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Working Memory Contributions to Human Learning and Remembering

Minireview

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Understanding the cognitive and neural architectures that support learning (memory encoding) and remembering (memory retrieval) is a fundamental goal of human memory research. This endeavor is challenging, as memory is not a unitary system but rather consists of multiple forms of learning and remembering that differ in their functional characteristics and neuroanatomic substrates (Schacter and Tulving, 1994). This minireview considers two forms of memory, episodic memory and working memory. Episodic memory is a form of long-term memory that supports the conscious remembrance of everyday experiences. For example, the ability to remember what you had for dinner last night typically requires retrieval from episodic memory and depends upon having initially encoded that information into episodic memory. Working memory, in contrast, is a transient form of memory that supports the temporary storage and maintenance of internal representations and mediates the controlled manipulation of these representations (Baddeley and Hitch, 1994). For example, mentally rehearsing a phone number so that it is available moments later depends on working memory maintenance operations.

Both episodic memory and working memory are partially subserved by prefrontal cortex. Neuropsychological studies indicate that frontal lesions yield strategic processing deficits that can impair episodic memory (Shimamura, 1995), with some evidence suggesting that these deficits are material specific: left frontal lesions differentially impair episodic memory for verbal material and right frontal lesions differentially impair episodic memory for nonverbal material (Milner, 1982). As with episodic memory, working memory is impaired following frontal lesions (Baddeley and Hitch, 1994), and single-unit recordings in monkeys indicate that prefrontal regions mediate working memory maintenance operations, with some neurons demonstrating a material-specific firing pattern (Wilson et al., 1993).

Recently, application of functional neuroimaging methods with relatively high spatial resolution—positron emission tomography (PET) and functional magnetic resonance imaging (fMRI)—has begun to shed light on the contributions of specific prefrontal regions to episodic and working memory in humans. As findings accumulate, parallels between prefrontal involvement in these two forms of memory are becoming apparent, raising the possibility that prefrontal activation during episodic memory reflects the recruitment of specific working memory processes in the service of episodic learning and remembering (Buckner and Koutstaal, 1998). This minireview briefly considers PET and fMRI evidence regarding the role of prefrontal cortex in episodic memory and highlights the parallels between these results and those from studies of working memory. Two patterns are emphasized. First, studies of episodic memory suggest that activation in inferior prefrontal cortices is associated with the nature of the material being processed (semantic, phonological, visuospatial) rather than the nature of the episodic memory operations being performed (encoding or retrieval). These activations may reflect the recruitment of material-specific working memory operations that support access to, maintenance of, and evaluation of specific event attributes. Second, studies of episodic memory suggest that activation in dorsolateral and anterior prefrontal cortices is material independent and is modulated by episodic retrieval but not by episodic encoding. These activations may reflect the recruitment of material-independent working memory operations that support the manipulation of the contents of working memory.

Inferior Prefrontal Contributions to Episodic Memory

Recent PET and fMRI studies suggest that there are functionally distinct regions in left and right inferior prefrontal cortices that are engaged during both episodic learning and episodic remembering, with the specific regions engaged dependent on the nature of the material being processed (verbal–semantic or visuospatial). These material-specific patterns of activation may reflect the recruitment of material- or process-specific working memory operations.

Verbal–Semantic Material. Episodic learning can occur incidentally or intentionally. During incidental learning, stimuli are processed in a task-directed manner without any intention of learning. For example, semantic aspects of a word may be accessed and evaluated in order to generate an associate of the word (e.g., generating a verb associated with a noun) or to classify the word (e.g., classifying a word as abstract or concrete). Similarly, nonsemantic aspects of a stimulus may be processed during task performance (e.g., classifying a word as printed in upper- or lowercase letters). Such task-directed processing of stimuli results in the incidental encoding of particular event characteristics (e.g., semantic or perceptual attributes). In contrast, during intentional learning, stimuli are processed with the explicit goal of learning them so as to be able to remember them later. A number of processing strategies may be adopted during intentional learning, including semantic elaboration, mental imagery, and rote rehearsal. Importantly, both incidental learning via semantic processing and intentional learning typically yield high levels of subsequent remembering, suggesting that the operations engaged during these conditions enhance later memory.

