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Memory and Working with Memory: Evaluation of a Component Process Model and Comparisons with Other Models

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Memory is not unitary but depends on the operation of potentially independent, but typically interactive, components. One of the jobs of a cognitive neuropsychologist is to identify these components and indicate how they interact with each other. Although we are far from being able to specify these components with the precision we would like, either functionally or structurally, there is sufficient information to tempt many of us to sketch the outlines of what we think a complete model might be like. I offer my version of such a model. A more detailed account appears in Moscovitch (1989, 1992a, 1992b) and Moscovitch and Umiltà (1991).

The model I sketch has four essential components, each of which mediates processes that dominate performance on four different types of memory tests: (1) a nonfrontal neocortical component made up of various perceptual and "semantic" modules that mediate performance on item-specific, implicit (indirect) tests of memory; (2) a basal-ganglia component that mediates performance on sensorimotor procedural tests of memory; (3) a medial-temporal/hippocampal component, *which also is modular,* that mediates encoding, storage, and retrieval on explicit-episodic-memory tests that are *associative/cue-dependent*; (4) a central-system frontal-lobe component that "works with memory" and mediates performance on *strategic* explicit and rule-based explicit tests. After sketching the model, I will discuss some of its implications and compare it with other models from the human and animal literature.

1 MODULES AND CENTRAL SYSTEMS

A distinguishing feature of this memory model is that its basic principles are derived from Fodor's (1983) notion that modules and central systems are the constituents of the mind (and brain). Carlo Umiltà and I proposed a modified version of Fodor's ideas that retained its core assumptions and suggested how Fodor's criteria of modularity can be translated to the neuropsychological level (Moscovitch and Umiltà, 1990, 1991).

Modules are computational devices that have propositional content and satisfy all of the following three criteria: domain specificity, informational encapsulation or cognitive impenetrability, and shallow output. *Domain specificity* entails that the type of information modules accept for processing is restricted or circumscribed. At the neuropsychological level, it must be shown that damage to a particular region or system, the structural embodiment of the module, leads to deficient processing in the purported domain with relative sparing of function in other domains. This condition is not sufficient by itself, since central-system structures can also be localized to circumscribed regions. *Informational encapsulation* implies that modules resist the effects of higher-order knowledge on processing and are cognitively impenetrable to probes of their content and operation. Only the module's shallow output is available for conscious inspection. Neuropsychologically, this criterion is satisfied if the processes mediated by a module are unaffected by gross intellectual decline caused by degeneration or focal damage to structures other than the module itself. For example, patients with generalized dementia caused by Alzheimer's disease fail to understand even simple words or appreciate the function of objects, but they can still read relatively well (Schwartz, Saffran, & Marin, 1980) and have a good three-dimensional representation of objects (Chertkow & Bub, 1990; Moscovitch & Umiltà, 1990; Warrington & Taylor, 1978). Informational encapsulation is also satisfied by evidence of a domain-specific deficit, despite preserved intellectual functions and semantic knowledge about material in the affected domain. Patients with associative agnosia may not recognize an object visually but can provide detailed semantic information about the object when given its name. Yet the patient may not be able to use this knowledge to identify the object visually (Behrmann, Winocur, Moscovitch, 1992; Moscovitch & Umiltà, 1990; Riddoch & Humphreys, 1987). *Shallow output* is output that has no meaning beyond the value assigned to it by the module; interlevel representations that led to the shallow output are not available for conscious inspection. The neuropsychological correlate of this criterion is evidence of normal domain-specific performance without any ability to interpret semantically the information pertaining to that domain. Here too patients with associative agnosia or dementia are the paradigmatic cases. Though such patients retain the ability to process objects, faces, and words at a structural, presemantic level, they cannot assign any meaning to the structural information they have computed (Bauer, 1984; Chertkow & Bub, 1990; Moscovitch & Umiltà, 1990, 1991; Tranel & Damasio, 1985; Warrington & Taylor, 1978).

Thus a module, no matter how complex its inner workings, is essentially a stupid, closed computational device that delivers its shallow output to interpretative *central systems*, where meaning and relevance are assigned. *None of the criteria of modularity apply to central systems* (but see Moscovitch & Umiltà, 1990, for some provisos). Unlike modules, central systems integrate information from superficially dissimilar domains and are open to top-down influences. The output of central systems is deep or meaningful, and the interlevel representations that give rise to the final output may be available to consciousness.

I will argue that memory, like perception, consists of the operation of modules and central systems. Although no memory test is likely to be process-pure (Jacoby, 1991), performance on some tests can be considered to be mediated primarily by modules, whereas performance on others depends more on central systems. Before considering which tests are modular and which are not, it is necessary first to classify memory tests into various types.

2 CLASSIFICATION OF MEMORY TESTS

Task analysis and evidence of preserved memory abilities in amnesic patients (Moscovitch, 1984) suggests that it is possible to distinguish between two broad classes of memory tests: explicit and implicit (Graf & Schacter, 1985). Explicit tests require conscious recollection of past events, whereas on implicit tests, memory for the past is inferred from changes in performance with experience or practice. To be implicit, a test must also be highly structured, so that the goal of the task and the means to achieve it are apparent and available to the subject (Moscovitch, 1984). When an implicit test does not meet the latter criteria, the amnesic patient shows no evidence of preserved learning even though conscious recollection may not be involved (Nissen, Willingham, & Hartman, 1989).

Implicit and explicit tests can each be further subdivided into at least two subtypes (see table 1). For implicit tests, the two are procedural and item-specific tests. *Procedural tests* are those that assess learning and retention of general sensory-motor skills, procedures, or rules. *Item-specific* tests, on the other hand, assess memory for a particular item, such as a certain word, face, or object, by seeing the effect that initial presentation of the item has on the accuracy or speed of identification of the item when it is repeated. The benefit gained is known as the *repetition priming effect*.

The two subtypes of explicit tests are associative/cue-dependent and strategic. *Associative* episodic memory tests are those in which the cue is sufficient for retrieval. When given the cue "Have your read *War and Peace*?" or "Have your seen *Gone with the Wind*? the answer automatically pops into mind as surely as the word "night" pops into mind to the semantic cue "day." For *strategic* tests, the cue does not automatically elicit the target memory but only provides the starting point of a memory search that has elements in common with problem solving. Such strategic processes can be initiated by questions that require the reinstatement of a particular spatial and temporal context, such as "What did you do two weekends ago?"

Few if any tests are made up of only a single component. The classificatory scheme suggests ideal prototypes against which impure tests can be compared and thus provides a crude framework for fractionating a test into its component parts.

Table 1 Classification of implicit and explicit tests

	Type of test					
	Implicit				Explicit	
	Item-specific		Procedural			
	Perceptual	Conceptual	Sensorimotor	Ordered/rule-based	Associative	Strategic
Characterization	Identification or classification of particular stimuli based on sensory cues	Generation, production, or classification of targets in response to conceptual or semantic cues	Acquisition and improvement of motor or sensory skills	Learning to solve problems with rules or organized response contingencies	Conscious recollection of episodes in which the cue is sufficient for retrieval	Conscious recollection of episodes in which extracue strategic factors are critical
Some variables and factors that influence performance	Perceptual variables (e.g., modality, representational format), retention interval	Semantic variables (e.g., levels of processing), number of presentations, proactive interference, attention (?)	Number of trials, feedback	Number of trials, feedback, hierarchical organization, monitoring	Semantic variables (e.g., levels of processing), retention interval, stimulus duration and repetition, interference, attention	Organizational variables (e.g., clustering), attention, cognitive resources
Typical tests used to assess memory	Identification of fragmented words or pictures (e.g., fragment completion or perceptual identification)	Generation of exemplars of category cues	Pursuit rotor, mirror drawing, reading transformed script	Tower of Hanoi	Simple recognition or cued recall	Free recall (particularly of categorized lists), memory for temporal order, conditional associative learning
Probable neural substrate	Perceptual input modules (representational systems) in the posterior neocortex	Interpretative multimodal central systems in the lateral temporal, parietal, and possibly frontal, lobes	Basal ganglia, cerebellum	Dorsolateral and midlateral frontal lobes	Hippocampus and related limbic structures in the medial temporal lobes and diencephalon	Dorsolateral and ventromedial frontal lobes, cingulate cortex

3 A NEUROPSYCHOLOGICAL MODEL OF MEMORY

3.1 Item-Specific Implicit Tests

Reactivation of perceptual and semantic records Memory begins with registering information in cortical modules that pick up and transform stimulus events into presemantic structural representations. The output of these modules is delivered to central-system structures for early semantic interpretation. The input modules and interpretative central systems, which are presumed to be located in the posterior and midlateral neocortex, are modified by the information they process, which thereby becomes, respectively, a *perceptual* and *semantic record* (Kirsner & Dunn, 1985) of the processing activity. The altered neuronal circuitry that underlies the records preserves information about the stimulating event and enables subsequently related events to be processed and identified more quickly. Reactivation of perceptual and semantic records is the basis for *perceptual* and *conceptual repetition-priming effects,* which are at the heart of item-specific implicit tests of memory. The term *engram* is reserved for the informational content of these records.

Registration: The rapid formation of records I propose that the term *registration* or *recording* be used to refer to the neocortical process involved in forming the perceptual records or engrams that support performance on item-specific implicit tests. By designating these processes with special terms, I indicate that they are different, at least at the functional level, from other processes involved in forming long-term memory traces, for which the generic term *consolidation* has traditionally been used.

