusions [43]. This suggests that one source of confabulation could be a tendency to confuse items that come from different contexts.

Frontal cortex lesions are also believed to contribute to failures of prospective memory, which can be regarded as the delayed fulfilment of intentions [7,8]. This kind of deficit may be more readily found in real life situations such as shopping than with experimental test procedures perhaps because the former place more demands on the executive processes needed for setting up and responding to the internal markers that may be required if delayed intentions are to be followed. It remains an unresolved question whether prospective memory deficits always co-occur with other 'frontal' memory problems or whether they can be dissociated from some of the other memory impairments.

It should be noted that many of the memory deficits which have been discussed so far are not only caused by frontal cortex lesions. Thus, Hirst et al. [18,19] have claimed that global amnesics are more impaired at free recall than they are at recognition, although this has been denied by Haist et al. [16] who found that their global amnesic patients were equally impaired at recognition and recall. A possible resolution of this conflict has been suggested by a study of Isaac and Mayes [20], who found that global amnesics were more impaired at free recall than at recognition of word lists. However, not only did this deficit pattern not appear

for several minutes, it was apparent for lists of semantically related words, but not unrelated words. Haist et al. [16] used lists of unrelated words whereas Hirst et al. found relatively preservation of recognition with semantically related word lists. Interestingly, Aggleton and Shaw [1] have also argued on the basis of a meta-analysis, that patients with selective damage to Papez circuit structures (hippocampus, fornix, mammillary bodies, anterior thalamus) were found to show relatively severe recall deficits for organized materials, with milder effects on recognition. Even though their claim has been disputed (see [38]), Vargha-Khadem et al. [50] have described three young patients with selective hippocampal lesions who were impaired on free recall despite showing normal item recognition, and the same pattern, specific to verbal materials, has been reported in a patient with damage to the left fornix and anterior thalamus [17]. Further, a patient with an adult onset selective hippocampal lesion has been reported to show not only this pattern of impaired recall, and intact item recognition, but also impaired temporal order memory (see [29]).

If both Papez circuit lesions and lesions of parts of the frontal cortex disrupt recall more than item recognition, and also impair temporal order memory, it is likely that Papez circuit lesions impair the basic memory processes (probably storage) primarily underlying free recall and temporal order memory. In contrast, frontal lesions may produce a broadly similar effect because they disrupt the planning processes which support the encoding and retrieval operations that are particularly critical for free recall. Not only do disproportionate free recall deficits, therefore, appear to be caused by Papez circuit as well as frontal cortex lesions, but the two kinds of lesion seem likely to be producing different functional impairments.

The same point may be true of other memory impairments that are caused by non-frontal as well as by frontal cortex lesions. Thus, amnesics also show impaired prospective memory in the sense that they fail to fulfil their intentions. However, unlike patients with frontal cortex damage who fail to fulfil their intentions, amnesics usually are unable to remember their intentions even when directly asked. This suggests that their failure may involve a storage impairment rather than a difficulty with executive processes. It is less clear whether the enhanced sensitivity to proactive interference that is found in amnesics with either midline diencephalic [31] or medial temporal lobe lesions [52] is caused by a different functional deficit than is the equivalent frontal impairment. Both patients with frontal cortex damage and amnesics, who show enhanced sensitivity to proactive interference also show increased numbers of intrusion errors from the A–B list when trying to retrieve A–C items. The more detailed pattern of the disorder in the two groups is, therefore, similar so it remains possible that the enhanced sensitivity to proactive interference results from identical underlying functional deficits.

The present study aimed to determine whether posterior neocortex lesions (that do not extend into the medial temporal lobe regions where lesions cause amnesia) produce similar patterns of deficit on recall and recognition tests and on other memory tests as do frontal cortex lesions that do not extend into the ventromedial frontal cortex (which might cause amnesia). There is evidence that activations are found in parietal and temporal neocortex structures during the performance of memory tasks (see [30]), but little is known from human studies about the effects of lesions to these structures on memory task performance. It, therefore, remains possible that the reported activations resulted from processing that was not critical for memory task performance. As well as verbal and visual item free recall and recognition, memory for temporal order, spatial memory and prospective memory were included in the comparative analysis. Some tests of executive function were also given to the patients in order to check previous evidence that lesions of posterior neocortex structures disrupt performance on such tests (e.g. [2]).

