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Frontal lobe damage produces episodic memory impairment

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Abstract

This article reports the outcome of a meta-analysis of the relation between the frontal lobes and memory as measured by tests of recognition, cued recall, and free recall. We reviewed experiments in which patients with documented, circumscribed frontal pathology were compared with normal control subjects on these three types of tests. Contrary to conventional wisdom, there is strong evidence that frontal damage disrupts performance on all three types of tests, with the greatest impairment in free recall, and the smallest in recognition. (*JINS*, 1995, *1*, 525–536.)

Keywords: Frontal lobes, Memory, Prefrontal cortex

Introduction

The topic motivating this review is the relation between the frontal lobes and memory. While it is commonly accepted that patients with damage restricted to the frontal lobes are not amnesic (Schacter, 1987; Stuss, Alexander et al., 1994), we believe that the frontal lobes do play a role in remembering, even in some of the more basic tests of memory. Recent opinions on the issue have varied. A comprehensive review of the relation between frontal lobes and memory, based on studies published up to 1984, concluded that there was little evidence for the involvement of the frontal lobes in the kind of memory processes that are impaired in amnesia (Stuss & Benson, 1986). By contrast, other studies have suggested that there are some specific memory deficits present in patients with frontal lobe damage (Luria, 1973; Stuss & Benson, 1984, 1986; Shimamura, 1994). Although there have been other reviews of this area in recent years (Schacter, 1987; Petrides, 1989; Shimamura, 1994; Stuss, Eskes et al., 1994), they have generally focused on cognitive abilities that are peripheral to the basic acts of encoding, storing, and retrieving factual information. It is commonly thought that frontal lobes are involved in the placement of such information into spatial and temporal contexts, and with the initiation and execution of complex mnemonic strategies. This role is sometimes classified as *working-with-memory* (Moscovitch, 1992), because frontal lobes can influence both the quantity and quality of recollective experiences.

This review is about frontal patients' performance on those tests that are universally agreed to be "standard" tests of declarative, episodic, or explicit memory: free recall, cued recall, and recognition. There is some ambiguity as to whether or not the frontal lobes mediate performance on these tests. Only a few years ago, findings were reported that were interpreted as associating frontal damage with "normal recall and recognition memory for . . . words and facts" (Shimamura et al., 1990, p. 803), while a more recent paper noted that "frontal patients were impaired relative to control subjects for both recall and recognition" (Mangels et al., 1994, p. 359; see also Stuss, Alexander et al., 1994). Thus, the situation calls for clarification.

This review consists of three major sections. First, we define the terms and concepts we will use when discussing both memory and the frontal lobes. The next section describes the results of an empirical review, which was motivated by the question: What is the result of frontal pathology on tests of free recall, cued recall, and recognition? We conclude by summarizing the major findings from the review, and also by pointing out some of the problems with the research efforts so far.

Definitional matters

Memory

Memory is the comprehensive label used to designate the capability of living organisms to acquire, retain, and uti-

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lize knowledge and skills. Within the boundaries of this broad definition one can distinguish diverse forms of memory and nearly an endless variety of memory phenomena. This means that any general reference to "memory" is usually too vague to be very useful in clinical and scientific analyses of memory's many manifestations.

In this review, we concentrate on three popular and widely used *tasks* of episodic memory—recognition, cued recall, and free recall. Episodic memory tasks assess subjects' ability to answer questions about previously experienced events. All episodic memory tasks consist of two phases—study and test (or encoding and retrieval). In the study (encoding) phase the subject is presented a collection of to-be-remembered items; in the test phase their ability to retrieve the presented information is measured.

Recognition, cued recall, and free recall tasks may have identical study or encoding phases, but they differ with respect to the kind of information that the subjects are provided at *test* or *retrieval*. (Because of this fact, they can also be referred to as recognition, cued recall, and free-recall *tests*.) In recognition tasks, this information (*retrieval cues*) is comprised of items that are nominally identical with the studied items (target items) and is usually interspersed with items that differ from studied items (distractors, or lures). In cued recall tasks, the retrieval information is provided in the form of cues that are somehow specifically related to the target items. Their relations to target items may assume many forms: associative relatedness, semantic meaning, conceptual relatedness, synonymity, phonological similarity, and the like. In free recall tasks, subjects are provided with no specific cues, only general instructions to recall as many items as they can, in any order, from a designated, previously studied collection.

The to-be-remembered materials, encoding conditions, and retrieval conditions (including the retrieval cues) are held constant in any given task. Differences in performance among groups of subjects, therefore, reflect differences in the subjects' ability to perform the mental computations necessary for the recovery of the studied items *under the constant conditions of a given task*. It would be misleading to claim that individual variability in performance on any one of the three tasks reflects differences in subjects' "memory abilities." Similarly, if it is observed that brain damage (such as frontal lesions) affects performance on one or more of these tasks, it would be misleading to conclude that the brain damage in question has produced an overall "memory impairment."

Frontal lobes

The concept of the frontal lobes in relation to behavior has not always been used consistently. When researchers talk of the loss of certain psychological processes after brain damage, they often use terms such as "frontal lobe dysfunction." While this term refers to those types of impairments that are most typically found after focal frontal lesions (i.e., the supervisory or "executive" functions), "frontal dysfunction" has been reported in circumstances when there is no focal anatomical pathology. The circumstances eliciting such deficits include aging, sleep deprivation, and task demands (Kinsbourne, 1977; Herscovitch et al., 1980; Moscovitch, 1994). This does not mean that functions normally associated with the frontal lobes are not controlled by the prefrontal brain. It does suggest that any diffuse brain dysfunction will disrupt executive functions before it will disrupt other, more overlearned functions (Goldberg & Builder, 1987) and that observation of such impairment does not necessarily allow localization of pathology.

When we refer to "frontal" dysfunction as related to memory tests, we take a narrow definition. We specifically have in mind changes in behavior after focal, anatomical damage to the frontal lobes. Unfortunately, there is no universal agreement in how this anatomical area is defined. The frontal lobes may be globally defined as that brain region anterior to the central sulcus; all reports of frontal pathology in this review refer to brain lesions concentrated in this area. Some researchers, using the term frontal lobes, actually are referring to a large subsection of the frontal lobes, the *prefrontal* area anterior to the motor (Brodmann area 4) and premotor (Brodmann area 6) regions. The term "frontal lobes" is ill-defined even by these anatomical landmarks. Published reports infrequently identify the regions of the frontal lobes in question. There are at least three surface demarcations: dorsal, medial, and orbitofrontal. Moreover, there is increasing evidence of more specific architectonic differentiation within the frontal cortex (Pandya & Barnes, 1987; Barbas & Pandya, 1991; Petrides & Pandya, 1994). Some implications of the inconsistent definitions and inadequate demarcation of brain region involved are presented in the discussion.