Perceptual input modules and perceptual repetition priming In accordance with the criterion of *domain specificity,* perceptual input modules restrict their operation to a specific domain. Since they are *informationally encapsulated,* their operation is not affected by higher-order semantic information, nor are their workings and informational content accessible to conscious inspection. By the criterion of *shallow output,* the information that perceptual input modules deliver is restricted to presemantic structural descriptions within the specific domain of the module. Carlo Umiltà and I (Moscovitch & Umiltà, 1990, 1991) identified a few systems that can qualify as perceptual modules: the visual-word-form system (Warrington & Shallice, 1980), a visual-object or structural-description system (Riddoch & Humphreys, 1987; Warrington & Taylor, 1978), a face-recognition system (Bruce & Young, 1986), and a phonological-word-form system (Schacter, 1992) or speech module (Liberman & Mattingly, 1989). From the properties of modules, it follows that the perceptual record formed in each module also contains domain-specific, presemantic, structural information about the stimulus that gave rise to it.

Anatomical localization Structures in the posterior neocortex are presumed to be the locus of the perceptual input modules mediating repetition-priming effects. There is both negative and positive evidence implicating these structures. The negative evidence is that the medial temporal lobes and related limbic structures in the diencephalon, which are crucial for performance on explicit tests of memory, are not necessary for normal performance on implicit tests. Repetition-priming effects are well-preserved in amnesic patients with damage to these structures (for reviews, see Moscovitch, Vriezen, & Goshen-Gottstein, 1993; Shimamura, 1986; Squire, 1992, this volume). Similarly, demented patients whose pathology spares the sensory or parasensory areas of the posterior neocortex perform normally on perceptual item-specific implicit tests (see Moscovitch et al., 1993), just as they can read and identify objects at a presemantic perceptual level (Chertkow & Bub, 1990; Schwartz, Saffran, & Marin, 1980). In short, to the extent that their input modules are intact, amnesic and demented patients show normal perceptual-repetition effects.

Suggestive positive evidence for the localization of perceptual input modules to the posterior neocortex comes from studies of patients with domain-specific agnosias and from PET scan studies in normal people. Umiltà and I (Moscovitch & Umiltà, 1990) distinguished between two types of agnosic patients: those whose input modules are damaged and those whose modules are intact but whose shallow outputs are inaccessible to interpretative central systems (see also Schacter, McAndrews, & Moscovitch, 1988). These patients correspond to apperceptive and associative agnosics, respectively (Lissauer, 1890). Patients in the former group include individuals with damage to the word-form system in the left occiptotemporal region (Warrington & Shallice, 1980), the face-recognition system in the right lingual, fusiform, and parahippocampal gyrus (Sergent & Signoret 1992), the object-recognition system in the left and right temporoparietal region (McCarthy & Warrington, 1990; Warrington & Taylor, 1978), and phonological-word-form system in the left superior temporal region (Kohn & Friedman, 1986; Saffran & Marin, 1977).

As yet only with respect to face-recognition has it been established firmly that damage to the critical region impairs face-recognition on both explicit and implicit tests of knowledge (see reviews in Bruyer, 1991; Sergent & Signoret, 1992; Young, 1994). Such patients also show no repetition-priming effects for faces (Newcombe, Young, & de Haan, 1989; Sergent & Signoret, 1992). On the other hand, prosopagnosic patients whose damage spares the crucial region can respond differentially to familiar and unfamiliar faces on implicit tests (de Haan, Bauer, & Greve, 1992) and also show normal repetition-priming effects (de Haan, Young, & Newcombe, 1987; Greve & Bauer, 1990). Similarly, dyslexic patients who show evidence of an intact word-form system, as indicated on implicit tests of reading, also show preserved repetition-priming effect for words (Schacter, Rapcsak, Rubens, Tharan,

& Laguna, 1990). Thus, as predicted by Moscovitch & Umiltà (1990, 1991), if the module is sufficiently well-preserved to support performance on *implicit*, domain-specific perceptual tests of knowledge, then it will also support performance on perceptual repetition-priming tests.

Functional neuroimaging studies of perceptual priming are a potential valuable source of evidence. As yet only one report has been published, but its findings, though broadly consistent with the view presented here, are somewhat puzzling (see my discussion in section 4.1).

3.2 Conceptual Repetition Effects and Semantic Records

What distinguishes conceptual from perceptual item-specific tests is that the target is not repeated at test, even in degraded form, but rather is elicited by semantic cues, such as a related word or a question. Because conceptual repetition-priming effects, unlike perceptual ones, are influenced by semantic variables, it is unlikely that conceptual repetition effects are mediated by presemantic input modules. I suggest that they are mediated by central systems, which interpret the shallow output of perceptual modules and store a *semantic* record of their activity or representations (see Tulving and Schacter, 1990, for similar views). Accordingly, performance on conceptual implicit tests should not be sensitive to either modality or format but should be affected by level-of-processing manipulations. In general, these predictions have been confirmed (for reviews, see Blaxton, 1989; Roediger, 1990; Roediger & McDermott, 1993). As yet it is not clear whether attention at encoding is a necessary component. If conceptual repetition-priming effects can be preserved when material is presented under anaesthesia, as some studies have indicated (see Kihlstrom & Couture, 1992), then this suggests that establishing semantic records can occur automatically (see Moscovitch & Umiltà, 1990, for a discussion on derived versus associative semantics).

Damage to the hippocampal component alone spares conceptual repetition-priming effects. Amnesic patients, though severely impaired on explicit tests, can show normal conceptual repetition effects (Gardner, Boller, Moreines, & Butters, 1973; McAndrews, Glisky, & Schacter, 1987; Tulving, Hayman, & Macdonald, 1991; Winocur & Weiskrantz, 1976), though more studies are needed to confirm the generality of these observations.

Because they are mediated by interpretative central-system structures, conceptual, repetition-priming effects are reduced or absent in demented patients with Alzheimer's disease (Butters, Heindel, & Salmon, 1990). Blaxton (1992) reports a similar pattern of impaired conceptual, but preserved perceptual, repetition effects in patients with unilateral temporal lobectomies. Because gross intellectual decline is not typical in these patients, her findings, if replicated, would suggest that the anterior, lateral temporal cortex is necessary for storing semantic records but not for interpreting information semantically. The studies on patients with Alzheimer's disease suggest that other regions of the temporal and parietal association cortex may be important. Future work on patients with focal lesions and on functional neuroimaging in normal people should help specify the crucial areas.

3.3 The Hippocampal Component: A Module for Episodic, Associative Memory

The hippocampal component consists of a variety of structures in the medial temporal lobes and diencephalon that form a circuit. In addition to the hippocampus, these structures include the parahippocampal gyrus, the entorhinal and perirhinal cortices, the mammilary bodies and dorsomedial nucleus of the thalamus, the cingulate cortex, and the fornix. Amnesia in humans is associated with bilateral damage to any one of these structures, except for the fornix and cingulate, for which the evidence is equivocal (Squire, 1987).

The input modules and central systems deliver their output to working memory (Baddeley, 1986), whose content is accessible to consciousness (see Moscovitch & Umiltà, 1990, 1991, for a discussion of working memory and consciousness), and to procedural systems that can affect behavior but whose operation cannot be inspected consciously. Consciously apprehended information is necessarily picked up by the hippocampal component (see figure 1).

The hippocampal component is thus a module whose specific domain is consciously apprehended information. *To the extent that an event does not receive full conscious attention, it is not processed by the hippocampal component.* Using reciprocal pathways that connect the hippocampus to the cortex, the hippocampus binds or integrates the engrams of the modules and central systems

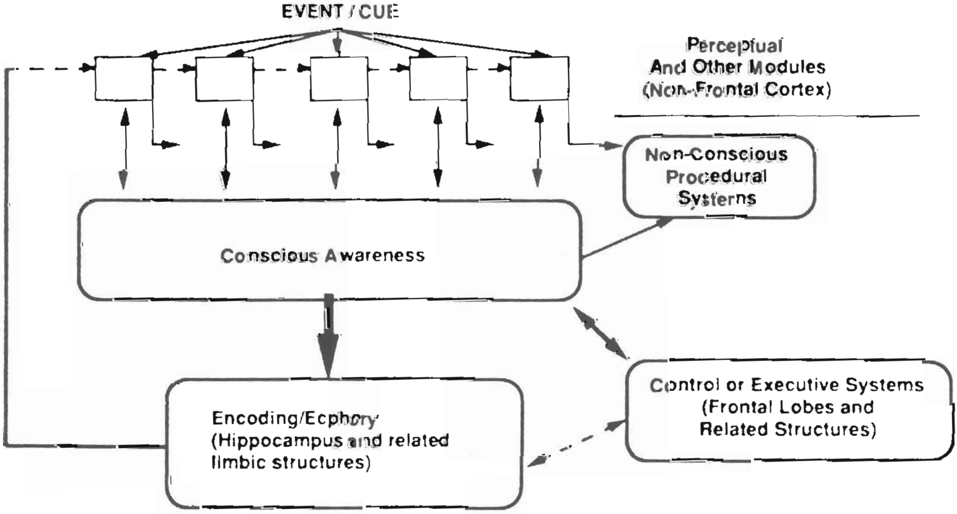

Figure 1 A sketch of the interaction of modules and central-system structures in a neuropsychological model of memory (from Moscovitch, 1989).

whose output contributed to the conscious experience as well as those elements that make the experience conscious. In this way "consciousness" is bound by the hippocampal formation to other aspects of the event. The resulting collection of bound engrams constitutes a *memory trace*, which is encoded as a file entry or index within the hippocampal component (Teyler & Di Scenna, 1986).

To recollect a recent event consciously, a memory trace must be reactivated either directly or via the hippocampal component. This occurs when an external cue or internally generated cue automatically interacts with a memory trace, a process called *ecphory* by Semon, who also coined the term *engram* (1921; cited in Schacter, Eich, & Tulving, 1978). The product of that interaction is delivered to consciousness or, simply put, is made conscious.

Once initiated, ecphoric processes are rapid, obligatory, informationally encapsulated, and cognitively impenetrable. The same is true of the initial formation and encoding of memory traces. We are aware only of the input to the hippocampal component and the shallow output from it. Thus we remember countless daily events without intending to remember them: memories may pop into mind, much as preattentive perceptual stimuli pop out of their background.