Neuroimaging studies of episodic learning have primarily examined the encoding of meaningful and nameable stimuli, such as words and pictures of everyday

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Table 1. Prefrontal Regions Active during Episodic Encoding and Retrieval and Posited Working Memory Functions

Region	Brodmann's Area	Episodic Memory Stage	Working Memory Functions
Posterior left inferior prefrontal (LIPC)	44/6	Encoding and retrieval	Phonological access, maintenance, and evaluation
Anterior left inferior prefrontal (LIPC)	47/45	Encoding and retrieval	Semantic access, maintenance, and evaluation
Right inferior prefrontal (RIPC)	44/6 and 45	Encoding and retrieval	Visuospatial access, maintenance, and evaluation
Right dorsolateral prefrontal (RDLPC)	46/9	retrieval	Material-independent manipulation of representations
Right anterior prefrontal (RAPC)	10	retrieval	Material-independent manipulation of representations

objects (Buckner and Koutstaal, 1998). Although activation has been observed in many prefrontal regions during the processing of verbal–semantic stimuli, two regions within left inferior prefrontal cortex (LIPC) consistently demonstrate greater activation during the performance of tasks that yield higher levels of subsequent remembering: a posterior and dorsal region (hereafter termed posterior LIPC) and an anterior and ventral region (hereafter termed anterior LIPC; Table 1). For example, greater activation has been observed in anterior LIPC and posterior LIPC during verb generation, semantic classification, and intentional word learning compared to lower-level controls (Nyberg et al., 1996). Moreover, recent event-related fMRI findings indicate that the magnitude of anterior and posterior LIPC activation during the incidental learning of words predicts whether the word will be later remembered or forgotten (Wagner et al., 1998c).

Anterior and posterior LIPC activation during episodic encoding may reflect the contributions of semantic and phonological working memory processes to memory formation. Compared to control tasks, tasks that yield greater LIPC activation typically demand greater semantic processing and greater processing of the speech sounds associated with a stimulus (phonological processing). Current findings suggest that anterior LIPC may mediate semantic working memory processes such as the retrieval, selection, maintenance, or evaluation of semantic knowledge that is represented elsewhere in cortex (Demb et al., 1995; Thompson-Schill et al., 1997). Retrieval involves the arrangement of search cues and the querying of long-term semantic stores for representations matching those cues. Selection involves the resolution of competition between retrieved representations. Maintenance involves the rehearsal or refreshing of representations. Evaluation involves synthesis of the retrieved information and use of this information to determine the proper response. These processes may be involved in task performance, while simultaneously serving to organize semantic aspects of the event in consciousness. These event attributes may be input to medial temporal structures that are thought to bind together event characteristics into an episodic memory trace (Wagner et al., 1998c). During the intentional learning of verbalizable stimuli, anterior LIPC activation may reflect the volitional adoption of an encoding strategy that includes semantic elaboration (Kapur et al., 1996).

Posterior LIPC, in contrast, may mediate phonological working memory processes such as the retrieval, maintenance, or evaluation of lexical and phonological aspects of stimuli (Buckner, 1996). Posterior LIPC is active during tasks demanding access to lexical and phonological codes stored in long-term memory. For example, posterior LIPC is active during lexical decision, in which words and nonwords (e.g., "PAKE") are presented and the task is to determine for each stimulus whether it represents a word. Posterior LIPC is also active during word-stem completion, for which the task is to complete word stems (e.g., "STO__") with the first word that comes to mind (e.g., "STORE"). Furthermore, posterior LIPC activation has been noted during phonetic discrimination and monitoring. Finally, whereas studies directly examining verbal working memory often fail to reveal activation in anterior LIPC, these studies have consistently demonstrated activation in posterior LIPC during tasks requiring phonological maintenance, with activation monotonically increasing with phonological memory load (Jonides et al., 1998).

Posterior LIPC activation during intentional learning is consistent with the hypothesis that this region mediates phonological working memory processes. Behavioral studies indicate that subjects volitionally engage phonological rehearsal/maintenance operations during attempts to intentionally learn (Kapur et al., 1996). Within the context of incidental encoding, posterior LIPC activation during semantic processing tasks may reflect the phonological processing demands inherent in these tasks. Such demands may include the need to access and temporarily maintain the phonological codes of the target stimulus and of the retrieved semantic knowledge. Although these processes are likely engaged for a shorter duration during semantic processing tasks compared to typical phonological working memory tasks (and compared to intentional encoding conditions), this difference may be quantitative (i.e., a difference in duty cycle) rather than qualitative.