Empirical review

The goal of this review is to explore the relation between frontal damage and performance on tests of recognition, cued recall, and free recall. We have examined the data from selected articles and summarized our observations in two ways. One approach relied upon the outcomes of statistical tests of inference: We tabulated the relative frequency with which frontal pathology has, and has not, been associated with a statistically significant deficit in the performance of the three types of tests. For the second approach, we compared the different performance levels of two subject groups (controls and "frontals"), without regard to the outcome of statistical tests. To allow for easy comparisons across the experiments, the performance measures on the various tests were converted to proportions. The performance measure for each group represents that group's mean score on a test divided by the maximum possible score on that test. The converted measures were used to determine effect sizes for each experi-

ment. Note that our effect size measure is not identical to the most common use of the term (e.g., Rosenthal, 1991). Our measure does not take into consideration the within-group variances, as this statistic was not reported in a majority of the relevant papers. Here, effect size simply refers to the numerical difference in the proportions between the two groups.

Flagging of articles

Articles were flagged through a computerized search of the MEDLINE and PsycLIT databases (in August 1994). The review was limited to papers published since January 1984, since Stuss & Benson (1986) thoroughly reviewed the existing literature to that time. Articles were selected if their titles, keywords, or abstracts mentioned both "memory" and "frontal lobe" (or "frontal lobes" or "prefrontal cortex"). The search was limited to articles published in English that involved adult, human subjects, because that was our domain of interest. The journals *Brain*, *Brain and Cognition*, *Cortex*, *Cognitive Neuroscience*, and *Neuropsychologia* were scrutinized directly. Finally, we solicited unpublished manuscripts from researchers active in the area of frontal lobes and memory. The solicitation netted manuscripts by Gershberg & Shimamura (in press) and Shimamura et al. (in press). The studies thus flagged were then examined to determine if they were appropriate for the present analysis.

Selection criteria

To be included, a study had to include two groups of subjects: (1) a group of patients with documented, focal frontal pathology, and (2) a control group comprised of patients with no history of neurological damage. Many studies included additional subject populations (e.g., patients with temporal lobe damage, Alzheimer's patients), but the performance of these groups was not included. For inclusion, a study also had to contain at least one episodic memory experiment, in which the "frontal group" was compared to the "control group" on a test of either free recall, cued recall, or recognition. Most articles that met the inclusion criteria contained more than one relevant experiment, and each experiment is summarized separately in our review. We excluded comparisons that required subjects to overcome experimentally produced proactive interference (Kesner et al., 1994; Shimamura et al., in press) or output interference (e.g., Incisa della Rocchetta & Milner, 1993, Experiment 2). All experiments summarized here examined the role of the frontal lobes on basic, straightforward episodic memory tests that were uncomplicated by experimenter-produced interference. We also excluded recall tests for prose, or text, because such tests do not fit into any of our three categories of tests. Prose recall is not cued recall, as subjects are not given cues that are related to specific subsets of the text. Neither is it free recall, since rememberers are not free to recall material in any order. Text recall is best classified as *noncued recall*.

Variables summarized in this review

For each experimental comparison, the following information was extracted: (1) author(s), and year of publication; (2) the lesion side (either left, right, bifrontal, or mixed frontal pathology); (3) the lesion etiology (usually either surgical excision, head injury, or vascular accident); (4) the study materials, and any pertinent information about the study instructions or retrieval conditions; (5) the number of items in the to-be-remembered list; (6) the retention interval between study and test; (7) the mean performance measure for both subject populations, along with the standard error of the mean whenever it was available; and (8) whether or not the difference between the two groups reached statistical significance. The performance measures and results of the significance tests were used to summarize the results. All of the extracted information is reported in Appendices A through C for recognition, cued recall, and free recall, respectively.

Results

Results are reported in two different ways, corresponding to the two ways of assessing the relation between the frontal lobes and memory. The first approach considers the types of conclusions that are typically drawn from individual studies: results are categorized according to the outcome of statistical tests. We asked: how many *published articles* since 1984 have concluded (or implied) that patients with frontal pathology have a *statistically significant* impairment on tests of recognition, cued recall, and free recall? By tabulating the findings at the level of the research article, rather than the memory experiment, one can get a sense for the proportion of published studies that associate frontal lesions with impaired performance on these three tests. This approach considers each of the experiments in a single article only once; an article either implies that frontal pathology is associated with impaired remembering, or it does not.

A second way to look at the data is not dependent upon the outcome of any inferential tests. Again, we have determined the numerical difference in the performance of the two groups (i.e., the effect size) for each relevant memory experiment and plotted the distribution of effect sizes across the various studies. It will become clear that the two approaches lead to different conclusions about the relation between the frontal lobes and memory.

Note that it was not possible to conduct a statistical meta-analysis for two reasons. First, the majority of published experiments included neither a measure of variance nor a test statistic (e.g., a t value); at least one of these values is necessary to calculate statistical effects across studies. Also, much of the empirical work relating the frontal lobes and memory has come from two laborato-

ries, one in Montreal (Smith & Milner, 1984; Zatorre, 1985; Incisa della Rocchetta, 1986; Milner et al., 1991; Incisa della Rocchetta & Milner, 1993; Jones-Gotman & Zatorre, 1993) and the other in San Diego (Janowsky et al., 1989a, 1989b, 1989; Shimamura et al., 1990). Therefore, there is substantial overlap in the identity of the patients with frontal pathology, and the observations in the different articles are not truly independent. Fortunately, for the types of conclusions that we are going to draw, a sophisticated meta-analytic computation will not be necessary. There are important conclusions that can be drawn simply by looking at the patterns of results across all of the studies.

Statistical inference tests

We have tabulated the number of published articles which conclude that patients with frontal pathology did, and did not, demonstrate a statistically significant memory impairment, compared to normal controls. Results were summarized as a function of the three types of memory tests at two different retention intervals: (1) short, defined as 30 min or less between study and test, or (2) long, 1 h or more between study and test. No published experiments employed a retention interval between 30 min and 1 h. We were interested in uncovering any possible effects of retention interval since articles by Smith and Milner (1984) and Jetter et al. (1986) associated frontal pathology with impairment on a free recall test following long (1 d), but not after short (less than 20 min) retention intervals.

Some articles included experiments that fell into more than one category; for example, Janowsky et al. (1989) report experiments that employ a free recall test at a short retention interval and recognition tests at both long and short intervals. Therefore, this article received three entries into the results. Also, if a published study included two or more experiments in the same category that led to differing conclusions (see Hirst & Volpe, 1988; Wirsen, 1991; Incisa della Rocchetta & Milner, 1993), then that study was classified as demonstrating a statistically significant difference between the two groups, since at least one experiment did find such an effect.

Results are summarized in Table 1; the table reveals the following points:

1. Frontal pathology led to a statistically significant impairment in fewer than one half (44%) of the cases. This low percentage is a likely reason that psychologists are reluctant to attribute basic memory processes to the frontal lobes; if frontal lobes are necessary for the encoding, storage, and retrieval of information, then one might expect to find a more statistically reliable effect of lesions to the frontal lobes.
2. Frontal pathology is most likely to result in a deficit on a free recall test (80% of the relevant cases) and least likely on a recognition test (8%). The finding is consistent with some extant hypotheses of frontal lobe functioning, namely those that attribute search and retrieval processes to the frontal lobes (Moscovitch, 1992; Shimamura, 1994).
3. Our data do not support the hypothesis that frontal pathology is more detrimental following a longer retention interval than a shorter interval, with 44% of relevant studies showing a frontal-related memory impairment after a long delay (1 h or more) compared to 43% following a short delay (30 min or less). Again, however, two articles (Smith & Milner, 1984; Jetter et al., 1986) have reported impressive evidence for such a hypothesis, and further empirical work may substantiate the relation between frontal damage and retention interval.