This analogy of memory with perception is appropriate insofar as aspects of both are modular. Just as it would be maladaptive to have a perceptual system that is too much under our control and subject to our motivations and expectations, so it would not be useful to have a memory system that relies on our intentions to remember. Because most often we do not know in advance what is worth committing to memory, it is important to have a system capable of encoding and storing information automatically, as a natural consequence of apprehending the material consciously. Moreover, because events unfold at their own pace, most of them would not be encoded by the time we can determine that they were worth remembering.

The central idea of levels-of-processing theory (Craik & Lockhart, 1972), that remembering is a natural by-product of cognition, follows directly from this view that the hippocampal component is modular. According to the levels-of-processing framework, what determines what is remembered is not the intention to remember as such but the extent to which events are attended and information from them is processed to a deep level and properly organized. Paying close attention to the target and encoding it semantically makes it distinctive and makes its memory traces more easily retrievable (Moscovitch & Craik, 1976). Once events are fully apprehended in consciousness, they are obligatorily picked up and encoded by the hippocampus. Conversely, without a hippocampal component, no lasting memory traces can be formed and recovered, no matter how deeply the information is processed (Cermak, 1982; Cermak & Reale, 1978).

An additional benefit of an automatic hippocampal component is that it does not draw cognitive resources away from other activities. If committing something to memory always required additional effort beyond that involved in apprehending the relevant information, it would lead to a peculiar tradeoff: resources allocated to attention and comprehension would be unavailable for memory and vice versa. We would remember well only those items that were processed poorly, an unacceptable and counterfactual condition.

The cost of being modular is that the hippocampal component lacks the intelligence for self-organization, strategic intervention, and monitoring. Events are encoded only by simple contiguity and by associations that memory traces form with each other and with cues. The hippocampal component responds reflexively to cues; it cannot conduct a memory search if cues are initially ineffective or monitor the ecphoric output to determine whether the recovered memories are veridical or even plausible. In other words, its output is shallow, in the sense that it is not interpreted properly in relation to other memories; that is, the output cannot be related to a spatial and temporal context with respect to other events. I call this latter context *organizational* or *historical*, in contrast with the hippocampal component's *associative* context, which is the multimodal spatial and temporal background within which the target is embedded and that constitutes an event. The job of organizing the input, verifying the shallow output, and placing it in a proper historical context is left to pre- and postecphoric, extrahippocampal processes probably mediated by the frontal lobes. Because its organization and retrieval method is associative and cue-dependent, I refer to the hippocampal component as an associative/episodic-memory component, a term that also describes the explicit memory tests mediated by it.

3.4 The Frontal Lobes: Central Systems and Strategic Explicit Tests

The prefrontal cortex is a large, heterogeneous structure consisting of a number of distinct areas, each with its own projections to and from other brain regions and each having presumably different functions (Pandya & Barnes, 1987). It has been appreciated for some time that lesions to the dorsolateral and orbital regions of the prefrontal cortex produce different deficits (Milner, 1964). More recently, evidence has been accumulating that the functions of other, smaller regions can also be distinguished one from another (Goldman-Rakic, 1987; Petrides, 1989).

Despite the evidence for localization of function among regions of prefrontal cortex, Umiltà and I argued that they are central-system structures that contribute to performance on strategic explicit tests of memory (Moscovitch & Umiltà, 1990, 1991). The frontal lobes are prototypical organizational structures crucial for selecting and implementing encoding strategies that organize the input to the hippocampal component and the output from it, for evaluating that shallow output and determining its correct temporal sequence and spatial context with respect to other events, and for using the resulting information to guide further mnemonic searches, direct thought, or plan future action. In short, the frontal lobes are necessary for converting remembering from a stupid reflexive act triggered by a cue to an intelligent, reflective, goal-directed activity under voluntary control. When you try to place a person that looks familiar or to determine where you were during the last week of July, the appropriate memory does not emerge automatically but must be ferreted out, often laboriously, by retrieval strategies.

Memory disorders following frontal lesions are not related to deficits in storage and retention, which are hippocampal functions. Instead, they are associated with impaired organizational and strategic processes. As befits a central-system structure, for which the criterion of domain specificity does not apply, the frontal lobes' function with respect to memory is similar to its function in other domains. The frontal lobes organize the raw material made available by other modules and central systems. The frontal lobes' representations are available to conscious inspection, and the output is deep. If the hippocampal circuit can be considered to consist of raw-memory structures, then the frontal lobes are "working-with-memory" structures that operate on the input to the hippocampal component and the output from it. Winocur and I (Moscovitch & Winocur, 1992a) prefer this term to the superficially similar term *working memory* (Baddeley, 1992, this volume) because the latter is too theoretically loaded: use of it implies endorsing aspects of a working-memory theory in the human and nonhuman literature that may not only be incompatible with each other (see, for example, how the term is used by Olton et al., 1979) but may be wrong or inappropriate when applied to frontal-lobe functions (Moscovitch & Umiltà, 1990, 1991). If we restrict our consideration only to the functions of the central executive in working memory, my conception of working-with-memory structures is very closely related to Baddeley's (1992, this volume) and to the various reflective subsystems proposed by Johnson (1992; see also Johnson & Chalfonte, this volume).

3.5 Procedural Implicit Tests

Of the various types of tests discussed so far, procedural implicit tests are the most heterogeneous, consisting of a large variety of subtypes that do not have obvious components in common. The tests range from mastering a motor skill (e.g., a pursuit rotor), to acquisition of general perceptual skills (reading geometrically transformed script), to learning and applying the rules necessary to solve intellectual puzzles like the Tower of Hanoi. Even classical conditioning of skeletal responses may be a subtype of procedural implicit tests of memory. To make the procedural implicit tests more amenable to analysis, I will use the term to refer to only two subtypes: (a) acquisition and retention of sensorimotor skills, (b) implicit learning and application of rules.

Sensorimotor skills The model I have developed is not directly applicable to the domain of sensorimotor skills, because its main concern is with encoding sensory input. Nonetheless, the same principle may apply: acquisition and retention results from modification of the very structures involved in performing the task. Just as perceptual structures are modified by the act of perceiving so as to form perceptual records of their activity, so motor structures involved in programming are altered so as to leave behind a *sensorimotor record*. Reactivation of sensorimotor records accounts for performance on implicit sensorimotor tests of memory.

Two predictions follow from this assertion: insofar as the tests are truly implicit (Moscovitch, 1984), acquisition and retention of sensorimotor skills should be normal in amnesic and demented patients with intact sensorimotor structures; deficits should be observed only in patients with damage to sensorimotor structures, regardless of how well preserved their intellect is.

Both predictions are confirmed by the neuropsychological evidence. Acquisition and retention of sensorimotor skills, such as mirror drawing and the pursuit rotor, is normal in the amnesic patient H.M., who had bilateral surgical excision of the medial temporal lobes (Corkin, 1968; Milner, 1966), in patients with lesions to other portions of the hippocampal circuit, and in demented patients with Alzheimer's disease (Butters, Heindel, & Salmon, 1990). Learning a general perceptual skill, such as reading geometrically transformed script, is also preserved in these patients (Butters et al., 1990; Cohen, 1984; Moscovitch, Winocur, & McLachlan, 1986).

By contrast, deficits on the same sensorimotor implicit tests have been noted in patients with Huntington's or Parkinson's disease, which are degenerative disorders associated with damage to the basal ganglia, structures that are part of the extrapyramidal motor system (Butters et al., 1990). The same patients, however, perform normally on perceptual, item-specific implicit tests, which suggests that the deficit concerns only the formation of sensorimotor records or programs.

Rule learning Amnesic patients can learn and apply mathematical rules, such as the Fibonacci rule (Kinsbourne & Wood, 1975) or the rules for deriving square roots of two-digit numbers (Charness, Milberg, & Alexander, 1988). Amnesic patients with lesions restricted to cortical or diencephalic parts of the hippocampal circuit may also normally acquire and retain recursive rules necessary for solving puzzles like the various versions of the Tower of Hanoi (Cohen, 1984; Moscovitch, Osimani, Wortzman, & Freedman, 1990; Saint-Cyr, Taylor, & Lang, 1988). Amnesic patients can even learn to write simple computer programs (Glisky, Schacter, & Tulving, 1986).

Implicit derivation and application of rules that require planning and monitoring of responses are dependent on the frontal lobes. The Tower of Hanoi is such a goal-directed task. Predictably, patients with focal frontal lesions have difficulty with it (Shallice, 1982), as do patients with frontal dysfunction that accompanies degenerative diseases of the basal ganglia (Butters et al., 1990; Saint-Cyr et al., 1988). The difficulty that Korsakoff patients have in solving Tower of Hanoi problems is attributable more to their impaired frontal-lobe functions than to their amnesia (Joyce & Robbins, 1991). Korsakoff patients, however, may not be deficient at learning mathematical rules (Kinsbourne & Wood, 1975) if they do not have to be derived and their application provides little opportunity to diverge from the goal-directed path (Moscovitch, 1984).

Independence of procedural and item-specific implicit tests The evidence from studies of patients with neurological disorders indicates that performance on many implicit procedural tests is independent of performance on implicit perceptual or conceptual item-specific tests. Studies of normal people support these conclusions. Using an anagram-solving task, McAndrews and I (1990) showed that studying a target and learning a solution rule without awareness contributed additively to the speed and accuracy of solving anagrams. More recently, Schwartz and Hashtroudi (1991) showed that the general perceptual skill involved in learning to read perceptually degraded letters affected perceptual identification of words independently of whether the target item was studied.

4 IMPLICATIONS OF THE MODEL AND COMPARISON WITH OTHER MODELS AND FRAMEWORKS

In the following sections, I will explore some of the implications of the model I presented, determine how consistent they are with the available evidence, and, where evidence is lacking, suggest studies that could provide useful information. I will compare the model with others and discuss ways in which the various models can be evaluated.