2. Method

2.1. Subjects

Three groups of subjects took part in this study: a group of patients with unilateral frontal lobe damage (FL, $n = 10$), a group of patients with unilateral damage to the posterior cortex (PL, $n = 10$) and a healthy control group (NC, $n = 10$) matched to the patients groups on age and IQ. All patients were in-patients at the Neurology Units of different hospitals. In all cases, the location of the lesion was established on the basis of CT or MRI scans. In the FL group, six patients had right-sided and four patients had left-sided lesions, and there was no evidence of additional damage to posterior cortex areas. The aetiologies of the lesions were intracerebral hemorrhage ($n = 6$), contusion ($n = 2$), aneurysm surgery ($n = 1$) and tumor removal ($n = 1$). There was evidence of damage to the dorsolateral frontal cortex in eight cases, and the

Table 1
Subject group characteristics (means and SDs)

	FL	PL	NC
Sex	3 m, 7 f	6 m, 4 f	5 m, 5 f
Age	40.4 (8.2)	42.5 (11.4)	39.4 (8.6)
Affect-Arousal	36.0 (15.3)	31.1 (15.3)	35.8 (11.0)
IQ	112.9 (8.4)	107.8 (7.3)	112.2 (10.0)

ventromedial frontal cortex was not affected in any of the patients. A more detailed description of the lesion sites within the frontal cortex was not possible on the basis of the available data.

In the PL group, five patients had suffered damage to the right posterior cortex and five patients to the left posterior cortex. In nine cases, the lesion involved the temporal or the parietal cortex or both, and one patient had a right occipital lesion. The lesions did not extend medially into the medial temporal lobe region, the posterior cingulate and retrosplenial region, or into the midline thalamus (lesions to which may cause organic amnesia). The aetiologies comprised intracerebral hemorrhage ($n = 2$), tumor removal ($n = 3$), contusion ($n = 1$) and infarct ($n = 4$). The assessment described in this paper was carried out in the FL group on average 14.7 months ($SD = 20.4$) and in the PL group 15.8 months ($SD = 9.9$) since the lesion had occurred. One FL and one PL patient were receiving antiepileptic medication, and another FL patient was on antidepressant medication.

The control subjects (NC) were recruited by advertisements; they received a small reimbursement for travel expenses. None of the NC subjects had a history of psychiatric or neurological disorder or took medication at the time of testing. All patients and NC subjects were right-handed.

Information on demographic variables in the three groups is given in Table 1. All subjects completed a short version of the German Wechsler Adult Intelligence Scales [9]. This version is based on performance on the subtests Vocabulary, Similarities, Picture Completion and Block Design. Present state affect-arousal was assessed with visual analogue scales which consisted of pairs of adjectives describing mood states (e.g. "alert-drowsy", see [6]). The three groups did not differ significantly with regard to age, mood or IQ (all $p > 0.37$).

2.2. Procedure

The neuropsychological assessment for each subject involved completing two testing sessions, each of which lasted about 90 minutes. The same order of tests was used for each subject.

2.3. Tests of frontal lobe function

A modified version of the Wisconsin Card Sorting Test (WCST [35]) was administered to assess the ability to form and shift cognitive sets. The number of categories achieved and the number of nonperseverative and perseverative errors were recorded.

The verbal fluency task used in this study involved a semantic category (countries), a phonemic category (letter "B"), a category restricted by two rules (4-letter words beginning with "D"), and a further subtest which required the subject to name vegetables and first names of boys alternately. In each condition, the subject had to produce as many exemplars as possible within a time limit of 1 min.

The third standard test of frontal lobe function was a German adaptation of the Cognitive Estimates Test [42]. Subjects had to estimate the answers to 10 problems, such as "How long is the average man's spine?" The items which were specific for the British context were changed to the German context, e.g. instead of being asked about the height of the Post Office Tower, subjects were asked about the height of Cologne Cathedral.

The following procedure was used to evaluate the performance of the patients on this task: The control subjects' mean and standard deviation was determined for each item that required a quantitative response. For each patient, the number of items eliciting a response more than one standard deviation away from the controls' mean scores was determined. Two items did not require a quantitative estimate (best paid profession in Germany, largest household object). As none of the patients gave unrealistic estimates on these items, they did not add to the scores.

2.4. Memory assessment

2.4.1. Verbal memory: Recall and recognition

Measures of verbal memory included free recall (after a 5 minute delay) of the prose passage from the Wechsler Memory Scale [5] and recall and recognition of word lists. For story recall, the number of correctly reproduced details as well as the number of intrusion errors (i.e. any details which were produced by the subject that were not part of the original story) were recorded.

Two word lists which were matched for word length and word frequency were developed. Each list comprised 16 words, which were drawn from four different categories (such as animals, musical instruments,

professions etc) with four words in each category. The words were presented individually on cards in random order and they had to be read aloud by the subject. To assess recall, the subject was asked to reproduce the first list after a 30 minute delay. The number of correct items and the number of intrusion errors, i.e. items which the subject claimed to remember, but which were not on the original list, were recorded.