Table 1. Number of articles that have associated frontal pathology with impaired performance on memory tests, as a function of type of test and retention interval

	Outcome		
	Y	N	%
Type of test			
Recogntion	1	11	.08
Cued recall	5	5	.50
Free recall	8	2	.80
Retention Interval			
Short delay	10	13	.43
Long delay	4	5	.44
All studies combined	14	18	.44

Note. Y = yes, there was a statistically significant deficit associated with frontal pathology; N = there was no statistically significant deficit associated with frontal pathology; % = proportion of studies that reported a memory deficit associated with frontal pathology.

Effect sizes

An effect size was computed for each of the experimental comparisons in the Appendices. Again, the effect size is simply the difference between the performance measure of the control group and the performance measure of the group with frontal pathology (these measures are reported in the Appendices). Effect sizes for each experiment are plotted in Figures 1, 2, and 3, for recognition, cued recall, and free recall, respectively. Comparisons are plotted from the top to the bottom of each table in order of their size; in other words, the experiment with the largest effect size showing a numerical advantage for the control group is plotted at the top of the table, and that experiment most favorable to patients with frontal pathology is at the bottom.

Visual inspection of the three figures leads to one obvious conclusion: The control subjects are performing

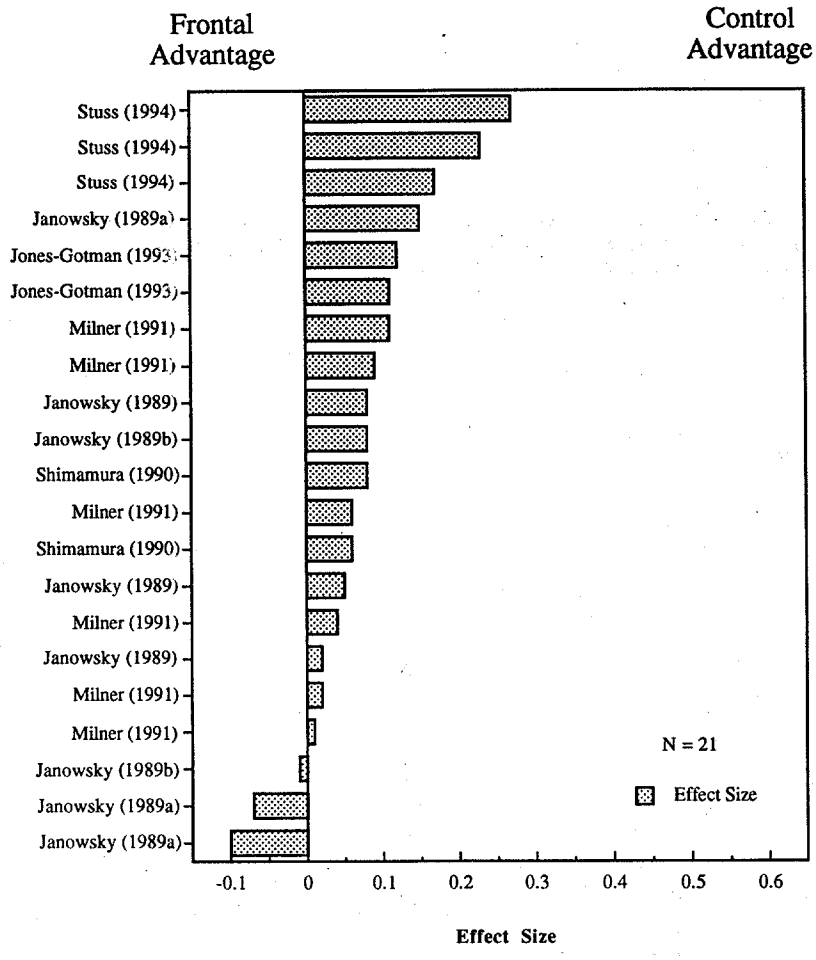

Fig. 1. Distribution of effect sizes for recognition experiments. Effect sizes are labeled by lead author and year of publication.

better than patients with damaged frontal lobes. Virtually every comparison demonstrated a numerical advantage for control studies, and this conclusion holds across all three types of memory tests. We do not want to overinterpret the results since, again, many of these comparisons employed the same subjects from the same laboratories, but a rough estimate of an "overall effect size" might come from a median effect size for each type of test. On tests of recognition, the median effect size showed a numerical advantage of .08 for control subjects, while the corresponding figures for cued recall and free recall are .17 and .16, respectively.

Again, the effects appear larger in recall tests than recognition tests. There is also substantial variation in the effect sizes, even within each individual type of test. The variation is most striking in cued recall experiments, where one published article (Vogel et al., 1987) provided 12 of the 27 experimental comparisons (see Appendix B). The effect sizes from this article represent 12 of the 14 largest effects in Figure 2; without the article, the distribution of effect sizes would have looked very different. We discuss the Vogel et al. (1987) paper in the General Discussion, but for now the most important point is the presence of variability in the effect sizes of the various experiments. Once again, the major conclusion from the analysis of effect sizes is that the overwhelming majority of individual experiments show a numerical advantage for the control groups on tests of recognition, cued recall, and free recall. Given such results, it is clear that damage to the frontal lobes affects performance on these tests.

General discussion

Historically, memory disorders have been benchmarked in relation to the "amnesic syndrome." The recognition and recall performance of patients with focal frontal pathology does not resemble the profile of amnesic patients (Janowsky et al., 1989). A more difficult issue, and the one which has been addressed by this review, is does frontal damage affect performance on recognition, cued recall, and free recall tests, when affected patients are compared to healthy control subjects? While it is generally agreed that frontal lobes have some involvement in remembering, a typical statement in the literature is that "frontal lesions do not produce a straightforward, general memory impairment" (Squire, 1987, p. 234). We have looked at those tests that are the most common of them all: recognition, cued recall, and free recall. Our review showed that frontal pathology is clearly associated with deficits in the performance of all three types of tests. Our