4.1 Perceptual Item-Specific Tests: Implications

The hypothesis that long-lasting effects of repetition priming result from the reactivation of perceptual records in perceptual-input modules accounts for a variety of findings.

Modality Repetition-priming effects are modality-specific if input from different modalities activate modules that operate in different domains. Thus repetition-priming effects for written and spoken words are diminished if they are presented in different modalities at study and test (Roediger, 1990; Schacter, 1992; Tulving & Schacter, 1990), because there are separate input modules for spoken and written words. I should note that the crucial factor in the model, however, is not modality per se but domain specificity. If the domain of the module includes information that crosses modalities, then strong cross-modal repetition priming should be observed for some material. A possible candidate is the perceptual-speech module whose domain, according to some theorists, is the speech gesture—not a particular set of acoustic features but the intended gesture that the wave form conveys (Liberman and Mattingly, 1989). This means that the same information can be conveyed not only through sound but also through vision, as in lip reading (McGurk & MacDonald, 1976). Thus the effects of cross-modal repetition priming might be observed for vocal (auditory) and lip-reading (visual) speech (Campbell, Landis, & Regard, 1986), since both are encoded by a single speech module.

Format Even when stimuli are presented in the same modality, the effects of repetition priming are diminished if the stimuli are represented in different representational formats at study and test. Priming from pictures to words (and vice versa) is very weak (Roediger, 1990; Roediger & McDermott, 1993), as would be expected if separate modules exist for pictures and words.

The results are more complicated when stimuli are in the same format but different tokens of the same item are presented at study and test. For line drawings of real and novel objects, if crucial features are visible, the effects of repetition priming are maintained between study and test across transformations of size, reflection, orientation, and foreshortening (Biederman & Cooper, 1991, 1992; Cooper, Biederman, & Hummel, 1992; Cooper, Schacter, Ballesteros, & Moore, 1992; Jolicoeur, 1985; Jolicoeur & Milliken, 1989). Changing exemplars between study and test, say from one kind of dress or airplane to another that looks quite different, reduces the repetition-priming effect substantially. Similarly, in tests of lexical decision, naming, and perceptual identification, changes in surface features of written words, such as font and color, have little effect on repetition priming (Carr, Brown, & Charalambous, 1989). On the other hand changes in the language in which the word is written greatly reduces repetition effects (Kirsner & Dunn, 1985). These findings are consistent with the hypothesis that input modules and their perceptual records store information about particular objects rather than generic objects (a particular dog or dress rather than protypical ones, as Fodor, 1983, assumed) and about their invariant properties rather than their surface features. The effects of repetition priming can thus tolerate changes in surface features so long as the structurally invariant properties of the stimulus are similar at study and at test.

Evidence from other studies, however, is contradictory. On tests of visual-word-stem or visual-word-fragment completion, changes in surface features reduce repetition-priming effects (Hayman & Tulving, 1989). Changes in voice and other acoustic features have similar effects on auditory versions of word-stem completion (Schacter, 1992, this volume). Presenting different degraded versions of the same line drawing at study and at test also reduces repetition effects in comparison with the condition in which identical versions are presented on both occasions (Snodgrass & Feenan, 1990; Srinivas, 1993).

On the basis of these latter findings, a number of investigators have proposed that repetition-priming effects are *hyperspecific*, in the sense that the stored representations are accessible through highly specific cues, so that any alteration, even in sensory features, is likely to lead to diminished repetition effects (Roediger, 1990; Squire, 1992, this volume; Tulving & Schacter, 1990). The available evidence, however, suggests that extreme hyperspecificity may be peculiar to studies in which the stimuli are fragmented or degraded. As a result, the gestalt of the target is broken, making it difficult to recover a structural description of it. Under such conditions, more precise, specific information is needed to reactivate the perceptual record of the target than when a stimulus is presented intact.

A related explanation is that the processes involved in cleaning up the degraded stimulus are separate from those involved in forming or reactivating a perceptual record (Schwartz & Hashtroudi, 1991; Snodgrass, 1989). McAndrews and Moscovitch (1990) and Schwartz and Hashtroudi; (1991) showed that the two components make independent contributions to the repetition-priming effect (see Moscovitch et al., 1994, for an extended discussion).

A third possibility, suggested by Squire (1992, this volume) and Schacter (1992, this volume), is that hyperspecificity of repetition effects, at least for words, is mediated by right-hemisphere input modules whose perceptual records store information about sensory features. Their suggestion is based on evidence from tachistoscopic (Marsolek, Kosslyn, & Squire, 1992), dichotic-listening (Zaidel, 1985), and PET studies (Squire et al., 1992) that format-specific repetition effects for words show involvement of the right, but not the left, hemisphere. These sensory-sensitive right-hemispheric modules are the mates of corresponding left-hemisphere visual-word-form and phonological-word-form modules that code information about graphemic and phonological features of words, respectively. The evidence for corresponding, but different, left and right modules is consistent with studies of left- and right-hemisphere reading (Coltheart, 1980; Coslett & Saffran, 1989; Moscovitch, 1976, 1981; Patterson, Vargha-Khadem, & Polkey, 1989; Rabinowicz & Moscovitch, 1984; Zaidel & Peters, 1981) and speech perception (see the references in Schacter, 1992, this volume).

An interpretation that combines aspects of the last two proposals is that the right hemisphere specializes in cleaning up degraded perceptual input and delivers the decoded message to input modules. It is the reactivation of these right-hemisphere processes that accounts for a right-hemisphere effect on format-sensitive tests of repetition priming.

Another alternative, suggested by a study by Kinoshita and Wayland (1993), is that the sensitivity to low-level sensory featuers observed on some implicit tests may result from their contamination by explicit-memory processes. They found that only normal people, not amnesic patients, benefitted from having word fragments repeated in the same font, as compared to a different font, at study and at test.

Levels of processing Because perceptual records are presemantic and because modules are informationally encapsulated, the depth to which a stimulus is processed should have no influence on repetition-priming effects. In contrast to explicit tests of memory, where information to deep semantic levels enhances performance considerably, levels-of-processing manipulations have only a small effect on implicit perceptual tests in normal people (for reviews, see Roediger & McDermott, 1993; Schacter, 1992; this volume). This residual but consistent effect of level of processing is probably caused by contamination of ostensibly implicit tests by explicit retrieval strategies. In normal people unaware that their memory is being tested, even small levels-of-processing effects are eliminated (Bowers & Schacter, 1990; but see Graf, Squire, & Mandler, 1984, for amnesia, and Howard, Fry, & Brune, 1991).

Attention and consciousness The uptake of information by input modules is obligatory and requires minimal attention or cognitive resources (see the discussion in Moscovitch & Umiltà, 1990, on different types of modules). Consequently, manipulation of attention and even of conscious awareness at the time of encoding should have much less effect on performance on implicit tests of memory than on explicit tests. The mere uptake of information by the module is sufficient to modify it and leave a perceptual record of the stimulating event. This prediction is confirmed by evidence of substantial and long-lasting perceptual repetition effects in studies in which the stimulus is so degraded that the subject is often not aware of it and his explicit recognition of it is no better than chance (Merikle & Reingold, 1991; for a summary of studies, see Moscovitch & Bentin, 1993). Similarly, engaging attention by having subjects perform a demanding concurrent task at study has relatively little influence on performance on perceptual implicit tests but marked influence on performance on explicit tests (Eich, 1984; Jacoby, Woloshyn, & Kelley, 1989; Parkin, Reid, & Russo, 1990). Most impressive of all are a number of reports that repetition priming can be observed for items that are picked up even while the individual is anaesthetized (Kihlstrom, Schacter, Cork, Hurt, & Behr, 1990; Kihlstrom & Conture, 1992; Bonke, Fitch, & Millar, 1990).

Interference and speed of acquisition These two properties, though not derivable from notions of modularity, may also be crucial features of perceptual repetition priming. Registration is rapid and can occur in the first trial. A single brief exposure to the stimulus may be sufficient to produce asymptotic performance on tests of perceptual repetition priming (Challis & Sidhu, 1993; Schacter et al., 1991), though some studies have reported that multiple presentations can improve performance (Bentin & Moscovitch, 1988; Rueckl, 1990). The effects of perceptual repetition priming are not very susceptible to interference (Graf & Schacter, 1987), though additional studies are needed to confirm this finding. I will discuss these aspects of repetition priming more fully below.

4.2 Perceptual Item-Specific Tests: Comparison with Human Models

The framework I proposed to account for performance on item-specific perceptual and conceptual tests of memory has much in common with the proposals advanced by Squire (1992, this volume) to explain repetition priming and by Johnson (1992; Johnson & Chalfonte, this volume) to explain perceptual learning. Squire suggests that repetition-priming effects are mediated by neocortical structures involved in picking up, decoding, and storing presemantic stimulus information. His proposal that repetition-priming effects are likely mediated by the right-hemisphere goes farther than I am willing to venture at the moment. Johnson's approach is a more functional, process-oriented one than mine, though clear similarities are discernable between her perceptual subprocess P-1 and P-2 and the processes that Umiltà and I presume to be mediated by perceptual-input modules and first-order interpretative central systems (Moscovitch & Umiltà, 1990, 1991). The primary difference between our view and hers is that the separate perceptual modules we propose are distinguished from each other on the basis of informational content, with different modules for written and spoken words, faces, objects, voices, and so on. Her distinctions concern processes that in principle can cut across these various representations. Aside from the question of whether she has correctly identified the appropriate subprocesses (many of them sound too much like a description of what the subject does, e.g., placing, identifying, tracking), it may be that what determines the representational content of the module are the distinctive subprocesses that constitute its operation (see Farah, 1994). Repetition-priming effects occur because these processes are reiterated more quickly with repetition. It remains to be seen whether a processing account or representational account, or some combination of the two, best describes repetition-priming effects.