The second word list was presented in the second testing session, and a 4-choice forced choice recognition test was carried out after a 30 minute delay. Each target was shown together with three distractor words matched for word length and frequency. Two of these distractor words were drawn from the same category as their target word and the third distractor was drawn from an unrelated category. Subjects had to indicate which words they had seen previously. A pilot study with control subjects had established that the two lists were of comparable difficulty as indicated by the similar memory (recall and recognition) scores shown for each list.

2.4.2. Visuospatial memory: Recall and recognition

This test involved a set of five geometrical patterns which consisted of five dots in a 3×3 matrix that were connected by straight lines. The number of lines was not constant across the different figures. The patterns were similar to those used by Gabrieli et al. [13]. The subjects were asked to copy and to memorize the patterns. In the recall part of the test, the items had to be drawn from memory 30 minutes after being copied. The number of correctly reproduced whole patterns and the number of correct and incorrect lines were determined.

In the recognition part of the test which was administered in the second testing session, the subjects were again asked to copy five dot patterns, and after a 30 min delay, a 4-choice forced choice recognition task was administered. Each choice comprised the target and three distractor patterns. For two of the distractors, the dots from the 3×3 matrix were identical to those of the target, but they were connected by different lines. The third distractor did not bear any similarity to the target. As for the word lists, a pilot study had established that the two lists of patterns, used in the first and second testing sessions, were of comparable difficulty.

2.4.3. Memory for temporal order

The order memory task centred on memory for the sequence of two lists of faces. Subjects were initially shown 12 of the photographs of faces from the Recognition Memory Test (RMT [51]) and instructed to remember them. The items were presented sequentially. After a filled interval of two minutes, a second set of 12 faces from the RMT was presented, again with memory instructions. Following a filled interval of 30 min during which other neuropsychological tests were carried out, 48 faces (the 24 targets and 24 distractors which were other faces from the RMT) were presented individually and the subjects had to indicate for each photograph whether or not they had seen it before. If the subject claimed to recognize a face, he/she was also asked to indicate whether the photograph belonged to the first or the second list. The following variables were recorded: number of hits, number of false alarms, a recognition index (hits minus false alarms divided by the total number of targets) and an order memory index (number of correctly allocated hits divided by the overall number of hits).

2.4.4. Memory for spatial positions

The spatial memory task comprised a grid consisting of 49 squares arranged in a 7×7 set-up, with each square measuring 4 cm $\times$ 4 cm. Sixteen miniature models of tools, household objects etc. were placed in different positions on the grid and the subjects were asked to guess the price of each item (see [46]). The models were then removed from the grid and after a 5 minute delay, the subjects were asked to put the toys onto the grid, in their original positions. The number of correctly located items and a deviation score were recorded. The deviation score was based on the number of squares between the target positions and the positions reproduced by the subject.

2.4.5. Prospective memory

At the beginning of the first testing session, three instructions were read to the subjects which involved conditional cues. They were: "When I stand up, please put the pencil into the mug." "When I take off my wrist watch, please go to the window and look out." "When I take my key out of my bag, please ask me for a handkerchief." Fifteen minutes, 30 minute and 45 minute after these instructions were given, the experimenter completed the first part of the respective instruction and recorded whether the subjects responded by carrying out the second part. At the end of the second session, they were asked whether they remembered what they should do when the respective behavioural cue was provided by the experimenter.

Table 2
Mean number of items produced on the four subtests of the verbal fluency task (SDs in brackets)

	FL	PL	NC
semantic	18.7 (6.7)	16.9 (4.4)	22.9 (3.1)
phonemic	12.3 (3.9)	12.0 (3.2)	16.4 (2.8)
alternate	13.7 (4.8)	13.3 (3.5)	15.6 (3.1)
two rules	2.6 (1.0)	1.9 (1.3)	3.8 (1.2)

2.5. Data analysis

Group differences were evaluated by analysis of variance (ANOVA) or repeated measures ANOVA where appropriate. If there were significant group differences in variances, nonparametric tests (Kruskal-Wallis ANOVA) were used. Post-hoc paired group comparisons were carried out using Tukey's honestly significant difference (HSD) tests or Mann-Whitney U-tests, respectively.