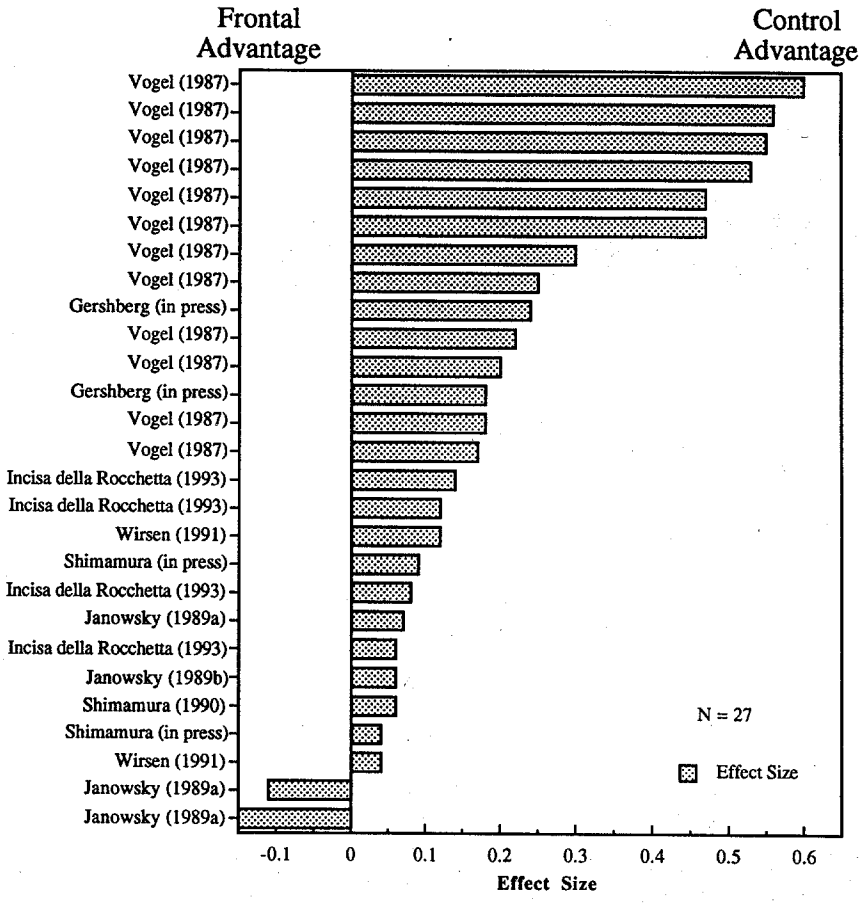

Fig. 2. Distribution of effect sizes for cued recall experiments. Effect sizes are labeled by lead author and year of publication.

findings are in accord with more recent lesion work that has demonstrated a significant role for the frontal lobes, even in recognition tests of episodic (Stuss et al., 1994) and semantic (Mangels et al., 1994) memory.

Note that our analysis is limited; data show differences between one particular patient group and controls and nothing more. For instance, the analysis does not tell us that frontal lobes play a more important role in memory than some other neocortical regions, such as parietal lobes. Similarly, we cannot imply that frontal lesions impair episodic memory more so than other cognitive functions (e.g., spatial rotation).

Given that the frontal lobes are involved, the next logical question is: How are they involved? It is important to remember that memory involves more than the simple execution of encoding, storage, and retrieval systems. A memory test can be powerfully affected by disorders of attention, language, or executive functions, for example. Frontal damage will disrupt memory to the extent that any of these cognitive domains are both (1) impaired and (2) necessary for the successful performance of the memory test.

One of the major conclusions from our review has implications for this issue; that is the finding that frontal lesions have a greater effect on recall tests than recognition tests. Examining the differences between the two types of tests should reveal some of the processes which are more dependent upon the frontal lobes. There is good evidence that there are multiple bases for recognition judgments, with one of them, the "familiarity" component, said to occur relatively automatically (Atkinson & Juola, 1974; Jacoby, 1991). By some accounts of frontal lobe functioning (Shallice, 1988; Moscovitch, 1992), the frontal lobes should play little, if any, role in automatic tasks. An obvious difference between recall and recognition tests is that, for successful free recall, a subject must be able to recollect the target items; it is not sufficient to simply have a feeling of familiarity. Any number of processes and subprocesses may be involved in successful recollection. Patients with frontal lesions may have difficulty initiating the recall process (Luria, 1973), and such patients are thought to be deficient at encoding and deploying appropriate mnemonic strategies (Hirst & Volpe, 1988; Petrides, 1989). These examples only begin to describe the varieties of abilities that have been attributed to the frontal lobes and are beneficial for free recall tests but not for tests of recognition (also see Shimamura et al., 1991; Stuss et al., 1994).

Again, the most important result of our meta-analysis is that frontal pathology affects performance on all three types of memory tests. It is important to ask, then, why others have not reached this same conclusion. The answer is that individual studies have relied upon the outcome of statistical tests. In most of the experiments summarized

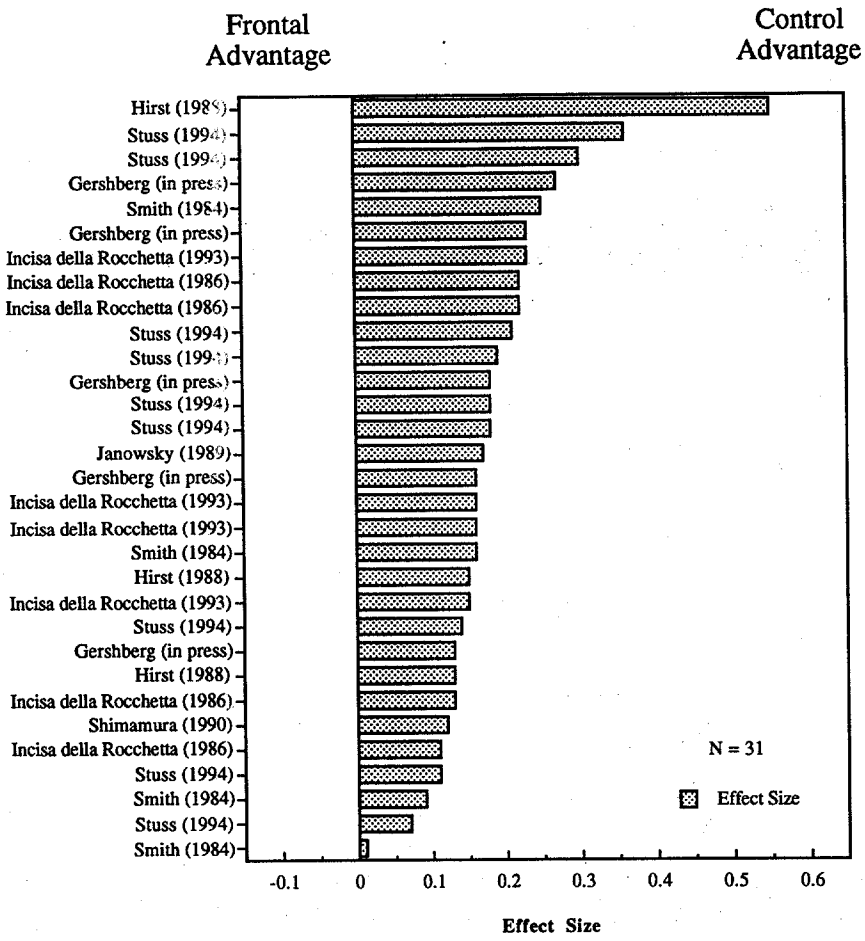

Fig. 3. Distribution of effect sizes for free recall experiments. Effect sizes are labeled by lead author and year of publication.