My idea that perceptual repetition-priming effects are mediated by a perceptual input modules most closely resembles Schacter's (1992, this volume) idea that they are mediated by a presemantic perceptual representation system (PRS). Both the PRS and perceptual-input modules are domain-specific and presemantic. One might even venture that the other criteria of modularity (informational encapsulation and shallow output) are implicitly assumed to apply to the PRS, though Schacter may prefer to maintain a more neutral, pragmatic stance in this regard. My commitment to a more principled notion of modularity allows me to place memory into a broad, unifying framework of modules and central systems, from which I can derive organizational principles about episodic memory as well as repetition priming.

In another sense, the component-process framework I have advanced is more flexible than Schacter's PRS. According to my framework, the magnitude of repetition-priming effects depends on the overlap between the components enlisted at study and those recruited at test (Moscovitch et al., 1986; Witherspoon & Moscovitch, 1989). Although reactivation of perceptual or semantic records may be crucial, the overall effect of repetition priming depends as well on the contribution of processes involved in gaining access to the record, as well as subsequent decision and response processes following reactivation of the record. Consideration of all the components is necessary to help account for the independence observed among different repetition-priming tests within the same domain, such as between fragment completion and perceptual identification (Witherspoon & Moscovitch, 1989), or even between different fragments of the same word (Hayman & Tulving, 1989).

Last, it may be worth reiterating that *not* all implicit tests of memory implicate the input modules or the PRS, as Baddeley (1992, this volume) seems to assume. Tulving and Schacter (1990), Schacter (1992, this volume), and I (1992a, this volume) have distinguished between perceptual and conceptual repetition effects. Beyond this, I have also indicated that some implicit tests are best conceived as procedural, of which various subtypes exist and which are mediated by neural components that differ from those involved in item-specific tests (see also Squire, 1992, this volume; Butters et al., 1990).

4.3 Perceptual Item-Specific Tests: Comparison with Animal Models

Reserachers working on animal models of hippocampal function were the first to promote the idea that there are at least two distinct memory systems: one that involves the hippocampus and related structures and another that is extrahippocampal (see Nadel, 1992, this volume). Their theoretical and research program was so successful that there is now hardly anyone conducting research on animals who would dispute their general claim. (This is in marked contrast with the current state of affairs in studies of normal human memory.) As the essays on animal models in this volume illustrate, what is at issue now is how best to describe the properties, operation, and function of the different memory systems.

In discussing the nonhippocampal memory system, many of these authors assert or assume that there is a close correspondence between animal and human models (Eichenbaum, 1992, this volume; Lynch & Granger, 1992, this volume; Nadel, 1992, this volume; Rudy & Sutherland, 1992, this volume; Squire, 1992, this volume). In particular, they draw comparisons between the spared memory abilities of animals with hippocampal damage and the performance of amnesic and normal people on perceptual repetition-priming tests. The implication in making these comparisons is that the preserved memory capacities of the rat and monkey are mediated by the same functional and structural systems that mediate repetition-priming effects in humans.

Although it is appealing for all kinds of reasons to hold this position, a number of important discrepancies between animal and human studies give one pause. Because the presumed or hoped-for similarities are discussed at length by some (Rudy & Sutherland, 1992, pp. 213–215; Squire, 1992, pp. 238–240) or noted briefly by others (Eichenbaum, 1992, this volume; Lynch & Granger, 1992, this volume; Nadel, 1992, this volume), I will not dwell on them here. Instead, I will focus on some of the inconsistencies.

Interference Nadel (1992, this volume) and especially Olton and Shapiro (1992; Shapiro & Olton, this volume) note that the hippocampus is necessary for reducing interference in memory. According to them, memory representations not mediated by the hippocampus are therefore much more prone to interference than those that are mediated by it. An extensive literature on learning and memory in rats and monkeys with hippocampal lesions generally supports this assertion.

On the basis of the implied correspondence between animal and human models of memory, one might infer that repetition-priming effects are much more susceptible to interference than explicit tests of memory, since only the latter are mediated by the hippocampus. The evidence on this point is contradictory but potentially revealing.

Tests of *A-B*, *A-C* paired-associate (negative-transfer) learning have been used to compare the effects of interference on implicit and explicit memory. In one set of studies, subjects learned a set of highly related words, *A-B* (e.g., *soldier-battle*) and then studied another similar set, *A-C* (e.g., *soldier-army*). Their memory for the *A-C* list was then tested. In the explicit version of the test, subjects had to try to recall the second member of the *A-C* pair when presented with the first, whereas in the implicit version they merely had to respond with the first word that came to mind. In normal people, interference from the *A-B* list was greater in the implicit version than in the explicit version (Mayes, Pickering, & Fairbairn, 1987; Winocur & Moscovitch, in press). High levels of interference on the explicit version were found only in amnesic people and people with left temporal lobectomy (see table 2).

Graf and Schacter (1987) combined the stem-completion technique with the negative-transfer paradigm. They had subjects study two sets of unrelated word pairs, *A-B* followed by *A-C*. Memory for the *A-C* association was then tested by presenting the first number of the pair and the initial three-letter stem of the second member. In the implicit version, subjects completed the stem with the first word that came to mind, whereas in the explicit version they attempted to complete it with the word they remembered as being associated with the first member. In contrast to other negative-transfer studies, interference was greater in the explicit version than in the implicit version.

Contrary to the view derived from animal models, these studies indicate that susceptibility to interference is not a universal characteristic of performance

Table 2 Mean response words recalled (maximum = 12) from the *A-C* or *A-B* list of associations on an explicit or implicit test of negative transfer

	Memory test						
	Explicit					Implicit	
List	Young	Old	R temp	L temp	Amnesic	Young	Old
(*N*)	(12)	(12)	(12)	(7)	(5)	(12)	(12)
A-C	9.8	9.0	10.6	7.4	3.5	3.8	2.9
A-B	1.6	2.1	0.3	2.7	6.5	4.3	4.8

Note: Subjects were normal young and old people, patients with right temporal (R temp) or left temporal (L temp) lobectomies, and amnesic patients.

on tests of memory not mediated by the hippocampus. As an implicit test of memory, stem completion is considered to be primarily perceptual, whereas the related association test is conceptual. One possible conclusion is that perceptual implicit tests are relatively immune to interference, whereas conceptual ones are especially susceptible. More studies are clearly needed to test the generality of this observation and to examine the effects of interference on procedural implicit tests about which almost nothing is known. Whatever the outcome of these studies, it is evident that there is no simple correspondence with respect to interference between nonhippocampal memory in animals and performance on implicit memory tests in humans. No common set of principles can be applied to all of them, as some animal-memory models imply by considering nonhippocampal memory systems as a unit governed by common principles or rules. A similar point can be made concerning the speed with which memories are acquired.

Speed of acquisition Nadel (1992, p. 182, this volume), in distinguishing between locale and taxon learning, considers the speed with which information is acquired to be a distinguishing characteristic of the two systems. Learning is all or none, and acquisition and extinction are rapid, in the hippocampally based locale system, whereas learning is incremental, and acquisition and extinction are slower in the nonhippocampally based taxon system. Although he concedes that not all forms of taxon learning are slow, the distinction between a fast and a slow system is central to his analysis and those of other investigators building computational models of memory (see Nadel, 1992, p. 186). Squire (1992, this volume) makes a similar point regarding the formation of new associations (see below).

Although Nadel did not specifically consider performance on perceptual implicit tests as a type of taxon learning, such performance does demonstrate nonhippocampal learning. Indeed, as I noted earlier, perceptual implicit tests have become the prototypical test of nonhippocampal learning in the human-memory literature. It is of interest to know, therefore, whether it satisfies Nadel's criterion that nonhippocampal learning (acquisition of information) is incremental and slow.

A number of studies on repetition priming for words and for line drawings of common objects, and of novel, meaningless forms, have shown that a single brief presentation is sufficient to produce a long-lasting priming effect (for reviews, see Moscovitch, Vriezen, & Goshen-Gottstein, 1993; Moscovitch, Goshen-Gottstein, & Vriezen, 1994; Roediger & McDermott, 1993). Moreover, increasing the duration of exposure or the number of presentations typically has little effect on repetition priming (Challis and Sidhu, 1993; Schacter et al., 1991), except perhaps when nonsense words (Musen & Squire, 1991) and novel faces (Bentin & Moscovitch, 1988) were used. On the other hand, these variables have a marked beneficial effect on explicit tests of memory, which are presumed to be hippocampally based. Contrary to Nadel, these studies indicate, therefore, that registration, the formation of perceptual records, can be rapid and nonincremental and can occur without the participation of the hippocampus.

4.4 Learning versus Registration: A Difference between Animal and Human Studies of Nonhippocampal Memory

The most likely explanation for the lack of correspondence between tests of nonhippocampally mediated memory in animals and tests of repetition priming in humans is that the two types of tests measure different things. Tests of repetition priming measure registration, i.e., the formation of rapid perceptual records. The individual is never asked to learn anything actively or to form new associations. If associations are formed, or registered, they are purely perceptual (see section 4.5). At the phenomenological level, the individual believes that he or she is merely perceiving or identifying a stimulus, such as a word or picture. Sometimes this activity is accompanied by the sense that some perceptions are more fluent (Jacoby, 1983), clearer, or longer (Witherspoon & Allen, 1985) than others and that some words or pictures come more easily to mind, though many subjects are not aware even of this.

By contrast, in the vast majority of animal studies, the animals have to learn to attach some significance to the stimulus and associate it with a response (but see Lynch & Granger, 1992, p. 191). As yet there are few animal studies, if any, designed to test registration independently of learning. Though this type of rapid acquisition and retention of perceptual (and perhaps semantic) information very likely also occurs in animals, no techniques have been devised to let the experimenter know that their perception of a stimulus or event improves with repetition.