3. Results

3.1. Tests of frontal lobe function

There were no significant group differences for the number of categories achieved or the number of nonperseverative errors on the Wisconsin Card Sorting Test (both $ps > 0.29$), and the comparison of perserverative errors did not reach significance either ($H = 5.30$, $df = 2$, $p = 0.070$). The FL patients on average made 1.1 perseverative errors ($SD = 1.9$), the respective error scores for the PL patients and NC subjects were 0.4 ($SD = 0.5$) and 0.0, respectively.

The results for the different subtests of the verbal fluency task are presented in Table 2.

The three groups differed significantly on the number of generated items in the semantic category ($F(2, 27) = 3.83$, $p = 0.034$), the phonemic category ($F(2, 27) = 5.36$, $p = 0.011$) and in the category restricted by two rules ($F(2, 27) = 6.76,\ p = 0.004$), but not in the alternating task ($p = 0.38$). The NC subjects achieved a significantly higher score than the PL patients in all three tasks (all $ps < 0.032$) and they performed better than the FL group in the phonemic subtest ($p = 0.029$) and the two-rule category ($p = 0.074$).

In the Cognitive Estimates Test, the FL patients produced a mean of 3.0 responses ($SD = 1.4$) and the PL patients produced a mean of 2.1 responses ($SD = 1.4$) that lay more than one standard deviation from the mean of the control subjects' estimates. The two patient groups did not differ significantly on this measure ($U = 61.5,\ p = 0.16$).

3.1.1. Verbal memory: Recall and recognition

The results for the free recall of a prose passage and a 16-item word list are presented in Fig. 1.

There was a significant group difference for the number of correctly recalled details of the story ($F(2, 27) = 7.94,\ p = 0.002$). The NC group remembered more details than the FL ($p = 0.005$) and the PL groups ($p = 0.005$). The three groups also differed on the number of intrusion errors (confabulatory responses) ($H = 6.36,\ df = 2,\ p = 0.041$); this result was due to a significantly higher score in the FL group compared to NC subjects ($U = 75.0,\ p = 0.013$). Most of the intrusion errors made by the control subjects and PL group were related to the story whereas 44% of the intrusion errors made by the FL group were unrelated to the story.

A similar pattern emerged in the analysis of word list recall. There were significant group differences for the number of correctly recalled words ($F(2, 27) = 4.17,\ p = 0.026$) and the number of intrusion errors ($H = 7.37,\ df = 2, p = 0.025$). The NC group recalled more items than the FL group ($p = 0.020$) and showed a smaller number of intrusion errors ($U = 81.0,\ p = 0.012$). The PL group also showed marginally fewer intrusion errors than the FL group ($U = 73.0,\ p = 0.066$). Other paired group comparisons did not approach significance.

In the recognition part of the word list task, the NC subjects correctly recognized 15.4 items ($SD = 1.1$), the scores of the FL and PL patients were 12.9 ($SD = 3.0$) and 12.6 ($SD = 3.5$), respectively. The significant group difference for this measure ($H = 7.27,\ df = 2,\ p = 0.026$) was due to a larger number of hits in the NC group relative to both the FL ($U = 20.5,\ p = 0.019$) and the PL groups ($U = 20.0, p = 0.017$). The few errors that were made involved selection of foils that were semantically related to targets.

3.1.2. Visuospatial memory: Recall and recognition

The means and SDs for the number of correctly reproduced whole patterns, the number of correct and incorrect lines and the number of correctly recognized dot patterns are presented in Table 3.

Analysis of free recall yielded significant group differences for the number of correctly reproduced whole patterns ($F(2, 27) = 7.26,\ p = 0.003$) and the number of correct lines ($F(2, 27) = 8.55,\ p = 0.001$). In all paired-group comparisons, the NC group performed better than both patient groups (all $p < 0.03$). Analysis of the number of incorrect lines yielded a tendency toward significance ($H = 4.74,\ df = 2,\ p = 0.093$);

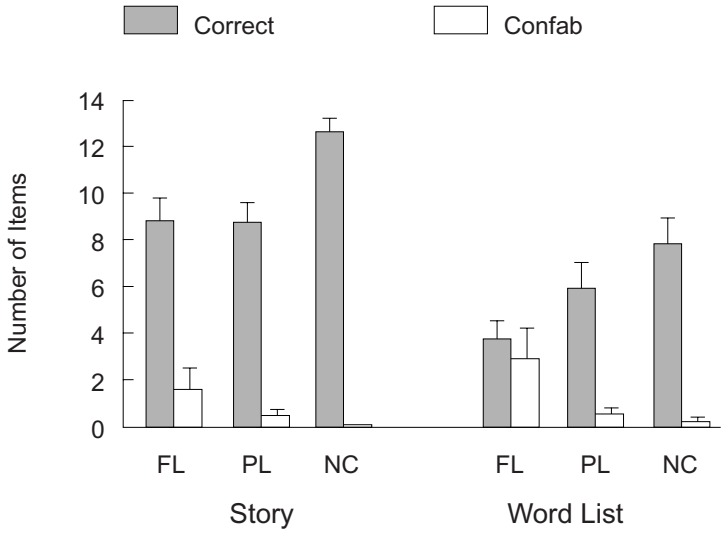

Fig. 1. Mean number of correctly reproduced items (± SEM) and mean number of confabulatory responses (± SEM) for story and word list recall.