in the Appendices, normal control subjects outperformed patients with frontal damage. Yet in many of these cases, the outcome of the statistical test was negative, and the authors could not conclude that frontal lesions had an adverse effect on performance. Further examination reveals that a number of these experiments included 12 or fewer patients with frontal pathology (Smith & Milner, 1984; Janowsky et al., 1989a, 1989b, 1989; Shimamura et al., 1990; Jones-Gotman & Zatorre, 1993; Shimamura et al., in press). A reasonable interpretation is that many experiments did not have sufficient statistical power to detect differences between the two groups. In experimental psychology, it is very rare that experiments are conducted with 12 or fewer subjects per condition in a between-subjects design. Given the time and difficulty of identifying suitable patients, however, small subject groups are probably unavoidable in neuropsychological studies. It is crucial that experimenters are not quick to accept a null hypothesis, which implies that there are no differences between the two groups. As the results show, the outcomes of individual significance tests can be misleading. When data are summarized across experiments, there is strong evidence for a relation between frontal lobes and tests of memory, and this relation was not evident in most individual research articles.

In light of the widespread effects of undifferentiated frontal damage, it would be very useful to make finer distinctions with respect to frontal lobe lesions or the involvement of specific neuropsychological processes. After demonstrating an "atypical" recognition deficit associated with frontal pathology, Stuss et al. (1994) associated the deficit to two separate processes. The first was a residual aphasia, which occurred in some patients with left frontal injury (some dorsolateral, some striatal, and some superior medial). These patients had a recognition deficit that was secondary to their naming difficulty. Another group of patients had lesions extending into the septal region. While the septal nucleus is physically within the posterior frontal lobe, it is an important part of the hippocampal-diencephalic circuit that is essential for the basic encoding of information. Damage to this area produces impairment more similar to medial temporal amnesia than a psychologically "frontal" syndrome. The importance of the Stuss et al. (1994) analysis is that impaired recognition performance was related to specific frontal lesion sites and neuropsychological mechanisms, rather than to undifferentiated frontal pathology.

Of course, if other studies included patients with damage extending into septal regions, then one would expect to find deficits on basic memory tests in these studies as

well. Vogel et al. (1987) reported substantial impairment on cued recall tests following frontal pathology, and the level of impairment was greater than any of the other cued recall experiments summarized in our review; personal communication with one of the authors (H. J. Markowitsch, personal communication, 1994) revealed that some of the "frontal" patients may have suffered lesions in the basal forebrain and septal regions, creating a condition similar to amnesia. It is to the benefit of cognitive neuropsychologists to eliminate, or at least to control for, the primary memory deficits associated with basal forebrain or septal pathology, if we want to draw specific conclusions about the role of prefrontal areas. Regardless, most of the studies in this review, to the best of our knowledge based on the reports of the studies, have not included patients with such damage. Our general conclusions are not altered by the presence of patients with mild amnesia in a few of the studies.

To summarize, our review yielded the following conclusions. Traditionally it was thought that frontal lobes are not involved in determining the outcomes of conventional memory tests. More recent work supports that the traditional may not be correct. Our analysis of the facts as revealed in the published literature since 1985 shows that frontal lesions clearly do disrupt performance. The analysis also confirms what has been suspected for some time: frontal lesions have a more pronounced effect on free recall tests than recognition tests. We interpret the apparent discrepancy between the conclusions drawn from individual studies and those arrived at in our quasi-meta-analysis as reflecting the lack of sufficient statistical power in single studies. By examining all evidence yielded by a larger collection of studies, a role for the frontal lobes in conventional memory tasks has been established.

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References

Atkinson, R.C. & Juola, J.F. (1974). Search and decision processes in recognition memory. In D.H. Krantz, R.C. Atkinson, R.D. Luce, & P. Suppes (Eds.), *Contemporary developments in mathematical psychology, Vol. 1, Learning, memory, and thinking* (pp. 243–293). San Francisco: Freeman.

Barbas, H. & Pandya, D.N. (1991). Patterns of connections of the prefrontal cortex in rhesus monkeys associated with cortical architecture. In H.S. Levin, H.M. Eisenberg, & A.L. Benton (Eds.), *Frontal lobe function and dysfunction* (pp. 35–58). New York: Oxford University Press.

Gershberg, F.B. & Shimamura, A.P. (in press). The role of the frontal lobes in the use of organizational strategies in free recall. *Neuropsychologia*.

Goldberg, E. & Builder, R.M., Jr. (1987). The frontal lobes and hierarchical organization of cognitive control. In E. Perecman (Ed.), *The Frontal lobes revisited* (pp. 159–188). Hillsdale, NJ: Lawrence Erlbaum.

Herscovitch, J., Stuss, D.T., & Broughton, R. (1980). Changes in cognitive processing following short-term cumulative partial sleep deprivation and recovery oversleeping. *Journal of Clinical Neuropsychology, 2*, 301–319.

Hirst, W. & Volpe, B.T. (1988). Memory strategies with brain damage. *Brain & Cognition, 8*, 379–408.

Incisa della Rocchetta, A. (1986). Classification and recall of pictures after unilateral frontal or temporal lobectomy. *Cortex, 22*, 189–211.

Incisa della Rocchetta, A. & Milner, B. (1993). Strategic search and retrieval inhibition: The role of the frontal lobes. *Neuropsychologia, 31*, 503–524.

Jacoby, L.L. (1991). A process dissociation framework: Separating automatic from intentional uses of memory. *Journal of Memory and Language, 30*, 513–541.

Janowsky, J.S., Shimamura, A.P., Kritchevsky, M., & Squire, L.R. (1989). Cognitive impairment following frontal lobe damage and its relevance to human amnesia. *Behavioral Neuroscience, 103*, 548–560.

Janowsky, J.S., Shimamura, A.P., & Squire, L.R. (1989a). Source memory impairments in patients with frontal lobe lesions. *Neuropsychologia, 27*, 1043–1056.

Janowsky, J.S., Shimamura, A.P., & Squire, L.R. (1989b). Memory and metamemory: Comparisons between patients with frontal lobe lesions and amnesic patients. *Psychobiology, 17*, 3–11.

Jetter, W., Poser, U., Freeman, R.B., Jr., & Markowitsch, H.J. (1986). A verbal long-term memory deficit in frontal lobe damaged patients. *Cortex, 22*, 229–242.

Jones-Gotman, M. & Zatorre, R.J. (1993). Odor recognition memory in humans: Role of right temporal and orbitofrontal regions. *Brain and Cognition, 22*, 182–198.

Kesnar, R.P., Hopkins, R.O., & Fineman, B. (1994). Item and order dissociation in humans with prefrontal cortex damage. *Neuropsychologia, 32*, 881–891.

Kinsbourne, M. (1977). Cognitive decline with advancing age: An interpretation. In W.L. Smith & M. Kinsbourne (Eds.), *Aging and dementia* (pp. 217–235). New York: Spectrum Publications.

Luria, A.R. (1973). *The Working brain: An introduction to neuropsychology*. (B. Haigh, Trans.) New York: Basic Books.