In principle, it should not be difficult to demonstrate registration, especially in monkeys. Rather than have the animals learn an association between a particular response and a target stimulus, have the animal emit an already established response in the context of a perceptual-judgment task. One possible procedure is to train a monkey to choose the clearer of two degraded stimuli. Having been trained, the monkey could then view a series of stimuli that are not degraded. This is the study phase. Later, during the test phase, previously studied stimuli are paired with unstudied stimuli, but both are now equally degraded. As in training, the monkey has to choose the one that appears less degraded. If perception is influenced by previous exposure to one of the stimuli, monkeys, like humans, should choose the previously studied stimulus as being the clearer of the two. A similar procedure may be used with smell in rats, though choosing on the basis of intensity, saturation, or even pleasantness would replace clarity.

Something like this has been tried with rats by Winocur (1990) and by Fleming and Winocur (personal communication). They exposed rats to a novel smell at study. In Winocur's study, the smell was that of a new food on the breath of a rat with which the experimental animal interacted socially. When later the experimental rats were exposed to two new foods, they chose to eat the one that carried the same smell that they had encountered earlier. Rats with hippocampal lesions could *register* the information rapidly and also showed the same preference as control rats when tested a day later. Their retention, however, was not as good, which indicates that there may also be a hippocampal component to this process. In another study, Fleming and Winocur (personal communication) exposed female parturient rats to pups for one hour, an exposure that is sufficient to elicit nonhormonally mediated maternal behavior as long as ten days later. Rats whose hippocampus was lesioned either before or after the initial exposure behaved no differently from normal rats.

These studies indicate that it is possible to demonstrate rapid, nonincremental acquisition of perceptual information in animals with hippocampal lesions. They also suggest, contrary to Nadel, that the rapid acquisition of taste aversions may be not an exception but the rule for all types of nonhippocampally based perceptual learning if the rat or monkey already has a repertoire that can readily reveal the information it has registered (Lynch & Granger, 1992, this volume).

The corollary to this hypothesis is that the slow, incremental learning that is observed results from nonhippocampal processes other than those that are not strictly perceptual. I suggest two candidates. One is that what is slow and incremental is the formation of nonhippocampally based stimulus-response associations, not the registration of stimulus input. These associations may be mediated by cortical-neostriatal networks, as others have suggested (Mishkin & Appenzeler, 1987; Packard & White, 1991; Squire, 1992, this volume). They also have their counterpart in humans' relatively slow, incremental acquisition of sensorimotor procedural tasks (Moscovitch, 1992a, this volume, 1992b). As in rats and monkeys, damage to neostriatal structures, particularly the caudate, impairs performance on these tasks (Butters et al., 1990).

Another candidate for slow, incremental learning may be the creation of modules, rather than the formation of perceptual records in preexisting modules. In a critique of Fodor's ideas on modularity, Umiltà and I proposed that there might be three types of modules, the third type being experientially assembled (Moscovitch & Umiltà, 1990). The creation of this type of module, we believe, involves a long and protracted process. The word-form system is one such module. Although the creation of new modules in an experiment is unlikely, it remains a candidate for a nonhippocampal learning process, at least in real life and possibly in the laboratory.

4.5 Learning New Associations between Stimuli: Repetition Priming for Novel Pairs of Items Is Perceptual

This brings us to the question of whether perceptual-input modules can support the formation of new associations between arbitrarily different stimuli. Nadel (1992, this volume) and Squire (1992, this volume) have asserted that "nondeclarative [nonhippocampally based] memory can support the gradual and cumulative acquisition of new associations, as in classical conditioning, but does not seem well adapted for acquiring novel associations rapidly" (Squire, 1992, p. 237). Though there is some truth to this assertion, it needs to be qualified.

Perceptual-input modules and perceptual-representation systems are conceived as dealing with single items or units: a word, an object, a face. Little consideration is given in theories as to whether perceptual-input modules can form perceptual records of conjoined stimuli. If the stimuli are from the same domain, there is no compelling theoretical reason why newly associated items might not be retained as domain-specific perceptual records in the way single items are. The question is therefore an empirical one: Is there evidence of perceptual repetition-priming effects for new associations?

Previous attempts to find *associative repetition-priming* effects have yielded inconclusive results in studies of both normal and amnesic people (see reviews in Lewandowsky, Kirsner, & Bainbridge, 1989; Moscovitch, Goshen-Gottstein, & Vriezen, 1994; Moscovitch, Vriezen, & Goshen-Gottstein, 1993). Even on the most reliable of the tests, word-stem completion, modality-specific associative priming effects were not found in many severely amnesic patients (Cermak, Bleich, & Blackford, 1988; Graf & Schacter, 1985; Mayes & Gooding, 1989; Schacter & Graf, 1986; Shimamura & Squire, 1989) nor in normal people who were truly unaware of the relation between study and test pairs (Bowers & Schacter, 1990, but see Howard et al., 1991). Overall, these studies suggest that associative priming in stem completion has an explicit-memory component mediated by the hippocampus and related structures.

Speeded reading may be a better implicit test of memory than stem completion because its rapid pace may not allow the intrusion of explicit retrieval strategies. Using speeded reading, Moscovitch et al. (1986) had subjects study pairs of radomly associated words and at test had the subjects read lists of studied pairs, new pairs, or old words in new pairings. All items were slightly visually degraded at test to slow down reading speed and allow the priming effect to emerge. We found that reading speed was fastest for the studied pairs when the results from amnesic patients and normal people were combined, which indicates that repetition-priming effects can be found for newly formed associations. We obtained a similar but even stronger result using sentences in which words could be interchanged to produce, at test, sentences that contained old words in new combinations (recombined sentences). Reading speed was faster for the old, intact sentences than for recombined sentences. Light and LaVoie (1993) also found that one or two trials were sufficient to produce associative repetition priming in the word-pair task in normal young and old people, but Musen and Squire (1993) needed to give several learning trials to obtain comparable results. It should be noted that Musen and Squire's scoring and testing procedures differed somewhat from those of Moscovitch et al. and that they never attempted to replicate the sentence

Table 3 Reaction time to make lexical decisions about pairs of newly associated words in the intact, recombined, and control conditions

	Condition		
Modality	Intact	Recombined	Control
Same	860	924	987
Different	907	917	1,019

Note: Study and test pairs were presented in the same or a different modality.

Table 4 Reaction time in milliseconds to make lexical decisions about pairs of newly associated words in the intact, recombined, and control conditions

	Condition		
Encoding	Intact	Recombined	Control
Elaborate	918	971	1,063
Shallow	916	947	998

Note: Encoding at study was elaborate or shallow.

study, which produced the stronger effect (but see Musen & Squire, 1991, for a comparable study with comparable results). In a subsequent experiment using perceptual identification as the measure, Musen and Squire (1993) did find a weak associative-priming effect but, again, only when the results from amnesic and normal control subjects were combined.

The partial successes of the previous studies and the indication that priming of new associations may be perceptual prompted Goshen-Gottstein and me (1992) to design a new procedure for obtaining reliable effects from associative repetition priming. As before, subjects studied simultaneously presented written pairs of randomly associated words. At test, old pairs, new pairs, and recombined pairs were again presented simultaneously and subjects had to indicate whether both members of each pair were words. On negative trials, at least one member of the pair was a pronounceable, but meaningless, letter string.

This modified lexical-decision task produced reliable effects from associative repetition priming in normal people (see table 3). Changing modalities from auditory to visual between study and test eliminated the repetition-priming effect, which indicates that it was likely mediated by domain-specific perceptual-input modules. Also, the effect was almost as great with shallow as with deep levels of processing at study (see table 4). Rueckl and Marsolek (personal communication) found similar results with the same procedure. Using this procedure, we have also obtained preliminary evidence of repetition effects in amnesic patients with confirmed bilateral medial-temporal-lobe lesions and in patients with right or left temporal lobectomies that included large hippocampal excisions.

These results thus suggest that perceptual input modules or the PRS can support the rapid formation of new, but domain-specific, associations without hippocampal involvement. Being represented as domain-specific perceptual records, these new associations have the same status as other perceptual records. They cannot be conjured up voluntarily as new memories but only elicited as percepts by perceptually similar input. In short, they are data-driven. They lack the mnemonic attributes of hippocampally mediated associations that we can recollect consciously. Because they are consciously accessible, we can represent them across modalities and manipulate them to serve our needs. I therefore agree with Eichenbaum (1992, this volume) that the hippocampus is necessary for the formation of flexible mnemonic associations that are not strictly bound to perceptual records and that contain information that can be integrated across domains.

4.6 The Hippocampal Module: Implications and Comparisons with Other Models

The idea that the hippocampus is a module that satisfies the same criteria as perceptual input modules implies that a component of conscious recollection is no more intelligent or under voluntary control than perception. Thus at the core of conscious, episodic memory lies an associative memory component that is informationally encapsulated (cognitively impenetrable) and for which encoding and retrieval are obligatory and not under voluntary control. This claim alone is sufficient to distinguish my proposal from most other models dealing with human memory (Johnson, 1992; Johnson & Chalfonte, this volume; Squire, 1992, this volume; Baddeley, 1992, this volume), which do not differentiate clearly between strategic and associative processes in memory.

The existence of an associative memory module is, however, compatible with animal and neural-network models of memory and the hippocampus, which are associative and content-addressable (Eichenbaum, 1992, this volume; Lynch & Granger, 1992, this volume; Metcalfe, Cottrell, & Mencl, 1992; Metcalfe, Menel, & Cottrell, this volume; Rudy & Sutherland, 1992, this volume; Squire, 1992, this volume; Teyler & Di Scenna, 1986). At issue is what kind of information is encoded, stored, and retrieved by this associative module and how these memory functions are implemented.