Table 3
Results for recall and recognition of five dot patterns (means and SDs)

	FL	PL	NC
Whole Patterns	1.1 (0.7)	0.8 (0.6)	2.0 (0.8)
Correct Lines	8.0 (4.0)	7.2 (3.6)	14.2 (4.8)
Incorrect Lines	5.7 (5.1)	2.3 (2.0)	2.1 (2.0)
Recognition	3.8 (1.0)	4.3 (0.5)	4.1 (1.3)

this result was due to a larger number of incorrect lines produced by the FL group relative to the NC group ($U = 74.5,\ p = 0.062$) and the PL group ($U = 74.0,\ p = 0.066$).

The three groups did not differ significantly on the recognition scores ($F(2, 27) = 0.64,\ p = 0.53$).

3.1.3. Memory for temporal order

Performance on face recognition (hits and false alarms) is depicted in Fig. 2.

The three groups did not differ significantly with respect to hits ($p = 0.43$), but significant group differences emerged in the analysis of false alarms ($H = 7.49,\ df = 2,\ p = 0.024$). Paired group comparisons indicated lower false alarm rates in both the NC and the PL groups compared to the FL subjects ($U = 83.0,\ p = 0.012$ and $U = 79.0,\ p = 0.028$, respectively). Both measures were used to calculate a recognition index (hits minus false alarms divided by the number of targets). Significant group differences for this index ($F(2, 27) = 5.75,\ p = 0.008$) were due to a better performance of the NC group ($p = 0.008$) and a marginally better performance of the PL group ($p = 0.060$) as compared to the FL patients.

On average, the NC subjects allocated 66% ($SD = 8.3$) of all hits to the correct list, while the FL patients scored 54% ($SD = 11.3$) and the PL patients scored 51% ($SD = 8.8$) correct list allocations. Analysis revealed a significant group difference for this measure ($F(2, 27) = 7.02,\ p = 0.003$), with both patient groups performing significantly more poorly than the control subjects (both $p > 0.022$).

3.1.4. Memory for spatial positions

The control subjects on average correctly reproduced 11.7 spatial positions ($SD = 2.8$); the FL and the PL groups reproduced 6.4 ($SD = 4.1$) and 8.9 ($SD = 3.0$) correct locations, respectively. When errors were made, the mean deviation from the correct spatial position was 5.6 squares ($SD = 4.1$) in the NC group, 15.6 squares ($SD = 9.9$) in the FL group and 9.8 squares ($SD = 5.5$) in the PL group. Both the significant group difference in the number of correctly reproduced spatial positions ($F(2, 27) = 6.17,\ p = 0.006$) and in the size of the deviation from the target positions ($H = 7.15,\ df = 2,\ p = 0.028$) were due to a significantly poorer performance of the FL group relative to the NC subjects ($p = 0.004$ and $p = 0.012$, respectively). Other paired group comparisons did not reach significance.

3.1.5. Prospective memory

The performance of the three groups on the prospective memory task is described in Table 4. The results were analyzed separately for the number of instructions

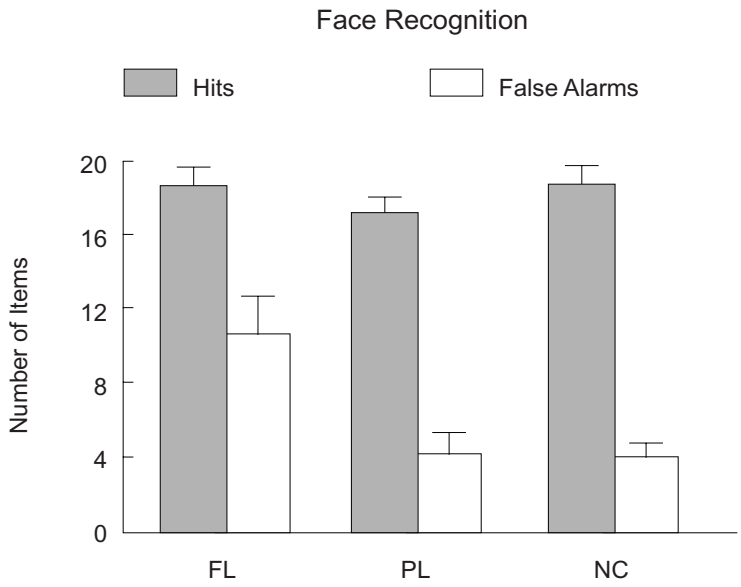

Fig. 2. Mean number of hits (± SEM) and false alarms (± SEM) in the face recognition task.