Mangels, J.A., Gershberg, F.B., & Shimamura, A.P. (1994). Impaired remote memory in patients with frontal lobe lesions. *Society for Neuroscience Abstracts, 20*, 359.

Milner, B., Corsi, P., & Leonard, G. (1991). Frontal-lobe contributions to recency judgments. *Neuropsychologia, 29*, 601–618.

Moscovitch, M. (1992). Memory and working-with-memory: A component process model based on modules and central systems. *Journal of Cognitive Neuroscience, 4*, 257–267.

Moscovitch, M. (1994). Cognitive resources and dual-task interference effects at retrieval in normal people: The role of the frontal lobes and medial temporal cortex. *Neuropsychology, 8*, 524–533.

Pandya, D.N. & Barnes, C.L. (1987). Architecture and connec-

tions of the frontal lobe. In E. Perecman (Ed.), *The frontal lobes revisited* (pp. 159–188). Hillsdale, NJ: Lawrence Erlbaum.

Petrides, M. (1989). Frontal lobes and memory. In F. Boller & J. Grafman (Eds.), *Handbook of neuropsychology* (Vol. 3, pp. 75–90). Amsterdam: Elsevier.

Petrides, M. & Pandya, D.N. (1994). Comparative architectonic analysis of the human and macaque frontal cortex. In F. Boller & J. Grafman (Eds.), *Handbook of neuropsychology* (Vol. 9, pp. 17–58). Amsterdam: Elsevier.

Rosenthal, R. (1991). *Meta-analytic procedures for social research* (Rev. Ed.). Newbury Park, CA: Sage.

Schacter, D.L. (1987). Memory, amnesia, and frontal lobe dysfunction. *Psychobiology, 15*, 21–36.

Shallice, T. (1988). *From neuropsychology to mental structure*. Cambridge: Cambridge University Press.

Shimamura, A.P. (1994). Memory and frontal lobe function. In M.S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 803–813). Cambridge, MA: MIT Press.

Shimamura, A.P., Janowsky, J.S., & Squire, L.R. (1990). Memory for the temporal order of events in patients with frontal lobe lesions and amnesic patients. *Neuropsychology, 28*, 803–814.

Shimamura, A.P., Janowsky, J.S., & Squire, L.R. (1991). What is the role of frontal lobe damage in memory disorders? In H.S. Levin, H.M. Eisenberg, & A.L. Benton (Eds.), *Frontal lobe function and dysfunction* (pp. 173–195). New York: Oxford University Press.

Shimamura, A.P., Jurica, P.J., Mangels, J.A., Gershberg, F.B., & Knight, R.T. (in press). Susceptibility to memory interference effects following frontal lobe damage: Findings from tests of paired-associate learning. *Journal of Cognitive Neuroscience*.

Smith, M.L. & Milner, B. (1984). Differential effects of frontal lobe lesions on cognitive estimation and spatial memory. *Neuropsychologia, 22*, 697–705.

Squire, L.R. (1987). *Memory and brain*. New York: Oxford University Press.

Stuss, D.T. & Benson, D.F. (1984). Neuropsychological studies of the frontal lobes. *Psychological Bulletin, 95*, 3–28.

Stuss, D.T. & Benson, D.F. (1986). *The frontal lobes* (pp. 180–193). New York: Raven Press.

Stuss, D.T., Alexander, M.P., Palumbo, C.L., Buckle, L., Sayer, L., & Pogue, J. (1994). Organizational strategies of patients with unilateral or bilateral frontal lobe injury in word list learning tasks. *Neuropsychology, 8*, 355–373.

Stuss, D.T., Eskes, G.A., & Foster, J.K. (1994). Experimental neuropsychological studies of frontal lobe functions. In F. Boller & J. Grafman (Eds.), *Handbook of neuropsychology* (Vol. 9, pp. 149–185). Amsterdam: Elsevier.

Vogel, C.C., Markowitsch, H.J., Hempel, U., & Hackenberg, P. (1987). Verbal memory in brain damaged patients under different conditions of retrieval aids: A study of frontal, temporal, and diencephalic damaged subjects. *International Journal of Neuroscience, 33*, 237–256.

Wirsen, A. (1991). Chronic effects of traumatic frontal lesions: Clinical, neurophysiological, and neuropsychological aspects. Unpublished doctoral dissertation, University of Lund, Lund, Sweden.

Zatorre, R.J. (1985). Discrimination and recognition of tonal melodies after unilateral cerebral excisions. *Neuropsychologia, 23*, 31–41.

Appendix A

Recognition tests—Information extracted from each experiment

Author(s)	Lesion side	Etiology	Study materials and test conditions[a]	L	RI	Ftl. PM (SEM)	Ctl. PM (SEM)	Sig. diff.
Janowsky et al. (1989)*	M	5 VA; 1 UK; 1 Surg.	word list	15	imm.	.94[bc]	.96[bc]	no
Janowsky et al. (1989)*	M	5 VA; 1 UK; 1 Surg.	word list	15	imm.	.92[bc]	.97[bc]	no
Janowsky et al. (1989)*	M	5 VA; 1 UK; 1 Surg.	word list	15	7 d	.68[cd]	.76[cd]	no
Janowsky et al. (1989a, Exp. 1)*	M	5 VA; 1 UK; 1 Surg.	general information facts[e]	20	6–8 d	.63 (.09)	.78 (.04)	no
Janowsky et al. (1989a, Exp. 2)*	M	5 VA; 1 UK; 1 Surg.	obscure facts[e]	15	5 min	.45[f]	.38[f]	no
Janowsky et al. (1989a, Exp. 2)*	M	5 VA; 1 UK; 1 Surg.	obscure facts[e]	15	2 h	.29[f]	.19[f]	no
Janowsky et al. (1989b)*	M	5 VA; 1 UK; 1 Surg.	sentences[g]	24	5 min	.83	.82	no[h]
Janowsky et al. (1989b)*	M	5 VA; 1 UK; 1 Surg.	sentences[g]	24	1–3 d	.48	.56	no[h]
Jones-Gotman & Zatorre (1993)*	L	11 Surg.	odors	24	[i]	.19 (.08)[j]	.31 (.05)[j]	no
Jones-Gotman & Zatorre (1993)*	R	18 Surg.	odors	24	[i]	.20 (.06)[j]	.31 (.05)[j]	no
Milner et al. (1991)	L	13 Surg.	word list[k]	29	imm.[l]	.92	.94	no
Milner et al. (1991)	L	13 Surg.	drawings[k]	29	imm.[l]	.92	.96	no
Milner et al. (1991)	L	13 Surg.	paintings[k]	22	imm.[l]	.83	.92	no
Milner et al. (1991)	R	13 Surg.	word list[k]	29	imm.[l]	.93	.94	no
Milner et al. (1991)	R	13 Surg.	drawings[k]	29	imm.[l]	.90	.96	no
Milner et al. (1991)	R	13 Surg.	paintings[k]	22	imm.[l]	.81	.92	no
Shimamura et al. (1990, Exp. 1)*	M	4 VA; 2 Surg.	word list[m]	15	imm.	.82 (.08)[e]	.88 (.06)[e]	no
Shimamura et al. (1990, Exp. 2)*	M	4 VA; 2 Surg.	obscure facts[m]	15	imm.	.80 (.08)	.88 (.03)	no
Stuss et al. (1994)	L	4 I; 4 VA; 2 HI	word lists[n]	48	1 h	.63[j]	.90[j]	yes
Stuss et al. (1994)	R	4 I; 3 VA; 1 HI; 1 T	word lists[n]	48	1 h	.73[j]	.90[j]	no
Stuss et al. (1994)	B	1 I; 5 VA; 5 HI; 2 T	word lists[n]	48	1 h	.67[j]	.90[j]	yes
Zatorre (1993)	R	10 Surg.	melodies	24	imm.	.97[o]	1.02[o]	no
Zatorre (1993)	L	7 Surg.	melodies	24	imm.	.61[o]	1.02[o]	no