Is hippocampally based memory spatial, conscious, or both? Anatomical and conceptual issues According to Nadel (1992, this volume), the hippocampus is specialized for dealing with spatial information. All the other investigators, however, consider the spatial-memory function of the hippocampus as only a particular instantiation of its much broader function, which is to bind separate representations of stimuli into relational or configural associations. My view (Moscovitch & Umiltà, 1990, 1991; Moscovitch, 1992a, 1992b) is that the hippocampus and its related structures encode any information derived from input that is consciously apprehended, in the sense that it receives full attention. Because I make no distinction between spatial information and other types of information, my view is closer to that of the other authors than to Nadel's.

It may be possible to reconcile the two views if anatomical considerations are taken into account. The hippocampal complex consists of a number of related structures that include the fimbria, fornix, entorhinal and perirhinal cortex, subiculum, and parahippocampal gyrus. It is becoming increasingly evident that damage to these structures have different effects on memory (Lynch & Granger, 1992; Nadel, 1992, this volume; Squire, 1992, this volume), though there is far from universal agreement on how best to characterize these differences. It may prove to be the case that damage to some structures are associated with spatial memory loss and damage to others with loss of nonspatial relational memory.

Research on humans may be relevant in this regard. Consistent with the specialized functions of the cerebral hemispheres in humans, only damage to the right hippocampal region is associated with spatial memory loss (Pigott & Milner, 1993; Smith, 1989; Smith & Milner, 1981, 1989). Left-hippocampal lesions are associated with loss of memory for verbal material, which indicates that the hippocampus can in principle mediate memory for nonspatial information (Milner, 1974, but see the discussions by O'Keefe, 1985, and O'Keefe & Nadel, 1978, on this point). In the region of the right hippocampus, anterior, medial lesions exacerbate the spatial deficits found after lesions to the temporal lobe (Smith, 1989) but to obtain a severe topographical-memory loss, the damage must include the right, posterior parahippocampal gyrus and subiculum (DeRenzi, 1982, chap. 8; Habib & Sirigu, 1987; Van Der Linden & Seron, 1987). Indeed, damage to that region may produce a selective loss of spatial memory with little effect on nonspatial functions. The deficit seems also to pertain to newly acquired spatial information, with old information being relatively preserved. More research on the effects of selective damage to different portions of the hippocampal complex in humans and in other animals is needed to adjudicate among the various hypotheses regarding the function of this region.

A tantalizing possibility is that consciousness and space are closely linked, in the sense that our conscious awareness always has a spatial component (Nadel, 1992, this volume; O'Keefe, 1985). Space is the medium in which all events occur. In this sense, space provides the context for the events we experience phenomenologically. If the hippocampus obligatorily processes all events of which we are conscious, as I have proposed, it must of necessity handle spatial information. To speculate further, it may be that structures involved in processing spatial information provide the primordial substrate for consciousness.

Recovered consciousness: A proposal to explain why conscious recollection is associated with hippocampal memories Before continuing to discuss the relation between consciousness and memory, I should indicate what sense of the word "consciousness" I wish to employ. In this context, I use the word "consciousness" in the ordinary-language sense of being conscious of something. This sense of consciousness is interchangeable with phenomenological awareness. With regard to memory, it means that the individual is aware of a memory rather than a percept or a thought. In the context of an experiment, the individual is aware of having a memory of a stimulus that he or she perceives or recalls, i.e., that was experienced before.

The general concensus that emerges from these chapters is that the hippocampus (and related structures) binds together the neural elements that make up our experience of an event into a multimodal, permanent memory trace. What is up for discussion concerns the nature of the content of that trace: is it spatial, relational, abstract, and so on? What has been neglected in this discussion, and what I wish to emphasize, is the relation of consciousness to memory. According to my model, the hippocampal component picks up only information that is consciously apprehended. The hippocampal component thus binds the neural elements that mediate the information that constitutes conscious experience. This includes the collection of records or engrams of the modules and central systems whose output form the content of conscious experiences as well as the elements that make experience conscious. In this way, consciousness is bound by the hippocampal component along with other aspects of an experienced event and becomes an intrinsic property of the memory trace.

At the neurophysiological level, one can think of collections of neurons or cell assemblies whose firing patterns determine the different properties of an event we experience: its color, form, texture, spatial relations, and so on. Insofar as conscious awareness is a quality of our experience, it too must have neural correlates that interact with other cell assemblies or are part of them. This network of cell assemblies, including the neural correlates of consciousness, are bound together in the memory trace.

When the memory trace is reactivated at retrieval, consciousness is recovered along with other aspects of the experienced event. This is just another aspect of the encoding-specificity principle (Tulving, 1983). *Consciousness in, consciousness out.*

It is the recovery of a trace imbued with consciousness that makes it feel familiar and immediately recognizable as something previously experienced. This *recovered consciousness* is the signal that distinguishes a memory trace from thoughts and perceptions (which involve *on-line consciousness*) and is at the core of conscious recolleciton. With respect to remembering, and perhaps with respect to no other function, consciousness is an inherent property of the very thing we apprehend.

I think this type of conscious awareness is primitive; it is something that enables an organism to experience an event rather than merely to live through it or react to it. For example, it is what underlies the difference between true sight and "blindsight" (caused by cortical lesions that leave the individual blind in terms of felt experience but nonetheless able to respond to visual stimuli of which he or she claims to be unaware) or between other forms of explicit and implicit knowledge (Schacter et al., 1988). Because it is primitive, I think that nonhuman mammals, and perhaps other species, possess this type of conscious awareness, and it enables them to recognize a memory as such. (For further discussion, see Moscovitch, 1994; O'Keefe, 1985.)

Organizational and historical contexts Because the hippocampus is associative and modular, the information handled by it is ordered according to principles of similarity and simple spatial and temporal contiguity. The hippocampus lacks the capacity for true temporal organization, in which events occurring over widely spaced intervals can be related to each other either sequentially or with respect to an overarching theme. Lynch and Granger (1992, this volume) propose that the hippocampus is necessary for connecting events across space and time, but they are concerned with time intervals that span only a few seconds, well within the realm of simple temporal contiguity but far short of the range of our capacity for temporal ordering.

Lynch and Granger's reference to recency memory and recency mechanisms as crucial components of the hippocampal complex is puzzling. I am assuming that they are referring to memory for recently occurring events or stimuli rather than to a mechanism for determining which events are the most recent. There is good evidence that the latter function, and temporal ordering in general, is affected by frontal rather than hippocampal damage (Milner, Petrides, & Smith, 1985; Shimamura, Janowsky, & Squire, 1991; Vriezen & Moscovitch, 1990). Patients who are poor at making recency judgements can indeed show relatively well preserved memory for recently occurring events; they just cannot remember their order.

Cohesion and consolidation: The formation and preservation of long-term memory traces The term *consolidation* has traditionally referred to any process involved in making long-term memory traces resistent to disruption by amnestic agents. Just as it is important to distinguish between *registration* and other processes involved in the formation of long-term memories, so it is important to distinguish between two types of consolidation processes, both of which involve the hippocampus. The first type is rapid and involves the formation of long-term memory traces by the hippocampus. I refer to this process as *cohesion* because it involves hippocampal binding of elements into a memory trace. Once bound, a slower process ensues that makes the memory trace permanent. This second process, which is *consolidation* proper, probably involves tonic input to the hippocampus. It is assumed to be complete when explicit memory for an event can survive disruption by amnestic agents. With this as the marker, consolidation has been estimated to take up to three years in humans (Milner, 1966; Squire & Cohen, 1982), weeks in monkeys (Zola-Morgan & Squire, 1990), and days in rats (Winocur, 1990). Once memory traces are fully consolidated, access to them can be gained via an extrahippocampal route, perhaps involving the frontal lobes (Kopelman, 1989).

The appropriate marker for the time course of cohesion, the formation of hippocampally mediated memories, is their susceptibility to memory loss following temporary disruption or inactivation of hippocampal processes, not hippocampal destruction. Temporary hippocampal disruption can be achieved by electroconvulsive shock, inhibition of protein synthesis, blockage of relevant neurotransmitters, and electrical stimulation. In studies using such methods, the designated procedure is applied at different intervals after the learning episode, and the subject is tested once the effects of the procedure have dissipated. With this as the measure, the estimation of cohesion time is typically on the order of seconds to minutes (for reviews, see Milner, 1970; Squire, 1987). Permanent memory loss for events that occurred at longer intervals is usually associated with extreme trauma, such as severe concussion or coma, which can cause hippocampal damage.

The rapid time course of cohesion is consistent with findings from studies of normal human memory that immediate free recall is mediated by a long-term memory component that must have been rapidly formed. The contribution of this long-term component is revealed, among other ways, in the primacy portion of the serial-position curve. This portion is greatly diminished in amnesia (Baddeley & Warrington, 1970) and in patients with left hippocampal lesions (Moscovitch, 1982), which suggests that the primacy effect is hippocampally mediated.

4.7 The Frontal Lobes and Strategic Tests of Memory: Implications and Comparison with Other Models

Without the frontal lobes, performance on *strategic, explicit,* and perhaps some *implicit* tests of memory is impaired (Milner et al., 1985; Moscovitch & Winocur, 1992a, 1992b; Petrides, 1989; Schacter, 1987; Shimamura et al., 1991). These tests include judgment of frequency of occurrence, self-ordered pointing, conditional associative learning, memory for temporal order, different types of delayed response that use a small, repeated set of items, and perhaps release from proactive inhibition. Consistent with my hypothesis, the tests are performed poorly not because the target event is forgotten, as is the case following hippocampal lesions on the very same tasks, but because organization at encoding and strategic search and monitoring at retrieval is deficient in frontal patients. Even recall (Incissa della Rochetta, 1986; Mayes, 1988) and recognition (Delbecq-Derouesné, Beauvois, & Shallice, 1990) are impaired if strategic processes are involved.