Table 4
Results for the prospective memory test (means and SDs)

	FL	PL	NC
Instructions followed and remembered	1.5 (1.3)	1.5 (1.3)	2.8 (0.6)
Instructions not followed but remembered	0.6 (1.1)	0.7 (0.9)	0.0
Instructions neither followed nor remembered	0.9 (0.9)	0.8 (0.8)	0.2 (0.6)

that were both followed and later remembered, not followed but later remembered, and neither followed nor remembered. None of the subjects followed an instruction without remembering it later.

A significant group difference emerged for the number of instructions being both completed and remembered ($F(2, 27) = 4.67,\ p = 0.018$). The NC group achieved a higher score than both the FL ($p = 0.035$) and the PL subjects ($p = 0.035$). The group difference for the number of instructions which were not followed but later remembered neared significance ($p = 0.10$). The score of the PL group was significantly higher ($p = 0.03$) and the score of the FL group was marginally higher ($p = 0.07$) than that of the control subjects.

4. Discussion

The executive and memory deficits shown by the patients with frontal cortex lesions in this study resembled those reported in previous studies. On standard tests of executive functions, they tended to perform worse than the control subjects. Thus, they made numerically (though not significantly) more perseverative errors on the WCST, they were less verbally fluent, and they showed some unusual cognitive estimates.

Similarly, with the memory tests, the patients with frontal cortex lesions showed deficits on many of the tasks on which impaired performance was expected. Thus, they performed more poorly than normal controls on free recall of stories, word lists, and dot patterns. The patients also showed signs of an impairment in prospective memory, which was indicated by their tendency to fail to act on a cue even though they still remembered what they should have done when questioned directly. The patients were impaired on the recognition tests for words and faces (but not for visuospatial patterns). Although recognition deficits are not commonly reported after frontal cortex damage, Stuss et al. [49] did find mild recognition deficits in their frontally damaged patients. These deficits were comparable in severity to the ones that we found. We also found that there was evidence for an abnormal number of false positive responses across several of the recall and recognition tests. The recall false positives are similar to the confabulations often shown by frontal patients for everyday events, and the recognition false

positive responses that have been reported by Schacter et al. [39] in a patient with frontal cortex damage.

It is of particular interest that patients with frontal cortex lesions were impaired compared to the normal control subjects at the list discrimination task, using faces. There has been only one previous report that frontal lobe lesions disrupt this kind of test of temporal order memory (see [24]). There is now evidence, therefore, that lesions disrupt the ability to judge which of two items was presented most recently within a long list [32], to place items from within a list in the same order as the one in which they were originally presented [45], and to judge in which of two temporally distinguishable lists an item was presented (the current study and [24]). Both the current study and that of Kopelman and his colleagues suggest that it is particularly lesions of the dorsolateral prefrontal cortex that disrupt list discrimination memory. Future work will need to determine whether all three kinds of temporal order memory deficit are produced by the same kind of executive processing impairment, caused by specific dorsolateral prefrontal cortex lesions, or whether they are dissociable deficits.

The one surprising result was the clear impairment of the patients with frontal cortex lesions on the spatial memory task. This is not consistent with the findings of Smith and Milner [46] and of Kesner et al. [23]. Unlike with the list discrimination task, only the patients with frontal cortex lesions were impaired on the spatial memory task although the patients with posterior neocortex lesions showed a trend towards impairment, and their performance did not differ significantly from that of the frontal group. A replication is clearly desirable although the difference between our results and those of Smith and Milner may relate to the different aetiologies of the patients used in the two studies. There are grounds for expecting that some frontal lobe lesions should impair spatial memory. Thus, frontal cortex lesions have been shown to produce visuospatial working memory deficits in humans [37]. Furthermore, recordings from single neurons within the dorsolateral frontal cortex in monkeys have shown that some neurons increase their firing rates during the delay period after inspecting visuospatial stimuli in a way that is specifically related to stimulus location [15]. If spatial working memory is impaired by certain frontal cortex lesions, it is likely that long-term memory will be also impaired unless the information retrieved in short- and long-term memory tests is subtly different (see [28]). Impairment on the spatial memory task might also be expected to the extent that performance on it is likely to be facilitated by efficient organization of encoding and retrieval processes.