Note. *Memory scores were estimated from the authors' figures. L = number of items within a list; RI = retention interval; Ftl. PM = performance measure of patients with frontal pathology; Ctl. PM = performance measure of normal control subjects; SEM = standard error of the mean was reported whenever available; HI = head injury; Surg. = surgical excision; VA = vascular abnormality; T = tumor; I = infarction; UK = unknown.

[a]unless otherwise noted, each test required subjects to make "old" versus "new" judgments to target items which were interspersed with distractor items; [b]averaged across five study-test trials; [c]scored as "hits" plus "correct rejections"; [d]delayed test for items that had been both studied and tested the week before; [e]eight-alternative forced-choice recognition test; [f]reflects the proportion of "old" facts correctly recognized minus the proportion of "new" facts correctly recognized; [g]seven-alternative forced-choice recognition test; [h]this significance test was combined across the two retention intervals; [i]tests were conducted immediately, after 20 min., and after 1 day, and performance measures were averaged across the intervals; [j]scored as "hits" minus "false alarms"; [k]two-alternative forced-choice recognition test; [l]test items were presented within the study list; [m]four-alternative forced-choice recognition test; [n]lists comprised: unrelated items, categorizable items (blocked by category), and categorizable items (not blocked by category); [o]data was scored as d'.

Appendix B

Cued recall tests—Information extracted from each experiment

Author(s)	Lesion side	Etiology	Study materials and retrieval cues[a]	L	RI	Ftl. PM (SEM)	Ctl. PM (SEM)	Sig. diff.
Gershberg & Shimamura (in press, Exp. 3)*	M	6 VA	word list[b]	24	imm.	.63[d]	.81[d]	yes[e]
Gershberg & Shimamura (in press, Exp. 3)*	M	6 VA	word list[bc]	24	imm.	.60[d]	.84[d]	yes[e]
Incisa della Rocchetta & Milner (1993, Exp. 1)*	L	12 Surg.	word list[f]	48	imm.	.65 (.06)	.79 (.08)	yes[e]
Incisa della Rocchetta & Milner (1993, Exp. 1)*	L	12 Surg.	word list[g]	48	imm.	.48 (.06)	.60 (.08)	yes[e]
Incisa della Rocchetta & Milner (1993, Exp. 1)*	R	8 Surg.	word list[f]	48	imm.	.71 (.06)	.79 (.08)	UK[h]
Incisa della Rocchetta & Milner (1993, Exp. 1)*	R	8 Surg.	word list[g]	48	imm.	.54 (.06)	.60 (.08)	UK[h]
Janowsky et al. (1989a, Exp. 1)*	M	5 VA; 1 UK; 1 Surg.	general information facts[i]	20	6–8 d	.40 (.10)	.47 (.04)	no
Janowsky et al. (1989a, Exp. 2)*	M	5 VA; 1 UK; 1 Surg.	obscure facts[j]	15	5 min	.44[k]	.29[k]	no
Janowsky et al. (1989a, Exp. 2)*	M	5 VA; 1 UK; 1 Surg.	obscure facts[j]	15	2 h	.38[k]	.27[k]	no
Janowsky et al. (1989b)*	M	5 VA; 1 UK; 1 Surg.	A-B (noun-noun) word pairs	10	imm.	.67 (.07)[l]	.73 (.07)[l]	no
Shimamura et al. (1990, Exp. 2)*	M	4 VA; 2 Surg.	obscure facts[i]	15	imm.	.33 (.05)	.39 (.04)	no
Shimamura et al. (in press, Exp. 1)*	M	6 VA	A-B word pairs (moderately related)	12	imm.	.90[l]	.94[l]	UK[h]
Shimamura et al. (in press, Exp. 2)*	M	6 VA	A-B word pairs (unrelated)	12	imm.	.67[l]	.76[l]	UK[h]
Vogel et al. (1987)	L	7 HI; 2 VA	A-B word pairs	16	imm.	.14	.69	yes
Vogel et al. (1987)	L	7 HI; 2 VA	A-B word pairs[m]	16	imm.	.38	.94	yes
Vogel et al. (1987)	L	7 HI; 2 VA	A-B word pairs[mn]	16	imm.	.51	.98	yes
Vogel et al. (1987)	R	2 T; 2 HI; 2 VA	A-B word pairs	16	imm.	.16	.69	yes
Vogel et al. (1987)	R	2 T; 2 HI; 2 VA	A-B word pairs[m]	16	imm.	.34	.94	yes
Vogel et al. (1987)	R	2 T; 2 HI; 2 VA	A-B word pairs[mn]	16	imm.	.51	.98	yes
Vogel et al. (1987)	L	7 HI; 2 VA	A-B word pairs	16	2 d	.04[o]	.26[o]	yes
Vogel et al. (1987)	L	7 HI; 2 VA	A-B word pairs[m]	16	2 d	.21[o]	.46[o]	yes
Vogel et al. (1987)	L	7 HI; 2 VA	A-B word pairs[mn]	16	2 d	.36[o]	.53[o]	yes
Vogel et al. (1987)	R	2 T; 2 HI; 2 VA	A-B word pairs	16	2 d	.08[o]	.26[o]	yes
Vogel et al. (1987)	R	2 T; 2 HI; 2 VA	A-B word pairs[m]	16	2 d	.16[o]	.46[o]	yes
Vogel et al. (1987)	R	2 T; 2 HI; 2 VA	A-B word pairs[mn]	16	2 d	.33[o]	.53[o]	yes
Wirsen (1991)	M	18 HI	word pairs[p]	30	imm.	.59 (.20)	.63 (.24)	no
Wirsen (1991)	M	18 HI	word pairs[p]	30	30 min	.43 (.08)[q]	.55 (.09)[q]	yes

Note. *Memory scores were estimated from the authors' figures. L = number of items within a list; RI = retention interval; Ftl. PM = performance measure of patients with frontal pathology; Ctl. PM = performance measure of normal control subjects; SEM = standard error of the mean was reported whenever available; HI = head injury; Surg. = surgical excision; VA = vascular abnormality; UK = unknown.