Importantly, LIPC activation is not restricted to episodic encoding and working memory tasks. Rather, tasks requiring episodic retrieval of verbal–semantic stimuli also elicit LIPC activation. For example, posterior LIPC activation has been noted during word-stem cued recall, where subjects are asked to complete word stems with words that were previously studied (Buckner, 1996). Similarly, comparison of yes–no recognition for words to that for nonverbalizable abstract visual patterns yields anterior and posterior LIPC activation (Wagner et al., 1998b). These results suggest that the same semantic and phonological working memory processes contribute to both the learning and the remembering of verbal–semantic stimuli.

Visuospatial Material. Although the vast majority of encoding and retrieval studies have examined episodic memory for verbal–semantic material, a number of studies have examined memory for stimuli with complex visual and spatial characteristics. In some studies, the stimuli were pictorial representations of objects that also could be verbally and semantically coded, such as drawings of common everyday objects. In other studies, the stimuli lacked semantic content and were difficult to verbally code, such as abstract visual patterns and faces. Importantly, the laterality of inferior prefrontal activation during episodic encoding and retrieval differs for visuospatial and verbal–semantic stimuli.

A number of lines of evidence suggest that right inferior prefrontal cortices (RIPC; Table 1) contribute to episodic memory for visuospatial stimuli. First, compared to control tasks, the intentional learning of visuospatial stimuli that also have associated verbal–semantic codes results in LIPC and RIPC activation. For example, posterior LIPC is more active during intentional object learning relative to passive object viewing, with this activation possibly reflecting phonological working memory processes that mediate the retrieval and maintenance of the phonological code (i.e., the name) for the object. Importantly, object learning also results in activation of a homologous region in posterior RIPC, a region that is not typically associated with the learning of verbal–semantic material (Kelley et al., 1998). Second, when intentional learning of verbal–semantic stimuli (e.g., words) is compared to that of visuospatial stimuli (e.g., abstract visual patterns and faces), RIPC regions are more active during visuospatial learning, whereas LIPC regions are more active during verbal–semantic learning (Kelley et al., 1998; Wagner et al., 1998b). Finally, this material-specific pattern of inferior prefrontal activation also has been noted when directly comparing the episodic retrieval of verbal–semantic stimuli to that of visuospatial stimuli, indicating that RIPC is engaged during the learning and the remembering of visuospatial events (Wagner et al., 1998b).

A recent review of the working memory neuroimaging literature suggests that, as in episodic memory studies, inferior prefrontal activation tends to lateralize based on the nature of the material being held in working memory. As discussed above, posterior LIPC is more active during verbal working memory conditions, whereas RIPC is more active during visuospatial working memory conditions (D'Esposito et al., 1998). RIPC regions have been posited to subserve visuospatial working memory processes that mediate the maintenance or evaluation of visual, iconic representations of stimuli and of the position of stimuli in visual space (Haxby et al., 1995). As with semantic and phonological working memory, visuospatial working memory appears to contribute to episodic memory. During the intentional encoding of visuospatial stimuli, RIPC activation may reflect the volitional recruitment of visuospatial rehearsal operations. During episodic retrieval, visuospatial representations of the test probe and of the retrieved products may be maintained in working memory as part of the retrieval process. Maintenance of the test probe may be necessary to carry out retrieval search, and maintenance of the products of retrieval may be necessary in order to make a memory decision.

One characterization of prefrontal contributions to episodic memory is the Hemispheric Encoding/Retrieval Asymmetry framework that posits that left prefrontal cortex is differentially involved in encoding, whereas right prefrontal cortex is differentially involved in retrieval (Nyberg et al., 1996). The present minireview suggests that distinct regions of LIPC and RIPC are involved during both episodic learning and remembering (Buckner, 1996). Inferior prefrontal activation associated with episodic memory appears to lateralize based on the nature of the stimuli being processed (semantic, phonological, visuospatial) rather than the nature of the mnemonic operations being performed (encoding or retrieval). It should be noted, however, that there also may be differences across encoding and retrieval in the extent to which semantic, phonological, and visuospatial working memory operations are engaged (Nyberg et al., 1996).