Although the patients with frontal cortex lesions showed deficits on tasks involving executive functions, free recall, recognition, prospective memory, temporal order memory, and spatial memory relative to the normal control subjects, they did not differ from the patients with posterior cortex lesions on most of these tasks. The patients with the more posterior cortical lesions were equally impaired relative to normal controls at free recall of a story and dot patterns, recognition of words, temporal order and prospective memory. This problem is mirrored in the debate about the specificity of the executive tests traditionally used in research with frontal patients. It is already known that impairments on the WCST are not caused only by frontal cortex lesions. For example, Anderson et al. [2] showed that there was no difference on any WCST measure between subjects with frontal and several non-frontal lesions. Some subjects, who had been shown by CT or MRI scans to have focal lesions in the occipital, temporal, parietal or subcortical regions, achieved very few categories and made many perseverative errors. The authors argued that deficits more specific to the frontal lobes may occur in patients with acute as opposed to chronic lesions. Even if true, the patients in the current study, like those of Anderson et al. were, of course, chronic. It has also been shown in a PET challenge task [4] that performing the WCST activates other areas than the frontal cortex including the inferior parietal lobe, the visual association cortex, the inferior temporal cortex, and portions of the cerebellum.

With the verbal fluency task, there was a tendency for both groups to perform worse than the control subjects. Little is known about the brain mechanisms that underlie performance on this task although it must depend on activity in regions where the verbal material is stored (possibly within the temporal neocortex) as well as on activity in the regions that are involved with organizing the search processes. Both patient groups also showed a number of unusual responses on the Cognitive Estimates Test. Although they did not differ significantly in the frequency with which they made such responses, an interesting pattern was seen when a stricter criterion for abnormal performance on this task was employed. For example, six of the 10 frontal patients gave three or more unusual estimates, whereas this applies to only three patients in the posterior group. Similarly, frontal lesion patients showed 1.1 perseverative errors on the WCST, while the patients with more posterior lesions only made 0.4 such errors. It is thus possible

that significant patient group differences might be seen if larger groups were investigated and, in the case of the WCST, if the more difficult original version rather than the short version had been used.

In general, there is now evidence that lesions in non-frontal brain regions may cause deficits on some executive tests that may prove hard to distinguish qualitatively as well as quantitatively from the deficits caused by frontal cortex lesions. It is nevertheless plausible to argue that because the tasks are complex they depend on the planned orchestration of several 'basic' cognitive processes so that deficits can result from disruption either of the planning processes or of the basic processes. There is also the possibility that some 'non-frontal' deficits are caused by damage to another part of a circuit concerned with executive processes of which frontal cortex structures form a component. For this reason, it cannot be assumed that frontal lesions disrupt all executive tasks in a qualitatively different way from all non-frontal cortex lesions.

As it has been argued in this paper that many, if not all, memory deficits caused by frontal cortex lesions might be secondary consequences of a disruption of one or several planning processes, it is not surprising that posterior cortex lesions may have a very similar effect to frontal lesions. All the memory tasks on which performance is similarly affected depend not only on the operation of basic memory processes such as storage and relatively routine encoding and retrieval processes, but also to some extent on the planned on-line organization of these processes. As with the executive tasks themselves, the memory tasks can be impaired either because the executive processes are disrupted or because the lesion has disrupted the basic memory processes.

In the case of the posterior cortex lesions in the current study, it seems most likely that one or more of the basic processes underlying memory task performance has been disrupted. Although these processes could include storage activities, they may also involve high level and integrative perceptual processes, disturbances to which may subtly disrupt encoding and hence memory performance. If this is so, then posterior cortex lesions should cause memory deficits even when the load on executive processes has been markedly reduced (e.g., when learning and retrieval are incidental rather than intentional). When this pattern is not found, then it remains possible that the posterior lesions have damaged part of a serial circuit concerned with executive functions of which parts of the frontal cortex form a component. It is important to note that the patients with posterior neocortex lesions were not amnesic and did not have damage that affected the medial temporal lobes or other structures, damage to which causes amnesia. Nearly all had damage to parietotemporal neocortex regions. Structures within these regions have sometimes been found to activate when memory encoding and/or retrieval processing occurs (see [30]) so these structures may be playing a role either in basic memory processing or in the executive processing that often directs this basic processing.