As central-system structures, the frontal lobes do not restrict their operation to a specific domain. Memory impairment associated with frontal damage is accompanied by deficits in other domains such as problem solving and attention (Milner, 1964; Stuss & Benson, 1986). One also sees an ordering deficit on temporal memory tasks when frontal patients recount well-rehearsed scripts of daily-life situations (Godbout, & Doyon, 1992) or reconstruct a motor sequence (Kolb & Milner, 1981). Even on memory tests, strategic impairment encompasses recent and remote memories (Moscovitch, 1989; Shimamura et al, 1991), and extends, as well, to information in semantic memory (see Moscovitch, 1992a, 1992b; Moscovitch & Winocur, 1992a, for details).

Memory without organizational or historical context is seen most clearly in confabulation. This disorder is almost always associated with lesions to the medial frontal lobes as well as basal forebrain structures caused by aneurysms of the anterior communicating artery. The behavior of confabulating patients is instructive because it suggests what remembering is like when it relies only on the shallow output from the hippocampal system (Moscovitch, 1989). Confabulations are usually not pure fabrications but often consist of accurately remembered elements of one event combined with those of another without regard to their internal consistency or even plausibility. Sometimes entire events are recalled but placed in an inappropriate context. Temporal order is grossly impaired, even for salient events separated by decades.

As expected, recognition memory in these patients is relatively spared in comparison with recall, which involves strategic, presumably frontally based retrieval processes, in addition to the hippocampal associative retrieval processes that suffices for most recognition tests (Moscovitch, 1989; Parkin et al., 1988; see also Parkin et al., 1993, for a case with similar frontal-system deficits but without confabulation). Recall performance can be improved if the cues that specify the target item are strong enough so that strategic processes need not be invoked (Delbecq-Derouesné, Beauvois, & Shallice, 1990; Parkin et al., 1993). Similarly, recognition can become impaired if performance depends on selecting target items from related interfering material that evokes associative (hippocampal) memories of their own (Delbecq-Desrouesné et al., 1990; Parkin et al., 1993).

Multiple frontal systems As I noted at the outset, the frontal lobes are not unitary but consist of a variety of subsystems, each presumably with different central-system functions. Although distinct neuroanatomical and functional regions have been isolated, it is still difficult to determine what global function to assign to them. Johnson's (1992; Johnson & Chalfonte, this volume) proposal of a variety of different reflective subsystems, as well as supervisory and executive functions, provides a useful framework for research on the frontal lobes. Such research would help determine whether her processing subsystems correspond to similar neuroanatomical subsystems in the prefrontal cortex or whether each is best viewed as a cognitive process that draws on a variety of frontal subsystems for its operation.

4.8 Cognitive Resources: Cortical Modules and the Frontal and Hippocampal Components

Because modules, including the hippocampal component, process information automatically, they are likely to require fewer cognitive resources for their

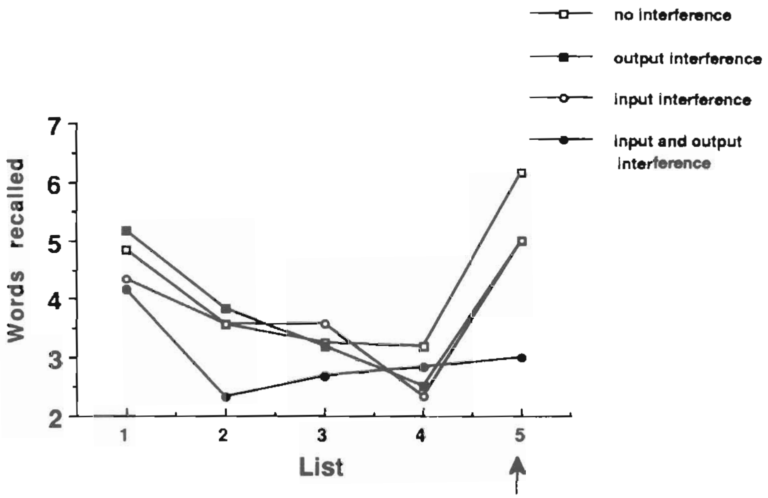

Figure 2 Release from proactive inhibition (PI). The graph shows number of words that college students recalled (of a possible twelve) per trial in various interference conditions. PI was built up on trials 1–4 and released on trial 5. Any word that is recalled within seven items of its presentation is assumed to come from primary or short-term memory, whereas all others are assumed to be recovered from secondary or long-term memory (Tulving & Colotla, 1970).

operation than would strategic central systems (see Moscovitch & Umiltà, 1990, 1991, on the interaction of central systems with a limited-capacity central processor). Interference by a concurrent task at test should be greater for memory tests sensitive to frontal damage than for tests sensitive to hippocampal damage. (Interference at study may affect both types of tests, since it disrupts organization and, if severe enough, may prevent information from being fully available to consciousness so that the hippocampus will not pick it up.)

To test directly the hypothesis of retrieval interference, we designed experiments that compared the effects of concurrent interference on "hippocampal" tests with those on "frontal" tests. The tests were administered either without interference or with interference at study, at test, or on both occasions. The interfering task was sequential tapping of the fingers in the order index, ring, middle, and small.

The tests we chose were Craik and Birtwistle's (1971) version of release from proactive inhibition and the California Verbal Learning Test (CVLT) (see Moscovitch, 1992a, 1992b, in press, for details). Concurrent interference at study and test, but at neither alone, had the predicted effect on both tests: failure to release from proactive inhibition and lower recall and clustering on all the trials on the CVLT (figures 2 and 3). Not affected by interference were the number of words recalled on the first trial in release from proactive inhibition and the improvement with repetition on the CVLT, both of which are presumed to depend on intact hippocampal functions.

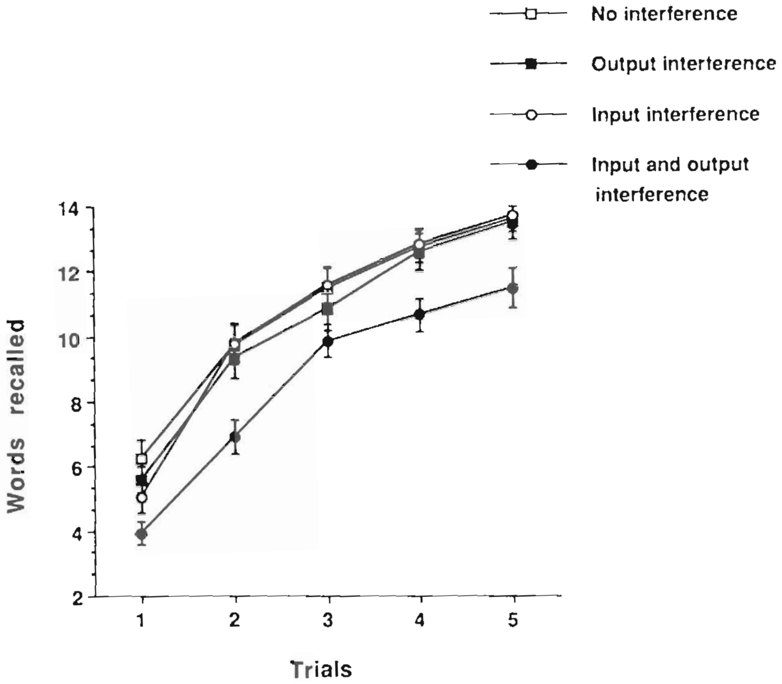

Figure 3 Recall of categorized lists. The graph shows number of words that college students recalled per trial in various interference conditions from categorized lists of the California Verbal Learning Test.

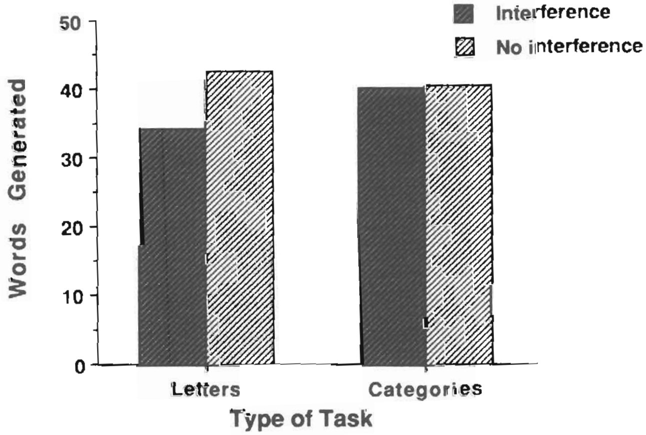

Figure 4 The average number of words subjects generated in 1 minute in a letter (phonemic) and category fluency task with, and without, a concurrent interfering task.

Because the frontal lobes are central-system structures, it was expected that concurrent interference would also affect performance on frontal tests in other domains. As predicted, sequential finger tapping led to a reduction of about 25 percent on a semantic memory test, letter fluency, which is sensitive to left frontal damage, but to less than a 5 percent reduction on category fluency, which is more sensitive to left temporal damage (figure 4).

Although other interpretations of the concurrent-interference studies are possible, the results are encouraging and support the hypothesis that strategic retrieval processes mediated by the frontal lobes are resource-demanding, whereas ecphoric hippocampal processes require less effort by comparison.

5 CONCLUSIONS

A major portion of this chapter was devoted to identifying the components involved in memory and remembering. Dissociation experiments on neurological patients and on normal people provided the main source of evidence for isolating the components and understanding their function. Given my emphasis on dissociations, it is easy to lose sight of the fact that these components, though isolable in principle, are typically highly interrelated. The function of the components is determined not only by their internal organization but also by their network of connections to other components. The interrelatedness of the various components specified in the model helps explain why memory tests (and memory in real-life situations) are not likely to be process (or component) pure when administered to people who are neurologically intact. Performance will depend on the interplay of components and the processes they mediate. By specifying the processes mediated by the various components, the information they represent, and some of the interactions possible among them, I hope that the neuropsychological model I proposed will prove useful in analyzing memory at both the structural and process level in people with normal or impaired memory.

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