Dorsolateral and Anterior Prefrontal Contributions to Episodic Memory

Although LIPC and RIPC contributions to episodic memory appear to reflect material-specific working memory operations, other prefrontal regions appear to contribute to episodic memory irrespective of the nature of the material being processed. Activation has been consistently demonstrated in right dorsolateral prefrontal cortex (RDLPC) and right anterior prefrontal cortex (RAPC) during episodic retrieval (Table 1; Nyberg et al., 1996). Although these activations have tended to be right lateralized, there have been many reports of left anterior prefrontal activation. Importantly, activation in these regions appears to generalize across episodic retrieval tasks and stimulus material (Buckner, 1996). In contrast to retrieval studies, most studies of episodic encoding have failed to demonstrate activation in RAPC and RDLPC (Nyberg et al., 1996).

Although RAPC and RDLPC have tended not to be engaged during episodic encoding, a recent study revealed greater RAPC activation during semantic classification relative to passive word reading (MacLeod et al., 1998). Importantly, the semantic condition in this study also required the simultaneous counting or estimation of the number of trials in which a stimulus fit within a target category, which necessitates continuous calculation, maintenance, and updating of information about the number or proportion of target trials. These latter processes may place additional demands on working memory control functions (MacLeod et al., 1998). Thus, the presence of RAPC activation in this study may not be due to the semantic processing and episodic encoding components of the task, but rather may reflect engagement of working memory processes that mediate the manipulation or updating of the contents of working memory.

Petrides and colleagues (Owen et al., 1996) have argued for a two-stage model of working memory such that ventrolateral and dorsolateral prefrontal regions mediate distinct working memory processes. Ventrolateral regions are posited to subserve the maintenance and evaluation of representations held in working memory. As discussed above, these inferior prefrontal regions may be material specific. Dorsolateral regions, in contrast, are posited to subserve the monitoring and manipulation of the representations in working memory. These processes, which appear to be engaged regardless of the nature of the material being processed, may include “active decisions about the occurrence or nonoccurrence of stimuli from a given set” (Owen et al., 1996). Consistent with the two-stage view, neuroimaging studies indicate that inferior prefrontal regions are engaged during tasks requiring maintenance of the contents of working memory, whereas both inferior prefrontal and dorsolateral prefrontal regions are engaged during tasks requiring manipulation or updating of the contents of working memory (D’Esposito et al., 1998). However, as D’Esposito et al. (1998) note, there have been a few reports of dorsolateral activation during working memory tasks that would appear to require only maintenance operations. One post hoc interpretation of these apparent inconsistencies is that engagement of dorsolateral prefrontal cortex during maintenance tasks may reflect the unexpected recruitment of episodic retrieval strategies (Jonides et al., 1998).

The consistent demonstration of RDLPC and RAPC activation during working memory tasks requiring content monitoring, updating, and manipulation suggests that activation in these regions during episodic retrieval does not reflect processes specific to episodic memory. Rather, activation of these regions may reflect the contributions of unique working memory control processes, above and beyond the material-specific processing contributions of inferior prefrontal cortices. RDLPC and RAPC activation during episodic retrieval may reflect processes that support explicit attempts to remember the past (Buckner and Koutstaal, 1998). These processes may include the monitoring and manipulation of the products of retrieval from long-term memory, such as the careful scrutiny of specific attributes of the test item in an effort to determine whether it was encountered in a particular context or the integration of retrieved item and contextual information. Recent evidence indicates that the recruitment of these processes is strategic and depends upon the context in which episodic retrieval is performed (Wagner et al., 1998a).

Concluding Remarks

The present minireview suggests that prefrontal activation during episodic learning and remembering may be best understood as the contributions of specific working memory operations to episodic memory. Material-specific working memory functions appear to be mediated by inferior prefrontal regions, with these functions contributing to both episodic encoding and retrieval. In contrast, material-independent working memory functions appear to be mediated by dorsolateral and anterior prefrontal regions, with these functions contributing primarily to episodic retrieval. Although initial hypotheses about the specific functions of these distinct prefrontal regions have been posited, additional studies are clearly necessary to more fully characterize the nature of these working memory mechanisms and their contributions to episodic learning and remembering.

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