[a]unless otherwise noted, the retrieval cues for each test of A-B word pairs were the A terms and the cues for the word lists were category cues; [b]categorized word list (not blocked by category); [c]subjects were given the category names at study; [d]performance measure is averaged across three study-test trials; [e]significant difference when combined across study conditions, but this specific comparison was not analyzed; [f]categorized word list (blocked by category); [g]categorized word list (not blocked by category); [h]data does not look significant, but this specific comparison was not analyzed; [i]questions like "who discovered the polio vaccine?"; [j]at test, facts were presented in the form of questions; [k]performance measure reflects the number of "old" facts correctly recalled minus the number of "new" facts correctly recalled; [l]performance measure is averaged across three study-test trials; [m]word pairs were presented within sentences; [n]test cue was sentence with the B term missing; [o]this was a second, identical test for the same items; [p]word pairs were studied in three consecutive lists of ten pairs each, and recall scores were combined for a single analysis; [q]this was another test of the same items.

Appendix C

Free recall tests—Information extracted from each experiment

Author(s)	Lesion side	Etiology	Study materials and test conditions[a]	L	RI	Ftl. PM (SEM)	Ctl. PM (SEM)	Sig. diff.
Gershberg & Shimamura (in press, Exp. 1)*	M	10 VA	words or pictures[b]	15	imm.	.61[c]	.74[c]	yes[d]
Gershberg & Shimamura (in press, Exp. 2)*	M	7 VA	word list[be]	15	imm.	.66[c]	.84[c]	yes[d]
Gershberg & Shimamura (in press, Exp. 2)*	M	6 VA	word list[be]	15	imm.	.66	.89	yes[d]
Gershberg & Shimamura (in press, Exp. 3)*	M	6 VA	word list[be]	24	imm.	.53[g]	.80[g]	yes[d]
Gershberg & Shimamura (in press, Exp. 3)*	M	6 VA	word list[bef]	24	imm.	.64[g]	.80[g]	yes[d]
Hirst & Volpe (1988)	B	2 VA; 3 HI	words on cards	20	2 min	.23 (.04)	.38 (.09)	no
Hirst & Volpe (1988)	B	2 VA; 3 HI	words on cards[h]	20	2 min	.29 (.07)	.84 (.06)	yes
Hirst & Volpe (1988)	B	2 VA; 3 HI	words on cards[hi]	20	2 min	.71 (.13)	.84 (.07)	no
Incisa della Rocchetta (1986)*	L	12 Surg.	pictures on cards[hi]	36	imm.	.47 (.17)	.69 (.08)	yes[j]
Incisa della Rocchetta (1986)*	R	12 Surg.	pictures on cards[hi]	36	imm.	.56 (.17)	.69 (.08)	yes[j]
Incisa della Rocchetta (1986)*	L	12 Surg.	pictures on cards[hi]	36	2 h	.47 (.17)	.69 (.08)	yes[j]
Incisa della Rocchetta (1986)*	R	12 Surg.	pictures on cards[hi]	36	2 h	.58 (.11)	.69 (.08)	yes[j]
Incisa della Rocchetta & Milner (1993, Exp. 1)*	L	12 Surg.	word list[k]	48	imm.	.46 (.04)	.69 (.02)	yes[d]
Incisa della Rocchetta & Milner (1993, Exp. 1)*	L	12 Surg.	word list[e]	48	imm.	.42 (.04)	.58 (.06)	yes[d]
Incisa della Rocchetta & Milner (1993, Exp. 1)*	R	8 Surg.	word list[k]	48	imm.	.54 (.04)	.69 (.02)	UK[l]
Incisa della Rocchetta & Milner (1993, Exp. 1)*	R	8 Surg.	word list[e]	48	imm.	.42 (.06)	.58 (.06)	UK[l]
Janowsky et al. (1989)*	M	5 VA; 1 UK; 1 Surg.	word list	15	imm.	.50[c]	.67[c]	yes
Shimamura et al. (1990)*	M	4 VA; 2 Surg.	word list	15	imm.	.33 (.06)	.45 (.09)	no
Smith & Milner (1984)	L	7 Surg.	toys	16	imm.	.49	.58	no
Smith & Milner (1984)	R	12 Surg.	toys	16	imm.	.57	.58	no
Smith & Milner (1984)	L	7 Surg.	toys	16	1 d	.46[m]	.71[m]	yes
Smith & Milner (1984)	R	12 Surg.	toys	16	1 d	.55[m]	.71[m]	yes
Stuss et al. (1994)	L	4 I; 4 VA; 2 HI	word list[k]	16	imm.	.47 (.27)[n]	.83 (.16)[n]	yes
Stuss et al. (1994)	R	4 I; 3 VA; 1 HI; 1 T	word list[k]	16	imm.	.64 (.22)[n]	.83 (.16)[n]	yes
Stuss et al. (1994)	B	1 I; 5 VA; 5 HI; 2 T	word list[k]	16	imm.	.53 (.22)[n]	.83 (.16)[n]	yes
Stuss et al. (1994)	L	4 I; 4 VA; 2 HI	word list[e]	16	imm.	.41 (.22)[n]	.59 (.16)[n]	yes
Stuss et al. (1994)	R	4 I; 3 VA; 1 HI; 1 T	word list[e]	16	imm.	.52 (.14)[n]	.59 (.16)[n]	no
Stuss et al. (1994)	B	1 I; 5 VA; 5 HI; 2 T	word list[e]	16	imm.	.41 (.16)[n]	.59 (.16)[n]	yes
Stuss et al. (1994)	L	4 I; 4 VA; 2 HI	word list	16	imm.	.34 (.17)[n]	.55 (.13)[n]	yes
Stuss et al. (1994)	R	4 I; 3 VA; 1 HI; 1 T	word list	16	imm.	.44 (.14)[n]	.55 (.13)[n]	no
Stuss et al. (1994)	B	1 I; 5 VA; 5 HI; 2 T	word list	16	imm.	.41 (.17)[n]	.55 (.13)[n]	yes

Note. *Memory scores were estimated from the authors' figures. L = number of items within a list; RI = retention interval; Ftl. PM = performance measure of patients with frontal pathology; Ctl. PM = performance measure of normal control subjects; SEM = standard error of the mean was reported whenever available; HI = head injury; Surg. = surgical excision; VA = vascular abnormality; T = tumor; I = infarction; UK = unknown.

[a]unless otherwise noted, subjects took a single free recall test for the study list; [b]two lists were studied and tested, but only the first list is summarized here; [c]performance measure is averaged across five study-test trials; [d]significant difference when combined across study conditions, but this specific comparison was not analyzed; [e]categorized word list (not blocked by category); [f]subjects were given the category names at study; [g]performance measure is averaged across two study-test trials; [h]items could potentially be categorized; [i]subjects were instructed to categorize the items at study; [j]significance tests were combined across the two RI's; [k]categorized word list (blocked by category); [l]comparison looks significant, but this specific comparison was not analyzed; [m]this was a second, identical test; [n]performance measure is averaged across four study-test trials.