Future lesion work will need to investigate whether frontal (and perhaps particularly dorsolateral prefrontal) neocortex regions, posterior (perhaps particularly parietal and lateral temporal) neocortex regions, and the medial temporal-midline diencephalic regions implicated in amnesia, each contributes to different processes vital for memory. Although we believe that these regions will be shown to make functionally distinct contributions towards memory task performance, demonstrating this will not be easy because of the surprising similarity in the kinds of memory performance disrupted by lesions in the three brain regions. Two further points should be stressed. First, all three regions are also almost certainly functionally heterogeneous although the paucity of localizing information in our study and the small numbers of patients involved prevents us from contributing to this issue. Second and relatedly, we do not believe that all posterior cortex lesions would disrupt the memory tasks used in this study, but suspect that the major effects will be found following lesions to parietal and temporal neocortex structures (where nearly all our patients were lesioned). In these structures, damage either may impair high level perceptual processes in subtle ways that impact on memory performance or disrupt circuits linked to the frontal lobes, which play a role in executive functioning. However, it remains possible that such damage also directly impacts on the kind of storage process that is believed to be impaired in global amnesics.

There was one very interesting and important exception to the finding that frontal and posterior cortex lesions had similar effects on memory performance. Across several of the memory tasks, the patients with frontal cortex lesions made more intrusion errors or false positive responses than either the normal control group or the group with posterior cortex lesions. These deficits, shown on formal tests, are like mild versions of the confabulations that some frontal patients make in their everyday lives although confabulation is a dramatic disorder the occurrence of which probably involves additional functional deficits (see [22,44]).

The effects were not always statistically significant, but when they were not, they were at least strong trends. The frontal patients made more intrusion errors on the story recall, the word list recall, and the dot pattern recall tests. They also showed significantly more false positive responses in the Yes/No recognition test for faces. At least on the recognition test, the poor memory of the patients with frontal cortex lesions does not seem to be a necessary condition for their tendency to produce false memories because their hit rate was indistinguishable from that of the group with posterior cortex lesions, who did not make abnormal numbers of false positive responses. A recent report by Schacter and his group [40] also suggested that poor recognition memory is not sufficient to cause a high level of false memory, as there was not a high level of false recognition of critical lures in patients with severe amnesia. It is less clear whether the increased numbers of recall intrusion errors made following frontal cortex damage were unrelated to the patients' poor memories because their recall was impaired. Future work should examine this issue by using a matching manipulation to equate the recall memory of patients with frontal cortex lesions and their controls before examining intrusion error rates.

The false memory abnormality may differ from the other memory deficits caused by frontal lobe lesions where posterior (probably temporoparietal) lesions have an equally disruptive effect. It seems likely that normal memory performance depends on the integrity of both basic memory processes and the executive processes that modulate and optimize the use of these basic processes. Posterior cortex lesions may disrupt the basic memory processes whereas frontal lesions may disrupt the executive processes. In contrast, the occurrence of false memory phenomena may be relatively independent of the efficiency of basic memory processes (such as storage), and, instead, be primarily driven by failures of certain kinds of executive function.

It is interesting to note that studies of normal ageing have also indicated the presence of increased false alarm rates and a tendency toward confabulatory responses in older individuals (e.g. [36]), and a recent study using tests identical to those of the current investigation observed a pattern of false memory phenomena similar to those seen in the frontal patients investigated here [10]. These recent reports have discussed their findings in relation to degenerative changes in the frontal lobes associated with ageing [10,36].

In summary, the results of the current study indicate that the abnormal tendency towards making false positive responses and intrusion errors in recognition and free recall tests respectively (and hence, probably the tendency towards confabulating) may be a relatively selective effect of certain frontal cortex lesions. As most of the frontal patients had damage to the dorsolateral frontal cortex, it is likely that the false memory phenomena may be associated with lesions to this region. The lack of more detailed information on the exact locus of the lesions does, however, exclude a more specific examination of this hypothesis. Schacter et al. [39–41] have argued that false memory phenomena arise because of inefficient memory retrieval mechanisms which lead to a deficit in the evaluation of retrieved information and the inhibition of irrelevant information. The patients may be impaired at the frontally dependent organization of searches that leads to detailed recollection; i.e., they may retrieve a small amount of detail compared with normal subjects. They may also be prepared to accept retrieved data as appropriate memories on the basis of much less evidence than normal subjects or they may inadequately check this evidence that retrieved data are appropriate memories. These problems can plausibly be interpreted as failures of executive functioning. Further testing is needed to confirm that intrusion errors and false positive responding are relatively selective effects of frontal lobe lesions, which are caused by one or more kinds of executive function disorder.

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